ABSTRACT

HESLER, GREGORY STEPHEN. Investigating the Mechanisms of Diamond Tool Wear Cutting Ferrous Materials Using a Quantitative Study of Machining Parameters. (Under the direction of Dr. Thomas A. Dow.)

Rapid tool wear occurs during the diamond turning of ferrous materials due to thermo-chemical mechanisms. Unconventional methods such as cutting in cryogenic environments and ultrasonic vibration-assisted machining have had limited success in creating specular surfaces on ferrous materials. A unique measurement technique in the scanning electron microscope has allowed the wear rate and tool edge to be quantified with sub-micron resolution. From this technique, a distinctive wear pattern was observed during ferrous machining of low-carbon steel (1215), where the wear land was not parallel to the machined surface as it is with abrasive wear.

The research described here provides a quantitative study of the dynamic parameters contributing to the thermo-chemical tool wear: temperature, tool forces, material flow and cutting edge geometry. The goal is to use these measured parameters to analyze the mechanisms behind the rapid diamond tool wear. Surface temperatures were measured with a thin-film RTD during machining. These measurements were used to predict peak temperatures during machining and compared to temperatures from finite element software. A high-speed imaging system was developed to capture images of the cutting process. The images were used to approximate the shear angle using the ratio between chip and workpiece speeds.

Machining experiments were performed using 6061 aluminum and 1215 steel to compare temperatures, forces and wear patterns. Peak temperature predictions for 6061 aluminum compared closely against previously published results. The wear measurements and peak temperature predictions for 1215 steel were used to advance an Arrhenius-type chemical wear model for diamond tools. The strong correlation is indicative of a temperature-dependent chemical mechanism for the diamond wear during ferrous machining. The wear results showed an optimal cutting speed of approximately 1 m/s at a 2 μm depth of cut for 1215 steel.

The cutting process was modeled using empirical and analytical simulations. Third Wave System’s software AdvantEdge is a finite element program for machining processes that
calculates both stresses and temperatures. The AdvantEdge software shows promise for modeling diamond tool wear during ferrous machining. The limitation of analytical wear models is the changing tool geometry. As the tool wears, the pressure, temperature and material flow across the surface changes. Finite element analysis can help model the effects of changing tool geometries by using discrete elements and nodes in the application of the wear rates. The current research compares the perimeter wear rates for the temperature model and Usui model in AdvantEdge. The predicted temperature gradient along the diamond cutting edge and rake face is low because of the high thermal conductivity of diamond. Due to the shape of the worn edge and low temperature gradient, it is predicted that other factors with temperature contribute to the localized recession at the tool edge.
Investigating the Mechanisms of Diamond Tool Wear Cutting Ferrous Materials Using a Quantitative Study of Machining Parameters

by

Gregory Stephen Hesler

A thesis submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the Degree of Master of Science

Mechanical Engineering

Raleigh, North Carolina

2014

APPROVED BY:

Dr. Ronald Scattergood
Dr. Michael Kudenov

Dr. Thomas A. Dow
Chair of Advisory Committee
BIOGRAPHY

Greg Hesler was born in Rochester, NY and moved to Charlotte, NC in 2000. He attended undergraduate at North Carolina State University and received his BS degree in Mechanical Engineering. He worked three co-op rotations with Duke Energy at various coal and natural gas plants in NC. At Duke Energy, he worked on the performance analysis of air quality control systems and as well as maintenance of plant equipment. He started at the PEC during his last semester of undergraduate in the fall of 2012, leading him to pursue his MS degree in Mechanical Engineering. His research at the PEC involves the modeling and analysis of diamond tool wear during the machining of ferrous materials. His interests outside of the lab include rugby, electric guitar, hiking, and fishing. After graduation, he is working with Siemens Energy in their Engineering Development Program.
ACKNOWLEDGMENTS

Special thanks to my parents and sisters. You all provided amazing support and have been remarkable examples for me to follow. I cannot thank you enough.

Special thanks to Dr. Dow for the opportunity and guidance throughout my graduate degree. You greatly improved my research, engineering and communication skills.

Thanks to Dr. Scattergood and Dr. Kudenov for serving on my advisory committee and all the helpful guidance during my research.

Truly special thanks to John Nowak, Sean Gunning and David Gebb for providing an enjoyable workplace. I definitely would not have made it through my graduate studies without your help and comic relief. David, I apologize about all the Brevard jokes.

Thanks to Ken Garrard for all the help with the equipment and Matlab programs. Stephen Furst for the initial DTM training and help with the data acquisition systems.

Thanks to Chardon Tool for providing the diamond tools used.

Thanks to Chuck Mooney at the AIF for the SEM training and help with the EBID measurements.

A copy of the AdvantEdge software license was granted by Third Wave Systems.

This project was funded by the National Science Foundation contract CMMI-1200318 monitored by Z. Pei.
TABLE OF CONTENTS

LIST OF FIGURES ......................................................................................................................... ix
LIST OF TABLES .............................................................................................................................. xviii
LIST OF SYMBOLS ............................................................................................................................ xxi

1 BACKGROUND ................................................................................................................................. 1
  1.1 Introduction .................................................................................................................................. 1
  1.2 Diamond Turning Overview .......................................................................................................... 2
    1.2.1 Heat Generated during Machining ...................................................................................... 7
  1.3 Review of Temperature Measurement Techniques ......................................................................... 9
    1.3.1 Resistive Thermometry Devices ......................................................................................... 10
    1.3.2 Thermocouples .................................................................................................................. 10
    1.3.3 Spectral Radiation Thermometry ....................................................................................... 11
    1.3.4 Thermophysical Materials ................................................................................................. 12
  1.4 Motivation and Work in This Thesis ............................................................................................ 12

2 TOOL WEAR DURING DIAMOND TURNING ............................................................................... 13
  2.1 Tool Wear Geometry .................................................................................................................. 13
  2.2 Thermo-Chemical Wear Mechanism ........................................................................................... 16
    2.2.1 Temperature Dependence of Wear Rate ........................................................................... 19
  2.3 Abrasive Wear (Archard Law) ..................................................................................................... 22
  2.4 Conclusion .................................................................................................................................. 24

3 DEVELOPMENT OF EXPERIMENTAL SETUP ........................................................................... 25
  3.1 Setup Overview .......................................................................................................................... 25
    3.1.1 Redesign of Tool Mount ..................................................................................................... 30
  3.2 Imaging System .......................................................................................................................... 31
    3.2.1 Microscope Flexure Design ............................................................................................... 36
    3.2.2 Cover Window Design ........................................................................................................ 40
  3.3 Temperature Measurement .......................................................................................................... 42
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.4</td>
<td>Wear Measurements</td>
<td>46</td>
</tr>
<tr>
<td>4</td>
<td>PRELIMINARY EXPERIMENTS WITH 360 BRASS</td>
<td>51</td>
</tr>
<tr>
<td>4.1</td>
<td>Force Measurements</td>
<td>51</td>
</tr>
<tr>
<td>4.2</td>
<td>Temperature Measurements</td>
<td>53</td>
</tr>
<tr>
<td>4.3</td>
<td>Imaging Results</td>
<td>57</td>
</tr>
<tr>
<td>4.4</td>
<td>Comparison to AdvantEdge Simulation Results</td>
<td>60</td>
</tr>
<tr>
<td>4.4.1</td>
<td>Forces</td>
<td>61</td>
</tr>
<tr>
<td>4.4.2</td>
<td>Temperatures</td>
<td>63</td>
</tr>
<tr>
<td>4.4.3</td>
<td>Chip Formation</td>
<td>65</td>
</tr>
<tr>
<td>4.5</td>
<td>Conclusions</td>
<td>67</td>
</tr>
<tr>
<td>5</td>
<td>PREDICTION OF PEAK TEMPERATURE</td>
<td>68</td>
</tr>
<tr>
<td>5.1</td>
<td>Analytical Model</td>
<td>69</td>
</tr>
<tr>
<td>5.1.1</td>
<td>Heat Input</td>
<td>69</td>
</tr>
<tr>
<td>5.1.2</td>
<td>Approximation of the Peak Tool Temperature</td>
<td>72</td>
</tr>
<tr>
<td>5.2</td>
<td>ANSYS Thermal Model</td>
<td>75</td>
</tr>
<tr>
<td>5.2.1</td>
<td>Boundary Conditions</td>
<td>77</td>
</tr>
<tr>
<td>5.2.2</td>
<td>Heat Input to Diamond Tool</td>
<td>78</td>
</tr>
<tr>
<td>5.2.3</td>
<td>Meshing</td>
<td>79</td>
</tr>
<tr>
<td>5.2.4</td>
<td>Process Diagram</td>
<td>80</td>
</tr>
<tr>
<td>5.2.5</td>
<td>Steady-State Relationships</td>
<td>81</td>
</tr>
<tr>
<td>5.3</td>
<td>Discussion</td>
<td>81</td>
</tr>
<tr>
<td>6</td>
<td>ALUMINUM 6061 WEAR EXPERIMENTS</td>
<td>83</td>
</tr>
<tr>
<td>6.1</td>
<td>Determining Machining Parameters for Average Cutting Speed</td>
<td>83</td>
</tr>
<tr>
<td>6.2</td>
<td>Force Measurements</td>
<td>85</td>
</tr>
<tr>
<td>6.3</td>
<td>Temperature Measurements</td>
<td>91</td>
</tr>
<tr>
<td>6.4</td>
<td>Imaging Results</td>
<td>96</td>
</tr>
<tr>
<td>6.5</td>
<td>Wear Results</td>
<td>98</td>
</tr>
</tbody>
</table>
6.5.1 Effect of Depth of Cut ................................................................. 103
6.5.2 Effect of Cutting Speed ............................................................... 105
6.6 Comparison to Ueda Temperature Results .................................... 107
6.7 Discussion of Aluminum Wear Experiments .................................. 115

7 STEEL 1215 WEAR EXPERIMENTS .................................................. 117
7.1 Force Measurements ..................................................................... 119
7.2 Temperature Measurements .......................................................... 122
7.3 Imaging Results ............................................................................ 129
7.4 Wear Results ................................................................................ 134
7.4.1 Crater Wear ............................................................................... 143
7.5 AdvantEdge Simulation Results for Steel ....................................... 147
7.5.1 Forces ....................................................................................... 152
7.5.2 Temperatures ............................................................................ 153
7.5.3 Chip Formation ......................................................................... 156
7.6 Steel and Aluminum Comparison .................................................. 158
7.6.1 Temperature Comparison for Steel and Aluminum ..................... 161
7.7 Discussion .................................................................................... 162

8 AVERAGE TEMPERATURE DEPENDENCY OF TOOL WEAR .............. 165
8.1 Temperature Dependency of Tool Wear ......................................... 165
8.2 Conclusions ................................................................................ 171

9 FINITE ELEMENT MODELING FOR TOOL WEAR ................................ 173
9.1 Third Wave AdvantEdge ............................................................... 173
9.1.1 Strain Hardening ....................................................................... 175
9.1.2 Strain Rate Sensitivity .............................................................. 176
9.1.3 Thermal Softening .................................................................... 176
9.2 Low Temperature Results Using Isothermal Boundary Conditions ...... 177
9.3 Micro-Machining Mode ............................................................... 181
Appendix K. Wear Measurements for 6061 Aluminum................................................................. 254
Appendix L. Force Measurements for 1215 Steel ........................................................................ 254
Appendix M. AdvantEdge Simulations for Steel ........................................................................... 256
Appendix N. Micro-mode AdvantEdge Simulations for Steel ....................................................... 258
Appendix O. Load Cell Amplifier Settings ..................................................................................... 259
LIST OF FIGURES

Figure 1-1. Cross-sectional view of cutting parameters and geometry for orthogonal cutting. 3
Figure 1-2. Primary, secondary and tertiary shear zones during chip formation. ............... 5
Figure 1-3. 20 μm DoC at 0.1 m/s with C36000 brass workpiece. .................................. 6
Figure 1-4. SEM image of a C36000 brass chip with 20 μm DoC and 0.1 m/s cutting speed. 7
Figure 1-5. Comparison of mean rake face temperatures predictions for 2 μm DoC for brass, steel and aluminum alloys from dimensional analysis (β = 0.1). 9
Figure 1-6. NIST temperature data for Type K thermocouple voltage. 11
Figure 2-1. Cross-sectional view of worn diamond tool. .................................................. 14
Figure 2-2. Tool profile results after 5, 10, 15, 20 m machining of AISI 1215 steel at 2.12 m/s [16]. .................................................. 15
Figure 2-3. Activation energy for chemical reaction. ....................................................... 20
Figure 2-4. Effect of activation energy and temperature on reaction rate. ....................... 22
Figure 2-5. Worn tool forces with different rake and flank friction coefficients [19]. 23
Figure 3-1. Overview of experimental setup. ................................................................. 25
Figure 3-2. Close-up of experimental setup. ................................................................. 27
Figure 3-3. Side view of orthogonal machining orientation showing the orthogonal cutting geometry. .................................................. 28
Figure 3-4. Multiple tool locations for variation of cutting parameters. ......................... 29
Figure 3-5. (a) Side view of the tool mount design and (b) tilt adjustment. .................... 30
Figure 3-6. Top view of tool mount on DTM axis showing the location of the tool mount, objective and focal point. ............................................. 31
Figure 3-7. Final scaling from imaging system at 4 μs of exposure time. ...................... 32
Figure 3-8. (a) Chip and cutting speed and (b) workpiece-chip mass balance. ............. 33
Figure 3-9. Workpiece, diamond tool and camera location during image capture. .......... 34
Figure 3-10. Flexure design for fine-adjustment of imaging system. ............................... 37
Figure 3-11. Free body diagram for the flexure design. ............................................... 38
Figure 3-12. Screw force and focal point displacement as a function of screw displacement. 39
Figure 3-13. Stress in flexure as a function of screw displacement..............................................40
Figure 3-14. Design of holder for objective cover window............................................................41
Figure 3-15. European curve for 1000 Ω platinum RTD resistance vs temperature. ...............43
Figure 3-16. (a) RTD measurement setup and (b) RTD size..............................................................44
Figure 3-17. Thin film RTD mounted on diamond tool.................................................................44
Figure 3-18. Wheatstone bridge circuit for RTD.............................................................................45
Figure 3-19. Depositing EBID strip on diamond tool edge [16].......................................................47
Figure 3-20. Imaging the EBID strip after rotating the diamond tool [16]......................................48
Figure 3-21. EBID measurement process from (a) original SEM image of EBID line (b) stretched image (c) traced EBID line using digitize11.m (d) calculation of worn area with verification of rake/relief angle and (e) rotation of tool profile using EBIDautorot.m ..........49
Figure 4-1. Cutting forces vs. DoC for 360 brass at 1 m/s cutting speed........................................52
Figure 4-2. Preliminary setup for thermocouple measurements during C36000 brass..............53
Figure 4-3. Thermocouple measurements for 2 μm DoC for C36000 brass at multiple speeds. .................................................................................................................................................54
Figure 4-4. Thermocouple measurements for 5 μm DoC for C36000 brass at multiple speeds. .................................................................................................................................................55
Figure 4-5. Thermocouple measurements for 10 μm DoC for C36000 brass at multiple speeds. .................................................................................................................................................56
Figure 4-6. Peak thermocouple temperatures vs. cutting speed at multiple depths of cut......57
Figure 4-7. Calculating chip speed and cutting speed for 20 μm DoC. Frame rate of 4000 fps and exposure time of 4 μs.................................................................58
Figure 4-8. Chip formation during machining of 360 brass with 20 μm DoC at (a) 0.1 and (b) 1 m/s cutting speed with exposure time of 4 μs.................................................................58
Figure 4-9. SEM image of C37700 brass chip from 20 μm DoC at 0.1 m/s cutting speed. ... 60
Figure 4-10. AdvantEdge simulation for 10 μm DoC with C3770 brass at 1 m/s.................61
Figure 4-11. Effect of AdvantEdge friction factor on cutting forces for C3770 brass. ..........62
Figure 4-12. Comparison of AdvantEdge (a) cutting and (b) thrust forces to experimental data for 360 brass at a cutting speed of 1 m/s.................................................................63
Figure 4-13. Peak tool temperatures from AdvantEdge for multiple DoCs and cutting speeds for C3770 brass. .................................................................................................................................................64
Figure 4-14. Peak thermocouple measurements and peak simulation tool temperature vs. cutting speed for (a) 5 and (b) 10 μm DoC. ................................................................. 64

Figure 4-15. Effective shear angle from AdvantEdge for (a) 0.5, (b) 1 and (c) 4 m/s cutting speed for 20 μm DoC with C3770 brass. ................................................................. 66

Figure 5-1. Diagram for heat input approximation. ......................................................... 69

Figure 5-2. Curve-fit for temperature measurement during 360 brass machining at 5 μm DoC and 0.5 m/s cutting speed ................................................................. 71

Figure 5-3. Expression for peak diamond temperature ............................................... 73

Figure 5-4. Distance of the heat input along worn tool edge (tool profile after 120 m machining 1215 steel) ........ ........................................................................ 74

Figure 5-5. Peak tool temperature predictions for C36000 brass machining. .............. 75

Figure 5-6. (a) Isometric (b) side and (c) top view of the CAD model for thermal analysis. 76

Figure 5-7. (a) Convective (h = 10 W/m²-K, T = 20°C) and (b) isothermal boundary condition surfaces ......................................................................................... 77

Figure 5-8. Effect of increasing convective coefficient on transient response in ANSYS. .... 78

Figure 5-9. Heat input for ANSYS thermal model ....................................................... 79

Figure 5-10. (a) Model overview and (b) diamond mesh for ANSYS thermal model. ....... 79

Figure 5-11. Process diagram for determining the relationship between the ANSYS peak temperature and the cutting velocity (steel at 1 m/s shown as example) ......................... 80

Figure 5-12. Peak RTD temperature rise vs. heat input for (a) steel and (b) aluminum workpiece widths (1 and 0.8 mm, respectively) ...................................................... 81

Figure 6-1. Tool forces during 2 μm DoC with Al 6061 at 1 m/s. .............................. 86

Figure 6-2. Average cutting forces for 2 μm DoC with Al6061 at 1 m/s cutting speed ..... 87

Figure 6-3. Average thrust forces for 2 μm DoC with Al6061 at 1 m/s cutting speed .... 87

Figure 6-4. Tool forces during 5 μm cut with Al 6061 at 1 m/s ........................................ 88

Figure 6-5. Average cutting forces for 5 μm DoC with Al6061 ........................................ 89

Figure 6-6. Average thrust forces for 5 μm DoC with Al6061 ........................................ 89

Figure 6-7. Average flank force for 2 and 5 μm DoC with Al6061 .................................... 90

Figure 6-8. Effect of cutting oil/coolant on surface temperature measurement for 2 μm DoC with Al6061 at 1 m/s cutting speed ......................................................... 91
Figure 6-9. RTD temperature for multiple cutting speeds at 2 μm DoC during Al6061 machining.

Figure 6-10. Peak temperature predictions for Al6061 at 2 μm DoC and cutting speeds of 1, 2 and 4 m/s.

Figure 6-11. Heat input from ANSYS model as a function of cutting speed.

Figure 6-12. Peak tool temperature prediction for 2 μm DoC with Al6061.

Figure 6-13. RTD temperature for multiple DoCs at 1 m/s cutting speed during Al6061 machining.

Figure 6-14. Image of chip formation machining Al6061 at 1 m/s and 2 μm DoC.

Figure 6-15. (a) EBID line on worn tool after cutting 7.5 km and (b) wear profiles for multiple cutting lengths for Al6061 at 2 μm DoC at average cutting speed of 1 m/s.

Figure 6-16. (a) EBID line on worn tool after cutting 2.5 km and (b) 5 km with (c) tool profile comparison for 5 μm DoC at average cutting speed of 1 m/s.

Figure 6-17. Wear volume from EBID measurements for 2 and 5 μm DoC with Al6061.

Figure 6-18. Edge radius from EBID measurements for 2 and 5 μm DoC with Al6061.

Figure 6-19. Archard coefficients for 2 (0.0116 μm³N⁻¹m⁻¹) and 5 μm (0.0036 μm³N⁻¹m⁻¹) depths of cut with Al6061.

Figure 6-20. EBID lines after 5 km cutting Al6061 at 1 m/s average cutting speed with (a) 2 μm and (b) 5 μm depth of cut with (c) tool profile comparison.

Figure 6-21. EBID lines after 5 km cutting Al6061 with 2 μm depth of cut at (a) 1.0 m/s and (b) 4.0 m/s average cutting speed with (c) tool profile comparison.

Figure 6-22. CAD diagram of RTD location for side-mounting.

Figure 6-23. Response time comparison of two RTD locations for 10 μm DoC at 0.5 m/s with Al6061.

Figure 6-24. RTD measurements for 10 μm DoC with Al6061 at multiple cutting speeds.

Figure 6-25. Summary of experimental RTD, model transient RTD, and model peak temperatures for multiple cutting speeds with Al6061 at 10 μm DoC.

Figure 6-26. Heat input from ANSYS model as a function of cutting speed for Al6061 at 10 μm DoC.

Figure 6-27. Relationship between peak tool temperature and heat input from ANSYS model for 10 μm DoC with Al6061.

Figure 6-28. Peak temperature predictions, RTD measurements and Ueda results.
Figure 6-29. Cutting forces vs cutting speed for 10 μm DoC with Al6061........................................ 115
Figure 7-1. Cutting forces during 1215 steel machining for 0-10 m cutting distance at 2 m/s and 2 μm DoC................................................................................................................................. 119
Figure 7-2. Cutting forces over cutting distances for multiple speeds with 1215 steel at 2 μm DoC................................................................................................................................. 120
Figure 7-3. Average cutting forces vs. cutting speed for 2 μm DoC with 1215 steel........... 121
Figure 7-4. Temperature during three wear intervals with 1215 steel at 4 m/s cutting speed. ................................................................................................................................................... 122
Figure 7-5. RTD measurements for 2 μm DoC with 1215 steel at multiple cutting speeds. 123
Figure 7-6. Summary of experimental RTD, model transient RTD, and model peak temperatures for multiple cutting speeds with 1215 steel at 2 μm DoC................................ 124
Figure 7-7. RTD temperature during 1215 steel machining at 0.5 m/s and 2 μm DoC....... 125
Figure 7-8. Heat input from ANSYS model as a function of cutting speed for 1215 steel with 2 μm DoC................................................................................................................................. 126
Figure 7-9. Peak tool temperature prediction for 2 μm DoC with 1215 steel................. 127
Figure 7-10. Cutting power (cutting force times cutting speed) and ANSYS heat input as a function of cutting speed for 1215 steel at 2 μm DoC................................................................. 128
Figure 7-11. Image of chip formation machining 1215 steel at 0.5 m/s and 2 μm DoC, 4 μs exposure time........................................................................................................................................... 129
Figure 7-12. Image of chip formation machining 1215 steel at 1 m/s and 2 μm DoC, 3 μs exposure time........................................................................................................................................... 130
Figure 7-13. SEM image of 1215 steel chip cut at 0.5 m/s................................................. 132
Figure 7-14. Higher magnification SEM image of 1215 steel chip edge cut at 0.5 m/s..... 132
Figure 7-15. SEM image of 1215 steel chip cut at 1 m/s..................................................... 133
Figure 7-16. Higher magnification SEM image of 1215 steel chip edge cut at 1 m/s........ 133
Figure 7-17. SEM images at 20 kX of tool wear after (a) 60 m at 0.5 m/s (b) 120 m at 1 m/s and (c) 120 m at 2 m/s with 1215 steel, 2 μm DoC................................................................. 135
Figure 7-18. SEM images at 25 kX of tool wear after (a) 120 m at 1 m/s (b) 120 m at 4 m/s and (c) 120 m at 6 m/s with 1215 steel, 2 μm DoC................................................................. 136
Figure 7-19. Worn tool profiles for 1215 steel for 0.5, 1 and 2 m/s cutting speeds and 2 μm DoC............................................................................................................................................... 137
Figure 7-20. Worn tool profiles for 1215 steel at 4 and 6 m/s cutting speeds and 2 μm DoC. ................................................................. 138

Figure 7-21. 2D wear area vs. cutting distance for all cutting speeds for 1215 steel. Linear regression (dotted) is also shown for each cutting speed. ................................................................. 139

Figure 7-22. 2D wear area vs. cutting time for all cutting speeds for 1215 steel. Linear regression (dotted) is also shown for each cutting speed. ................................................................. 140

Figure 7-23. 2D wear area vs. cutting distance for two separate experiments with 1215 steel at a cutting speed of 1 m/s and 2 μm DoC. ........................................................................ 140

Figure 7-24. Tool profiles at 20, 80 and 120 m cutting distances for 1215 steel at 2 μm DoC. ........................................................................ 140

Figure 7-25. Zygo NewView SWLI surface measurement of diamond rake face after 120 m machining 1215 steel at 1 m/s (37 nm PV). ........................................................................ 142

Figure 7-26. Zygo NewView SWLI surface measurement of diamond rake face after 120 m machining 1215 steel at 4 m/s (20 nm PV). ........................................................................ 143

Figure 7-27. Zygo NewView SWLI surface measurement of diamond rake face after 120 m machining 1215 steel at 6 m/s (20 nm PV). ........................................................................ 144

Figure 7-28. Zygo NewView SWLI surface measurement of rake face for a sharp diamond tool (7 nm PV) ........................................................................ 145

Figure 7-29. Crater wear for 1215 steel at 6 m/s cutting speed (x-scale in μm, y-scale in nm). ........................................................................ 146

Figure 7-30. AdvantEdge simulation with adjusted isothermal boundary conditions .......... 148

Figure 7-31. Final temperature contour plot with cutting forces and temperature plotted vs. time for 2 μm DoC at 1 m/s with 1118 steel. ........................................................................ 149

Figure 7-32. Tool temperature contour for 2 μm DoC at 1 m/s with 1118 steel. .......... 150

Figure 7-33. AdvantEdge and ANSYS temperature distributions along the cutting edge and rake face. ........................................................................ 151

Figure 7-34. Comparison of AdvantEdge and experimental tool forces as a function of cutting speed for a 2 μm DoC with 1118 and 1215 steel. ........................................................................ 152

Figure 7-35. Peak tool temperature projections and peak AdvantEdge temperatures vs. cutting speed. ........................................................................ 153

Figure 7-36. Orientation of distance variable from rake/relief data extraction in AdvantEdge. ........................................................................ 154
Figure 7-37. (a) Tool perimeter distance and (b) temperature distribution along the cutting edge and rake face for each cutting speed. ................................................................. 155

Figure 7-38. Effective shear angle (22.4°) from AdvantEdge for 1 m/s cutting speed for 2 μm DoC with 1118 steel using strain rate. ................................................................. 156

Figure 7-39. Workpiece material velocity distribution along the tool cutting edge for 1 m/s cutting speed with 1118 steel. ................................................................. 157

Figure 7-40. Worn tool profile comparison for 6061 aluminum and 1215 steel. .......... 159

Figure 7-41. Average wear rate comparison for steel and aluminum at 1 m/s and 2 μm DoC. ................................................................. 160

Figure 7-42. Temperature comparison between steel and aluminum for 1, 2 and 4 m/s cutting speeds and 2 μm DoC. ................................................................. 161

Figure 7-43. Comparison of peak temperature predictions for aluminum and steel as a function of cutting speed. ................................................................. 163

Figure 8-1. Arrhenius plot of for average 2D wear areas vs. peak temperature predictions. 166

Figure 8-2. (a) Distance wear rate and (b) time wear rate as a function of cutting speed with logarithmic x-scale for 2 μm DoC with 1215 steel. ................................................................. 168

Figure 8-3. Wear rate per distance as a function of cutting speed for 2 μm DoC with 1215 steel. ................................................................. 169

Figure 8-4. Tool profiles before and after cutting 120 m of 1215 steel at 6 m/s. .......... 170

Figure 9-1. 2D turning simulations in AdvantEdge [44]. ................................................................. 174

Figure 9-2. AdvantEdge model and mesh for large depth of cut (5-20 μm) simulations. .... 178

Figure 9-3. AdvantEdge cutting simulation for 10 μm DoC, 1 m/s cutting speed with C3770 brass. Peak tool temperature is 34.4°C. ................................................................. 178

Figure 9-4. Experimental and simulation temperature comparison for (a) 5 μm and (b) 10 μm depth of cut for brass. ................................................................. 179

Figure 9-5. Simplified 1D example showing insulating effect of tool shank. .......... 180

Figure 9-6. Micro-machining mode and standard mode comparison. .............. 182

Figure 9-7. Wear model options in AdvantEdge. ................................................................. 184

Figure 9-8. Final temperature contour plot with cutting forces and temperature plotted vs. time for 2 μm DoC at 6 m/s with 1118 steel. ................................................................. 188

Figure 9-9. Usui wear rate plotted with temperature, pressure and sliding velocity for 2 μm DoC, 6 m/s cutting speed with 1118 steel ................................................................. 189
Figure 9-10. Application of the Usui wear rate for 2 μm DoC, 6 m/s cutting speed with 1118 steel (K_u = 1.5E-14 1/Pa, α = 4015.2 K). ................................................................. 191

Figure 9-11. Wear rate from AdvantEdge temperature model plotted with temperature for 2 μm DoC, 6 m/s cutting speed with 1118 steel. ................................................................. 192

Figure 9-12. Application of the temperature wear rate for 2 μm DoC, 6 m/s cutting speed with 1118 steel (K_T = 8.5E-6, α = 4015.2 K). ................................................................. 193

Figure 9-13. Micro-mode temperature contour plot with cutting forces and temperature plotted vs. time for 2 μm DoC at 0.5 m/s with 1118 steel. ................................................................. 194

Figure 9-14. Tool temperature contour for micro-mode simulation at 0.5 m/s cutting speed. ................................................................................................................................. 195

Figure 9-15. Mesh for micro-mode simulation with 50 nm tool edge radius. ............... 195

Figure 9-16. Effective strain rate for 2 μm DoC at 0.5 m/s with 1118 steel (24°). ........... 196

Figure 9-17. Usui wear rate plotted with temperature, pressure and sliding velocity for 2 μm DoC, 0.5 m/s cutting speed from micro-mode simulation. .............................................. 197

Figure 9-18. Application of the Usui wear rate for 2 μm DoC, 0.5 m/s cutting speed from micro-mode simulation (K_u = 3.7E-13 1/Pa, α = 4015.2 K). ...................................................... 198

Figure 9-19. Wear rate from AdvantEdge temperature model in micro-mode (0.5 m/s). .... 199

Figure 9-20. AdvantEdge temperature contour for worn tool (6 m/s after 120 m), 2 μm DoC at 6 m/s cutting speed........................................................................................................ 200

Figure 9-21. AdvantEdge tool temperature distribution for worn tool (6 m/s after 120 m), 2 μm DoC at 6 m/s cutting speed. ........................................................................................................ 200

Figure 9-22. Usui wear rate plotted with temperature, pressure and sliding velocity for 2 μm DoC, 6 m/s cutting speed with a worn tool profile. ...................................................... 201

Figure 9-23. Application of the Usui wear rate for 2 μm DoC, 6 m/s with worn tool profile (K_u = 1.1E-14 1/Pa, α = 4015.2 K). .................................................................................. 202

Figure 9-24. Temperature model wear rate plotted with temperature, 2 μm DoC, 6 m/s cutting speed with worn tool profile. .................................................................................. 202

Figure 9-25. AdvantEdge strain rate for 2 μm DoC, 1118 steel at (a) 0.5 m/s in micro-mode, (b) 6 m/s in standard mode and (c) 6 m/s worn tool in standard mode......................... 203

Figure 0-1. Tool-cleaning holder for diamond preparation procedure. ...................... 219

Figure 0-2. SEM image of diamond tool with carbon tape near cutting edge. ............ 220

Figure 0-3. Thin-film RTD secured to top of diamond. ............................................... 221
Figure 0-4. Thermocouple amplifier circuit using AD8495 chip [53].............................. 223
Figure 0-5. Total internal reflection for diamond-to-air. .................................................. 225
Figure 0-6. Diamond tool IR-Fiber Raytrace for the manufactured segmented parabola. ... 226
Figure 0-7. Process diagram for the diamond tool pyrometer system. ............................. 227
Figure 0-8. Layout for the infrared detection system. ....................................................... 228
Figure 0-9. Refocusing coupler from JT Ingram Technologies ........................................ 229
Figure 0-10. Custom diamond tool for the pyrometer system ........................................ 230
Figure 0-11. MIR 8000 spectrometer .............................................................................. 231
Figure 0-12. Experimental setup for spectrum measurements ........................................... 233
Figure 0-13. Close-up of aluminum plate and diamond ................................................... 233
Figure 0-14. Non-calibrated response from single crystal diamond ................................. 235
Figure 0-15. Experimental intensity with respect to temperature at 1157cm⁻¹ ..................... 237
Figure 0-16. Theoretical intensity with respect to temperature at 1157cm⁻¹ ....................... 237
Figure 0-17. Calibration curve for a single wavelength (1157cm⁻¹) ................................. 238
Figure 0-18. Calibrated blackbody curve with $\varepsilon = 0.97$. ................................................. 239
Figure 0-19. Calibrated diamond spectra for multiple temperatures with background present. ....................................................................................................................... 240
Figure 0-20. Calibrated diamond spectra with background removed ............................... 240
Figure 0-21. Emissivity of diamond at varying temperatures ........................................... 241
LIST OF TABLES

Table 3-1. Equipment in experimental setup.......................................................... 26
Table 3-2. Diamond tool parameters. ........................................................................ 29
Table 3-3. Phantom v7.3 camera settings for high-quality DT images. .................... 35
Table 3-4. SEM settings for EBID measurement on diamond tool. ............................ 46
Table 4-1. Preliminary experiments with 360 brass. .................................................. 51
Table 4-2. Parameters for experiments measuring surface temperature during 360 brass machining................................................................. 54
Table 4-3. Calculation of shear angle from high-speed video for 360 brass. ............ 59
Table 4-4. C36000 and C37700 brass comparison [34]. ........................................ 61
Table 5-1. Thermal properties of experimental materials [34]. ................................ 68
Table 5-2. Dimensions, surface area and mass of diamond..................................... 70
Table 5-3. Heat input, temperature rise and growth rate for 2 μm DoC....................... 72
Table 5-4. Heat input, temperature rise and growth rate for 5 μm DoC....................... 72
Table 5-5. Heat input, temperature rise and growth rate for 10 μm DoC ................. 72
Table 6-1. Aluminum 6061-T6 material properties [34]. ........................................ 83
Table 6-2. Inputs and outputs from Wear_Distance program. .................................. 85
Table 6-3. Calculation of shear angle from high-speed video for Al6061. .................. 97
Table 6-4. Experimental wear results for 2 μm DoC with Al6061............................... 99
Table 6-5. Experimental wear results for 5 μm DoC with Al6061.............................. 101
Table 6-6. Comparison of wear results for 2 and 5 μm DoC with Al6061 at 1 m/s. ... 105
Table 6-7. Comparison of wear results for 2 μm DoC with Al 6061 at 1 and 4 m/s. 107
Table 6-8. Cutting parameters for temperature comparison. ................................... 109
Table 7-1. AISI 1215 steel material properties [34]. .............................................. 117
Table 7-2. Time to reach DoC and spindle speed for the steel wear experiments......... 118
Table 7-3. Calculation of shear angle from high-speed video for 1215 steel at 0.5 and 1 m/s. .............................................................................................................. 131
Table 7-4. AISI 1215 and AISI 1118 steel comparison [34]. ................................... 148
Table 7-5. Comparison of chip speed and shear angle for experimental and AdvantEdge for 2 μm DoC, 1 m/s cutting speed with steel. ................................................................. 157
Table 7-6. Comparison of specific cutting energy for steel and aluminum at 1 m/s cutting speed. .................................................................................................................. 158
Table 8-1. Data for Arrhenius-type model for 2 μm DoC with 1215 steel....................... 166
Table 8-2. Arrhenius coefficients from peak temperature predictions and average wear rates. ................................................................................................................................. 167
Table 0-1. cRIO thermocouple modules........................................................................ 222
Table 0-2. Thermocouple data...................................................................................... 223
Table 0-3. Summary of MATLAB codes. ...................................................................... 224
Table 0-4. Equipment for the diamond tool pyrometer design..................................... 225
Table 0-5. Temperature measurements during emissivity experiment........................ 234
Table 0-6. Properties of brass alloys............................................................................ 243
Table 0-7. Properties of steel alloys............................................................................. 244
Table 0-8. Properties of 6061-T6 Aluminum. ................................................................ 245
Table 0-9. Rake and relief data extraction in AdvantEdge............................................. 249
Table 0-10. Tool dimensions and mesh for large depth of cut models.......................... 250
Table 0-11. AdvantEdge process options for large depth of cut models...................... 250
Table 0-12. AdvantEdge mesh parameters for large depth of cut models..................... 250
Table 0-13. Force and peak temperatures for large depth of cut models...................... 251
Table 0-14. Wear measurements and Archard coefficient parameters for 2 μm DoC at 1 m/s for Al6061................................................................................................. 254
Table 0-15. Wear measurements and Archard coefficient parameters for 5 μm DoC at 1 m/s for Al6061 ................................................................................................. 254
Table 0-16. 1215 steel, 2 μm, 0.5 m/s......................................................................... 254
Table 0-17. 1215 steel, 2 μm, 1 m/s............................................................................. 255
Table 0-18. 1215 steel, 2 μm, 2 m/s............................................................................. 255
Table 0-19. 1215 steel, 2 μm, 1 m/s............................................................................. 255
Table 0-20. 1215 steel, 2 μm, 4 m/s............................................................................. 255
Table 0-21. 1215 steel, 2 μm, 6 m/s. ............................................................ 256
Table 0-22. Tool dimensions and mesh for steel models. ........................................ 256
Table 0-23. AdvantEdge process options for steel models. ..................................... 257
Table 0-24. AdvantEdge mesh parameters for steel models. ................................... 257
Table 0-25. Results for steel models. ...................................................................... 257
Table 0-26. Tool dimensions and mesh for micro-mode model. ............................... 258
Table 0-27. AdvantEdge process options for micro-mode model. ............................ 258
Table 0-28. AdvantEdge mesh parameters for micro-mode model. ........................... 259
LIST OF SYMBOLS

\( A \) Arrhenius Constant
\( A_c \) uncut chip area
\( c \) specific heat
\( d \) depth of cut (DoC)
\( d_b \) bolt diameter
\( d_f \) total cutting distance
\( dL \) sliding distance
\( ds \) cutting distance
\( dV \) worn volume
\( dW \) 2D wear area
\( E_a \) activation energy
\( E_c \) specific cutting energy
\( f \) feedrate
\( F_c \) cutting force
\( F_f \) average flank force
\( F_i \) piezoelectric preload
\( F_t \) thrust force
\( H \) material hardness
\( h \) convective coefficient
\( K_T \) Constant for Temperature Model - AdvantEdge
\( K_U \) Usui Material Constant - AdvantEdge
\( k \) thermal conductivity
\( m \) strain rate sensitivity
\( n \) strain hardening exponent
\( n^* \) tool life exponent
\( p \) pressure - AdvantEdge
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PEC</td>
<td>Precision Engineering Center</td>
</tr>
<tr>
<td>Q</td>
<td>heat input</td>
</tr>
<tr>
<td>q&quot;</td>
<td>heat flux</td>
</tr>
<tr>
<td>R</td>
<td>Universal gas constant</td>
</tr>
<tr>
<td>RPM</td>
<td>spindle speed</td>
</tr>
<tr>
<td>(\sigma_t)</td>
<td>normal pressure</td>
</tr>
<tr>
<td>T</td>
<td>temperature</td>
</tr>
<tr>
<td>(t_c)</td>
<td>average chip thickness</td>
</tr>
<tr>
<td>(t_f)</td>
<td>total cutting time</td>
</tr>
<tr>
<td>(T_L)</td>
<td>tool life</td>
</tr>
<tr>
<td>(\tau)</td>
<td>torque</td>
</tr>
<tr>
<td>v</td>
<td>cutting speed</td>
</tr>
<tr>
<td>(\bar{v})</td>
<td>average velocity</td>
</tr>
<tr>
<td>(v_c)</td>
<td>chip speed</td>
</tr>
<tr>
<td>(v_s)</td>
<td>sliding velocity</td>
</tr>
<tr>
<td>(\dot{V})</td>
<td>volume wear rate</td>
</tr>
<tr>
<td>w</td>
<td>workpiece width</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>Temperature Constant - AdvantEdge</td>
</tr>
<tr>
<td>(\mu_f)</td>
<td>flank friction coefficient</td>
</tr>
<tr>
<td>(\mu_r)</td>
<td>rake friction coefficient</td>
</tr>
<tr>
<td>(\rho)</td>
<td>density</td>
</tr>
<tr>
<td>(\phi)</td>
<td>shear angle</td>
</tr>
</tbody>
</table>
1 BACKGROUND

1.1 INTRODUCTION

Diamond turning (DT) is a precision lathe operation where workpiece material is removed by a single crystal diamond tool. The DT process is typically performed on a machine with precise air or oil bearings with axis displacement controlled with interferometric measurements. Developed in the early 1970s, DT allows for the creation of high-quality optical surfaces and molds for those surfaces without the need of traditional optical-polishing methods [1]. A DT process will typically have depths of cut of less than 10 μm.

With the highest hardness of any material, single-crystal diamond is an ideal cutting tool. It can be lapped to from an extremely sharp, smooth cutting surface. The smooth cutting surface of diamond can be used to create parts with a surface roughness less than 10 nanometers, giving a mirror-like quality to the surface. Despite these properties, the diamond will undergo wear from the contact during machining. Tool wear is an extremely important factor in the DT process. Excessive tool wear can lead to inadequate diamond turned parts by changing the edge geometry and degrading the surface finish [2]. The cutting edge of the diamond must remain sharp and free of defects to generate an optical surface. With the high cost of new and re-surfaced tools, the impact of tool wear on cost is significant. In the material removal process, especially DT, machining parameters are of great concern to improve the procedure and reduce costs associated with worn tooling. Tool wear is affected by many parameters, including tool and workpiece chemical properties and various cutting parameters (cutting speed, feedrate, coolant, and tool condition).

DT produces a high-quality surface finish by accurately cutting away a thin layer, or chip, of the workpiece surface. DT can create optical surfaces on soft ductile materials that would be difficult to produce in the traditional lapping or polishing method [1]. Some typical diamond-turnable materials are non-ferrous metals such as aluminum, brass, copper, and electroness nickel. Brittle materials like germanium, optical glass, zinc selenide, and silicon have also been successfully machined using DT [3]. Not all of these material are diamond machined easily
and require optimal manufacturing conditions to produce quality surface finishes. The preferred materials that can produce optically smooth and geometrically stable surfaces are 6061 aluminum, oxygen free high conductivity copper (OFHC) copper, electroplated copper, electroless nickel, brass and certain polymers [4].

One major disadvantage of DT is the high tool wear that occurs during the machining of ferrous materials (iron and steel). Ferrous alloy workpieces such as stainless steel are attractive for dies due to their high resistance to wear. Ferrous materials could be used to manufacture wear resistant precision molds if they could be produced economically. When compared to a brass of similar hardness, the wear rate of a diamond tool when machining steel is over $10^4$ greater [5]. The wear is believed to be caused by thermo-chemical effects, but the mechanisms behind this significant increase are not completely understood. Potential tool wear mechanisms include adhesion, abrasion and chemical wear. Chemical wear is a strong function of heat generated and increases with increasing temperature. During cutting, these mechanisms can occur simultaneously and interactively. Experiments by Evans et al. [6] have shown that the chemical reaction rate and wear can be reduced by cooling the workpiece or tool to cryogenic levels. Shi [3] investigated the effect of thermo-chemical mechanisms by evaluating the wear from two steels and comparing to non-ferrous materials. Vibration assisted machining (VAM), particularly elliptical VAM (EVAM) has been shown to increase the total cutting distance for diamond tools. Lane [7] observed that tool wear rates with VAM were not necessarily less than conventional machining at similar speeds, but that the unique cutting mechanics created a better surface finish at similar wear levels. Evaluating the tool temperature and modeling its effect on the diamond wear rate is the motivation behind this work.

### 1.2 DIAMOND TURNING OVERVIEW

This research utilizes a 2D orthogonal cutting setup where the tool rake face and cutting direction align [8]. Using a flat nose tool (infinite nose radius) results in the depth of cut to remain constant across the tool cutting edge. This allows the cutting process to be modelled two-dimensionally. Figure 1-1 shows a simplified cross-sectional view of the orthogonal diamond turning process. A diamond tool is fed at a constant federate into a rotating workpiece
to produce a desired depth of cut (DoC), \(d\). A chip forms as material is removed from the workpiece. The cutting speed, \(v\), is defined as the surface speed of the workpiece as it encounters the diamond tool. The tool shown in Figure 1-1 has a 0° rake angle and a 6° clearance angle.

![Diagram](image)

**Figure 1-1.** Cross-sectional view of cutting parameters and geometry for orthogonal cutting.

The direction of the tool thrust and cutting forces are shown in Figure 1-1. The workpiece material undergoes intense deformation and shearing in a plane between the workpiece surface and the tool rake face called the shear plane. Figure 1-1 shows the shear angle, \(\phi\), that defines the orientation of the shear plane. The removed material forms a chip with average thickness \(t_c\) and chip velocity \(v_c\) [9]. The shear angle, DoC, cutting speed, chip thickness, and chip velocity share the following relationship for a tool with 0° rake angle.
\[ \tan \phi = \frac{v_c}{v} = \frac{d}{t_c} \]  \hspace{1cm} (1.1)

As the shear angle increases, the average chip thickness decreases and the ratio of the chip velocity to cutting speed increases. Equation (1.1) can be used to calculate different cutting parameters from measured values such as chip speed or chip thickness.

The relationships shown in Figure 1-1 and Equation (1.1) are for the idealized orthogonal cutting where simple shearing takes place on an infinitely narrow zone (shear plane). The results are qualitatively correct, however, the model is oversimplified. In reality, metals will strain harden when deformed, which will expand the shear plane into a shear zone. This is typically referred to as the primary shear zone and is shown in Figure 1-2. Materials with higher strain hardening exponents and strain rate sensitivity will have larger primary shear zones. Heat is generated during shearing which raises the temperature of the material. The increased temperature reduces the flow stress called the thermal softening effect.
Figure 1-2. Primary, secondary and tertiary shear zones during chip formation.

The normal pressure on the tool rake face from the formation of the chip is large. Frictional heat is generated as the chip slides on the rake face. Sliding of the chip can be arrested when the product of the rake face friction coefficient and pressure exceed the material shear flow stress \( (\mu \sigma_t > \tau_f) \). At this point, intense shearing allows the chip material to move upwards when the material contacting the tool is stationary. The location of this process is known as the secondary shear zone and is another source of heat. At the tool cutting edge, the freshly generated workpiece surface rubs and slides past the tool. This third source of heat generation is known as the tertiary shear zone [9].

The actual chip formation will also deviate from the ideal case shown in Figure 1-1, where a chip of uniform thickness is continually generated. The periodic shearing will cause the inner side of the chip to be jagged as shown in Figure 1-3. At some intermediate speed, the formation of a built-up edge (BUE) will occur. The BUE is stationary material located on the tool edge
that acts as an extension of the tool. This increases the effective rake angle of the tool. Figure 1-4 shows a Scanning Electron Microscope (SEM) image of a C36000 brass chip with a corresponding shear angle of 26.5° (90°-63.5°). C36000 brass is a free-cutting material due to the addition of lead, which reduces the shear strength. As a result, the chip is more segmented with a non-uniform thickness [9].

Figure 1-3. 20 μm DoC at 0.1 m/s with C36000 brass workpiece.
1.2.1 Heat Generated During Machining

The vast majority of energy expended during the machining process will be converted into heat in the three zones shown in Figure 1-2. A percentage of the heat will be removed with the chip or enter the workpiece, but a portion of the heat will enter the tool. Shaw made an estimate of the temperature distribution along the tool (non-diamond) rake face using dimensional analysis and the assumption that all expended energy is converted into heat [10]. The dimensional analysis produces a single non-dimensional constant, $\beta$.

$$\frac{T_r}{E_c} \left( \frac{k \rho c}{v d} \right)^{1/2} = \beta \Rightarrow T_r = \beta E_c \left( \frac{v d}{k \rho c} \right)^{1/2},$$

(1.2)

where $E_c$ is the specific cutting energy, $T_r$ is the mean rake face temperature, $v$ is the cutting speed, $d$ is the DoC, $k$ is the thermal conductivity, $\rho$ is the density and $c$ is the specific heat. The specific cutting energy is defined as the cutting energy (cutting force, $F_c$, multiplied by
the distance, \( l \), over which the force acts) consumed to remove a unit volume of material [9], shown in Equation (1.3).

\[
E_c = \frac{F l}{dwl} = \frac{F_c}{dw}
\]  

(1.3)

The non-dimensional constant, \( \beta \), is for a specific tool and environment (cutting fluid and ambient temperature) [10]. Equation (1.2) shows that higher temperatures are expected for materials with high specific cutting energies, low thermal conductivities, low densities or low specific heats.

Figure 1-5 shows an example for the mean rake face temperature of a brass, steel and aluminum alloy at multiple cutting speeds with arbitrary \( \beta \) value of 0.1 using Equation (1.2). The material properties of the alloys are given in the Appendices (Table 0-6, Table 0-7 and Table 0-8). Figure 1-5 shows that the predicted mean temperature rise for the steel alloy is over 4x greater than the brass and aluminum alloy. This is due to the high specific cutting energy and low thermal conductivity of steel.
Temperature is an important parameter behind tool wear mechanisms, especially chemical-based wear. A system to measure the temperature at the chip-tool interface would be valuable to identify the tool wear mechanisms.

1.3 REVIEW OF TEMPERATURE MEASUREMENT TECHNIQUES
The measurement of temperature and its effects during the material removal process has been widely studied due to the importance it has on tool wear. Davies et al. [11] compares the benefits and limitations of six different temperature measurement methods for material removal processes. Resistance thermometry devices (RTDs), two types of thermocouples, single and two-color pyrometers, and thermophysical temperature measurement methods are discussed in detailed. Komanduri et al. [12] also evaluated the performance of six different experimental techniques used to measure heat generated in manufacturing processes. The review included single-point turning process as well as tribological applications such as heat
generated in sliding contact. The temperature measurement techniques examined included embedded and dynamic thermocouples, infrared photography, infrared pyrometers, thermal paint, material melting points, and metallographic methods. Komanduri provides an extensive review of previous experimental setups and results as a guide to select an appropriate temperature measurement technique.

The measurement methods can be summarized by four general types: resistive thermometry devices, thermocouples, spectral radiation thermometry and thermophysical materials.

1.3.1 **RESISTIVE THERMOMETRY DEVICES**

RTDs and thermistors are resistors whose resistivity changes with temperature. RTDs are positive temperature coefficient (PTC) sensors, so their resistance increases with increasing temperature. They are typically made of platinum or nickel, which offer predictable changes in resistance with temperature.

Thin film RTDs are available that have dimensions small enough to fit on the surface of the diamond tool with fast response times. In commercial thin film RTDs, platinum is deposited on a ceramic substrate with a glass coating. Yoshioka et al. [13] developed an in-process micro-sensor for diamond machining by using a thin layer of deposited platinum on the surface of the diamond tool. The micro-sensor essentially used the diamond as the substrate for the construction of a micro-sized RTD.

1.3.2 **THERMOCOUPLES**

Thermocouples consist of two dissimilar metal leads connected at a single point, typically called the hot junction. A voltage potential is generated between the wires when the hot junction is heated. This is known as the thermoelectric effect. Thermocouples are inexpensive and can be precision manufactured with small wire gauge and bead diameters (hot junction connection) to reduce response times. Figure 1-6 shows the relationship between voltage and temperature for Type K thermocouples, which is slightly non-linear.
The limitation of thermocouples is the non-linearity and small generated voltage. For a surface temperature of 100°C, the generated voltage is only approximately 5 mV. This low voltage can cause difficulty in the measurements. The hardness of the diamond prevents any temperature measuring device from being embedded in the tool, so thermocouples or RTDs have to be surface mounted to monitor tool temperature.

### 1.3.3 Spectral Radiation Thermometry

Spectral radiation thermometry (SRT) uses thermal radiation from a body to determine its thermodynamic temperature. SRT shows promise for providing high time-resolution and accuracy needed for the DT process. There are several classifications of SRTs depending on the radiation wavelength, detection method and number of wavelength bands measured. Narrow or spectral band thermometers collect light over one wavelength and are often referred to as single-color pyrometers. Ratio thermometers collect radiation over two narrow wavelengths to compare the energies and reduce the effect of emissivity, which is the ratio of the exitance of an actual source to the exitance of a blackbody [14]. These are often called two-color pyrometers. SRTs are non-intrusive and have fast response times making them attractive to applications relating to the material removal process.
Udea et al. [15] used an infrared radiation pyrometer to measure the temperature on the rake face during DT. The infrared (IR) photons radiated at the chip-tool interface were transmitted through the diamond and into a chalcogenide optic fiber. The fiber transmits the IR radiation to InSb and HgCdTe detectors. The maximum temperature and temperature distribution were also calculated numerically using a finite element model (FEM). From the IR radiation measurement, the maximum tool temperature was approximated using the calculated temperature distribution. For a 10 µm depth and a cutting speed of 10 m/s, the maximum temperature on the rake face was approximately 190°C for aluminum and 220°C for copper. As expected, the temperatures increased as the cutting speed increased. A pyrometer system was designed but not implemented in this research. Details of the design are discussed in Appendix E. Pyrometer Design.

1.3.4 THERMOPHYSICAL MATERIALS

This technique involves using materials that undergo thermophysical processes at known temperatures to predict the temperature at the area of interest. This includes thermo-sensitive paints, thermochromatic liquid crystals, thermographic phosphors, and pyromatic cones [11].

1.4 MOTIVATION AND WORK IN THIS THESIS

This research is a continuation from previous work conducted at the PEC analyzing the wear of diamond tools during ferrous machining [3,8,16,17]. The objective of this research is to provide a quantitative study of the parameters contributing to diamond tool wear: temperature, pressure, chip formation and cutting edge geometry. High-magnification images of the tool-chip interface with temperature and force measurements from the diamond cutting tool will provide a better understanding of tool wear conditions and a corroboration with models. With information from this project, more research can be conducted on the thermo-chemical mechanisms behind diamond tool wear. If the relationship between diamond temperature and diamond wear could be established, tool design and the accuracy of the models predicting the DT process could be improved. With improved models of the DT process, cutting parameters such as speed, feed, lubricant could be analyzed and optimized to reduce manufacturing cost.
2 TOOL WEAR DURING DIAMOND TURNING

The analysis of tool wear has been an important manufacturing research topic for the past century. The goal of research in this area is typically to identify the mechanisms behind the tool wear, and then take steps to mitigate the rate of tool wear. The capability to predict tool wear is important to the design of cutting tools and determination of optimal cutting parameters [9]. Reducing tool wear can help to significantly reduce manufacturing costs.

Progressive or gradual tool wear is produced by various mechanisms, which are typically temperature-dependent. The difficulty in the analysis of tool life and tool wear is the complex nature of the metal removal process. High strain rates and temperatures affect material properties. The variable material properties combined with the tool geometry and cutting parameters create a large number of variables. This chapter will outline tool wear basics and describe possible mechanisms contributing to the diamond tool wear in ferrous machining.

2.1 TOOL WEAR GEOMETRY

Figure 2-1 shows the typical profile of a worn diamond tool with the same orientation as the diamond tool shown in Figure 1-1. The basic profile in Figure 2-1 for a worn diamond tool includes of a round cutting edge with cutting radius $r$ and a flat wear land on the flank face. Crater wear refers to concave sections that form on the tool rake face. The changes in the cutting radius and wear land profile will combine to form the cross-sectional worn area shown in Figure 2-1. The cutting radius and cross-sectional worn area will increase as the cutting distance increases.
Previous diamond tool wear studies have produced different definitions and methods for the quantification of the tool ‘wear’ or ‘wear rate’. Lane [16] provides a detailed literature review of the different measures of wear and wear rate to compare the limits of previous methods. The term ‘wear rate’ will apply to the cross-sectional worn area (2D wear area) divided by the cutting distance. The longer distance a tool can machine while maintaining an acceptable surface finish, the more cost-effective manufacturing process. Defining wear rate in this manner allows the comparison to be made directly, regardless of cutting speed.

The sub-micron level of wear is the main difficulty in the analysis of diamond tool wear. This small scale of wear must be measured using equipment such as a scanning electron microscope (SEM), an atomic force microscope (AFM) or scanning white light interferometer (SWLI)
The measurement method in this research uses an electron beam induced deposition (EBID) line from a SEM to quantify the cross-sectional worn area shown in Figure 2-1. The method allows the tool profile to be measured and is discussed further in Section 3.4. Lane and Shi used this technique to observe the unique worn tool geometry that occurs during the diamond machining of the low-carbon AISI 1215 steel, as shown in Figure 2-2 [8,16,18,19].

![Cut Direction](image)

**Figure 2-2.** Tool profile results after 5, 10, 15, 20 m machining of AISI 1215 steel at 2.12 m/s [16].

Figure 2-2 shows the angled wear land on the diamond tool after 5, 10, 15 and 20 m cutting 1215 steel. The wear area is much less than 1 μm², requiring precision equipment like the SEM to measure. Combined with the difficulty of the wear measurement, thermo-chemical tool wear in precision diamond turning is difficult to model empirically due to the unknown temperatures and pressures that occur at the chip-tool interface. The high temperatures generated by the plastic deformation in the shear zones and tool-workpiece friction are thought to cause an
increase in thermo-chemical reactions that lead to rapid tool wear when machining ferrous materials.

The diamond tool wear during the machining of steel will be influenced by several different mechanisms. Li et al. [20] provide an extensive review of the diamond turning of ferrous materials. In the review, they categorize the diamond tool wear mechanisms into four groups:

a) **Tribo-thermal**: thermal degradation [6]

b) **Tribo-chemical**: graphitization, diffusion, carbide formation and oxidation

c) **Abrasion**: micro-chipping, fracture and fatigue

d) **Adhesion**: built-up edge (BUE) formation and removal (micro-welding)

Of these components, thermo-chemical wear has been considered the most dominant mechanism for the machining of ferrous materials.

### 2.2 Thermo-Chemical Wear Mechanism

Many researchers have investigated the wear of diamond tools during ferrous machining. Thorton et al. [5] propose that the high wear rate of diamond into steel can be caused by the graphitization of the diamond. Graphitization occurs when the carbon atoms in the diamond lattice break apart and form the lower energy compound graphite. The surface layer of graphite is then continually removed during the cutting process. However, little information was known about the temperatures at the cutting interface.

Shimada et al. [21] suggest that the primary thermo-chemical wear mechanism changes at around 900-1000 K. At temperatures greater than 1000 K (727°C), the wear rate is controlled by the disassociation of carbon atoms from the diamond tool, such as diffusion. Below 900 K (627°C), Shimada claims the mechanism involves the removal of carbon atoms from oxidization of the diamond combined with the deoxidization of the iron oxide. During experiments, Shimada generated erosion pits on diamond samples in contact with pure iron and stainless steel at wire temperatures of 873-1173 K. The pure iron caused a greater wear
rate than the stainless steel. At 1173 K (900°C), pure iron removed the diamond surface at 3.7 nm/s (0.0037 μm/s).

Li et al. [20] claim that graphitization of diamond carbon is the primary contribution to the chemical wear mechanism. Diamond is a metastable allotrope of carbon with graphite being the most stable form at standard conditions. There is a large activation energy barrier between diamond and graphite (730 kJ/mol for dodecahedral face and 1060 kJ/mol for octahedral face), the conversion process is negligible under atmospheric pressure and ambient temperatures [22].

They list four factors that can cause graphitization:

1) High temperatures at interface
2) Pressures beneath the diamond stable region
3) The catalytic action of the iron and atmosphere
4) Enhanced activity of the newly generated workpiece surface

Paul et al. [22] extensively reviewed and analyzed the chemical aspects to diamond tool wear. They hypothesized that the chemical mechanism in diamond tool wear is correlated with the unpaired “d” electrons in the workpiece sample. The unpaired “d” electrons in the workpiece allow the carbon-carbon diamond bond to break and undergo a metal-carbon (or metal-carbon-oxygen in the presence of oxygen) complex formation. Therefore, materials with unpaired “d” electrons will tend to cause high wear rates in diamond tools. Paul acknowledged that the complex formation can take several paths:

- Carbon atoms return back to diamond structure
- Form graphite structures
- React with environment (air or coolant hydrocarbons)

 Seal [23] heated diamond powder samples at 1000-2000°C. The samples heated up to 1200°C showed only diamond diffraction patterns. The samples heated up to 2000°C gave only graphite patterns. Samples heated to 1600°C gave both graphite and diamond patterns.
• Diffusion of carbon atoms into workpiece

They note that previous experimental results do not commonly differentiate between the final chemical mechanisms (i.e. diffusion or graphitization). Chemical reaction equations are often written as a single step (i.e. reactants → products). However, most chemical reactions involve multiple molecular events, or elementary steps, during the overall reaction. These types of reactions are known as multi-step reactions. In multi-step reactions, the rate of the overall reaction (reactants → products) is controlled by the slowest step in the reaction, known as the rate-limiting step\(^2\) [24]. Paul [22] concluded that for chemical tool wear in diamonds, the transition (metal-carbon) complex formation is the rate-limiting step. Since the reaction rate will be directly related to the diamond tool wear rate, the final step is not as important as the factors affecting the transition complex.

Brinksmeier et al. [25] experimented with previously examined wear reduction techniques including cryogenic turning, turning in inert gas atmosphere, ultrasonic vibrating cutting tool, tool modifications and protective coatings. Two of the results indicate evidence for thermo-chemical wear mechanisms. He showed that turning in cryogenic temperatures reduced the wear by an order of magnitude. The tool wear was quantified by measuring the width of the wear land with an AFM. The ultrasonic cutting experiments showed reductions in tool wear by two orders of magnitude\(^3\). More importantly, he noted that the maximum cutting distance (defined as the machined cutting distance until surface roughness exceeded 40 nm Ra) did not linearly vary with cutting time (defined as the fraction of the oscillation where the tool is cutting). This indicates the wear behavior is not simply a function of the mechanical contact time. The reduced cutting time during ultrasonic machining decreases the temperature of the tool. This implies that the temperature has an effect on the wear behavior, similar to the cryogenic experiments. Evans et al. [6] also performed cryogenic diamond turning

\(^2\) Also known as the rate-determining step.

\(^3\) Lane [16] showed that there is little reduction in tool wear from the EVAM or LVAM process. He concluded that the unique mechanics of the vibrating tool helps to improve surface finish even when machining with a worn tool. However, he showed no significant reduction wear rate.
experiments. They machined 35 mm diameter 400 series stainless steel flats with a surface finish of 25 nm Ra. Without cryogenic conditions, the rapid tool wear caused cutting to cease before the flat could be fully machined. The specific chemical mechanism was not discussed.

For further analysis of the specific reactions that are occurring, molecular dynamics (MD) simulations could help to predict the exact chemical mechanisms taking place. Narulkar et al. [26] used MD simulations between diamond and iron to investigate the chemical interaction taking place. They performed the simulations at three temperatures (300, 800 and 1600 K) and three contact times (0, 40 and 80 picoseconds). In the simulations, diffusion only occurred when a diamond-graphite interlayer was added to the diamond and no diffusion occurred at the lower temperature (300 K). In later MD simulations, Narulkar et al. [27] claimed to provide evidence of graphitization during the machining of pure iron with diamond.

Cheng et al. [28] also constructed MD simulations of the nanometric cutting of a single crystal silicon plate with a diamond atomic force microscope (AFM) tip. The simulations were created to model and analyze diamond tool wear. The stress and temperature in the diamond tip were calculated in the model. The inverse relationship between diamond sublimation energy and temperature was also noted. They proposed that the decrease in sublimation energy will weaken the cohesion bonds of carbon-carbon. They calculated a peak temperature of 813 K (540°C).

**2.2.1 Temperature Dependence of Wear Rate**

Paul et al. [22] proposed that the rate of chemical wear in diamond tools would depend on the formation of intermediary complexes. Once formed, the complexes can take several pathways. The carbon atoms could return to the diamond lattice, form graphite, react with environmental atoms or diffuse into the workpiece. However, the temperature dependency for these reaction rates are each governed by the Arrhenius function. The Arrhenius function defines the rate constant, $k$:

$$k = A \exp \left( -\frac{E_a}{RT} \right),$$  \hspace{1cm} (2.1)
where \( A \) is the pre-exponential constant, \( R \) is the universal gas constant, \( T \) is the temperature and \( E_a \) is the activation energy. The pre-exponential term \( A \) depends on the entropy of the specific complex formed [22]. Equation (2.1) provides empirical relationships for temperature-dependent processes such as diffusion or creep. The activation energy is the critical energy needed for the reaction to occur. The larger the activation energy, the more energy a reaction needs to reach the transition state (Figure 2-3).

![Activation energy for chemical reaction.](image)

**Figure 2-3.** Activation energy for chemical reaction.

When applying to chemical tool wear, the formula would describe the volumetric wear rate of tool material as

\[
\dot{V} = \frac{dV}{dt} = A \exp \left( \frac{-E_a}{RT} \right),
\]

where \( \dot{V} \) is the volumetric wear rate, \( A \) is the pre-exponential constant, \( T \) is the interface temperature (chip-tool or workpiece-tool) and \( E_a \) is the activation energy. \( E_a \) and \( A \) are
empirically determined constants from wear experiments. The volumetric loss in Equation (2.2) is associated with a thermo-chemical mechanism, such as graphitization or diffusion.

Lane [17] developed a chemical-based model for diamond tool wear for 1215 steel using FE temperature results and the Arrhenius function. The temperature results from the AdvantEdge FE simulations were linear with cutting speed. From wear measurements (2D area/cutting distance), cutting velocities and FE temperatures, he determined the Arrhenius coefficients by using Equation (2.3).

\[
\ln\left(\frac{dW}{ds}\right) = \frac{-E_a}{R} T^{-1} + \ln(A)
\]  

(2.3)

The slope of the linear regression for Equation (2.3) is the activation energy divided by the universal gas constant and the intercept is \(\ln(A)\). After the coefficients are known, the wear rate per distance can be calculated as a function of cutting speed using the following function:

\[
\frac{dW}{ds} = \frac{A}{v} \exp\left[\frac{-E_a}{RT}\right].
\]  

(2.4)

The exponential term in Equation (2.4) is plotted as a function of temperature in Figure 2-4. Increasing the temperature or decreasing the activation energy results result in the exponential increase of the reaction rate.
Figure 2-4. Effect of activation energy and temperature on reaction rate.

Lane showed that Equation (2.4) gave a minimum wear rate at a certain cutting speed. The minimum is at the balancing point between increased time for the chemical reaction to occur (lower cutting speed) and increased temperatures (higher cutting speed). Lane’s model predicted a minimum wear rate at 2.0 m/s at a 1 μm DoC with 1215 steel. Brinksmeir et al. [25] measured a minimum wear rate at a cutting speed of 75 m/min machining AISI 1045 at a 5 μm DoC. They were measuring the width of the wear land with an AFM to quantify the tool wear at a specific cutting distance.

2.3 ABRASIVE WEAR (ARCHARD LAW)

For the diamond turning of non-ferrous metals, abrasive wear is the main mechanism behind tool wear. For the Archard wear law, the wear is proportional to the applied force and sliding distance, \( V \):

\[
V = dWw = K F_d d_f ,
\]  

(2.5)
where $dW$ is the 2D wear area from the EBID measurements, $w$ is the material width, $K$ is a constant of proportionality (wear volume per unit load and sliding distance), $F_f$ is the average flank force, and $d_f$ is the sliding distance (total cutting distance).

To get the average flank force, $F_f$, from forces measured during cutting experiments, Lane [19] derived Equation (2.6). The force diagram for the worn tool is shown in Figure 2-5.

$$F_f = \frac{F_t - \mu_r F_c}{1 - \mu_r \mu_f}. \quad (2.6)$$

In Equation (2.6), $F_t$ is the thrust force, $F_c$ is the cutting force, $\mu_r$ is the coefficient of friction on the rake face and $\mu_f$ is the coefficient of friction on the flank face. For his experiments using 6061-T6 aluminum, a flank face friction coefficient of 0.2 was used and 0.4 for the rake face.

![Figure 2-5. Worn tool forces with different rake and flank friction coefficients [19].](image)
Lane [19] compared the tool wear rate while machining 6061 aluminum and 1215 steel. The 6061 aluminum has a greater distribution (3% to 1.5%) and size (44 μm² to 31 μm²) of hard particles when compared to 1215 steel [3]. Although greater abrasive wear is expected for 6061 aluminum, experiments showed over a 300x greater wear volume per cutting distance for 1215 steel compared to 6061 aluminum [19]. This indicates that another wear mechanism is dominant during the diamond turning of 1215 steel.

2.4 CONCLUSION

Rapid tool wear occurs during the diamond turning of ferrous materials. Strong evidence of thermo-chemical wear is the decrease of wear rate in low-temperature environments [6,25]. Another result indicative of temperature-dependent chemical wear is the presence of a minimum wear rate as a function of cutting speed [17,25]. The minimum wear rate is at the balancing point between slow-speed machining, where increased time is given for the chemical reactions to occur, and high-speed machining, where increased temperatures increase reaction rates. Other methods such as VAM increase the total cutting distance that can be achieved while maintaining acceptable surface finish, but do not decrease tool wear [16].

The goal of analyzing tool wear in manufacturing research is usually to identify the mechanisms behind the tool wear, and then take steps to reduce the rate of tool wear. The term wear rate in this research will refer to the measurement of wear (2D wear area) per cutting distance. This allows a direct comparison to be made, since the longer distance a tool can machine, the more cost-effective the process. By identifying the mechanisms behind the rapid tool wear, the cutting parameters can be optimized to improve the economics of diamond turning ferrous materials.
3 DEVELOPMENT OF EXPERIMENTAL SETUP

3.1 SETUP OVERVIEW

The experimental setup is shown in Figure 3-1 and Figure 3-2. The experiments utilized the Pneumo ASG 2500 Diamond Turning Machine (DTM). A DTM is a precision computer numerically controlled (CNC) lathe with a polished single point diamond tool. The ASG has two orthogonally configured precision slideways with hydrostatic oil bearings. The spindle is supported by a porous air bearing. Workpieces are mounted to the spindle (z-axis) using a vacuum chuck. The tool is mounted on the DTM x-axis.

Figure 3-1. Overview of experimental setup.
The ASG utilizes a laser interferometric measurement system to measure the $x$ and $z$ slide positions. The resolution of the measurement is 2.5 nm [29]. The high-speed camera is attached to the back of the microscope apparatus with the optical light source attached to the top. The entire optical system (camera, microscope, objective, and light source) is a separate mount, allowing the user to focus the image by adjusting the distance between the camera and the workpiece/tool. The cutting surface of the diamond tool is set parallel to the spindle movement in the $z$-axis. The DTM spindle moves in the $z$-axis, changing the distance from the camera. The cutting tool is focused using the camera microscope mount. Once the tool is located inside the camera’s field of view, the workpiece is brought into focus using the DTM $z$-axis. Table 3-1 gives the equipment used in the experiments.

<table>
<thead>
<tr>
<th>Table 3-1. Equipment in experimental setup.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DT Machine</strong></td>
</tr>
<tr>
<td><strong>Camera</strong></td>
</tr>
<tr>
<td><strong>Microscope Mount</strong></td>
</tr>
<tr>
<td><strong>Objective</strong></td>
</tr>
<tr>
<td><strong>Light Source</strong></td>
</tr>
<tr>
<td><strong>Load Cell</strong></td>
</tr>
<tr>
<td><strong>Load Cell Amplifier</strong></td>
</tr>
</tbody>
</table>
The cutting tool holder is secured to a three-axis dynamometer, or load cell, that measures tool forces. The orthogonal cutting setup is shown in Figure 3-3 with the positive $x$-axis and $z$-axis for the DTM and the orientation of the load cell. The Kistler 9251A load cell is a piezoelectric sensor with two axes in shear and one axis in compression. It has a range of $\pm 2.5$ kN in the $x$ (thrust force) and $y$ (cut force) directions with an approximate stiffness of 1000 N/μm. A natural frequency of 11.6 kHz was measured for the shear directions after an excitation with a mallet. The $z$ (side force) axis has a range of $\pm 5$ kN and stiffness of 2600 N/μm. The load cell has a sensitivity of 8 pC/N in the $x$ and $y$ directions and 4 pC/N in the $z$ direction [30]. The load cell output was connected to the 3-channel Kistler 5004 amplifier to increase the voltage. The settings for the 5004 amplifier are given in Appendix O. Load Cell Amplifier Settings with the calibration factors. The amplifier channels has a maximum output of 10 V. For the settings
given in the Appendix, this corresponded to a maximum force (cut and thrust) of approximately 40-45 N.

**Figure 3-3.** Side view of orthogonal machining orientation showing the orthogonal cutting geometry.

All the diamond tools used in this research were provided by Chardon Tool. The tools have flat cutting edges for 2D orthogonal cutting. Table 3-2 shows the dimensions and materials for the diamond tools.
Table 3-2. Diamond tool parameters.

<table>
<thead>
<tr>
<th>Diamond Type</th>
<th>Monocrystalline Synthetic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rake Angle</td>
<td>0°</td>
</tr>
<tr>
<td>Clearance Angle</td>
<td>6°</td>
</tr>
<tr>
<td>Cutting Edge Width</td>
<td>3.7 mm</td>
</tr>
<tr>
<td>Diamond Height</td>
<td>1.5 mm</td>
</tr>
<tr>
<td>Diamond Depth</td>
<td>4 mm</td>
</tr>
<tr>
<td>Tool Shank Material</td>
<td>High-Density Tungsten Alloy</td>
</tr>
<tr>
<td>Brazing Alloy</td>
<td>Cu-Ag-Ti</td>
</tr>
</tbody>
</table>

The 3.7 mm wide flat cutting edge allows for multiple locations for orthogonal cutting experiments. The width of the experiment workpieces ranged from 0.8 to 1.0 mm. Figure 3-4 shows the three locations that were used on the diamond tools. This allows multiple cutting parameters to be tested at the three locations. The cutting edge width and diamond depth from Table 3-2 are shown in Figure 3-4.

Figure 3-4. Multiple tool locations for variation of cutting parameters.

---

4 Mi-Tech Metals Super Chatter Free HD17.7 Tungsten-Based Metal
3.1.1 REDESIGN OF TOOL MOUNT

The tool mount was redesigned to allow image capture during orthogonal cutting. The design allows the fine adjustment of the tool height using the height adjustment knob and a fine thread set screw shown in Figure 3-5(a). The height is locked into place by using the height lock bolts. The tilt angle can be adjusted by using the \( \frac{1}{4} \)“ mounting bolt as a pivot. The tilt adjustment set screws can be rotated to control the tilt angle, as shown in Figure 3-5(b).

Figure 3-5. (a) Side view of the tool mount design and (b) tilt adjustment.

When preloading the load cell (25 kN specified by the Kistler datasheet), the tilt adjustment set screws are tightened against the \( \frac{1}{4} \)“ tool mount to set the desired angle of the tool. A torque wrench is used to apply the necessary preload using the following torque specification:

\[
\tau = KF_d, \quad (3.1)
\]
where τ is the calculated torque, K is the torque coefficient, $F_i$ is the piezoelectric preload, $d_b$ is the bolt diameter [31]. For a ¼” mounting bolt and a torque coefficient of 0.2, the calculated torque is approximately 32 N-m. Once the preload is applied, the tilt adjustment screws can be released. The design allows the objective to focus on the cutting interface, shown in Figure 3-6. The load cell location can also be seen in Figure 3-6.

![Figure 3-6](image)

**Figure 3-6.** Top view of tool mount on DTM axis showing the location of the tool mount, objective and focal point.

### 3.2 Imaging System

To record video and capture images of DT chip formation, an imaging system with a combination of high frame rate and high magnification must be used. High-magnification imaging of fast moving objects requires a short exposure time to reduce image blurring. For example, an object with a surface speed of 1 m/s will move 1 μm during every μs of exposure.
If the object size is 10 µm with an exposure time of 5 µs, the object will move half its size during the exposure, resulting in significant motion blur. The exposure time must be minimized to reduce blur caused by the workpiece motion for any high-magnification images.

Short exposure times require a high light intensity source that provides enough light to the area of interest. Short exposure time (2-3 µs) means there is little time for photons to pass through the polysilicon gate and generate a voltage on the camera’s sensor. The Prior Lumen 200 light source has a 200 W metal arc lamp and liquid light guide. The output of liquid light guide connects into the top of the microscope mount, as shown in Figure 3-1. The Prior Lumen 200 source provided enough illumination to capture magnified images of the machining process at 2-4 µs of exposure time. Figure 3-7 shows an image during the machining of 360 brass captured with 4 µs exposure time.

![Image](image-url)

**Figure 3-7.** Final scaling from imaging system at 4 µs of exposure time.
The Edmund ReflX 36x objective was chosen to provide the desired magnification. Figure 3-7 shows the imaging system’s field of view (446 x 334 μm). The Phantom® V7.3 camera has an 800x600 pixel resolution. The pixel scaling of the image is 0.5578 μm/pixel (446 μm divided by 800 pixels). The goal of the image capture is to observe the nature of the material removal process. Parameters such as chip thickness and speed need to be determined from the images to compare with the finite element models.

The chip thickness can be estimated using a conservation of mass equation. Figure 3-8(a) defines the variables and Figure 3-8(b) shows the mass balance diagram.

![Diagram](image)

**Figure 3-8.** (a) Chip and cutting speed and (b) workpiece-chip mass balance.

The cutting speed and chip velocity can be determined by analysis of the recorded videos. By tracking a feature on the workpiece and chip, the camera pixel spacing and camera frame rate can be used to determine the two speeds. After determining the chip velocity, $v_c$, from the recorded video, the average chip thickness, $t_c$, can be calculated as follows

$$ t_c = d \frac{v}{v_c}, \quad (3.2) $$
where \( v \) is the cutting speed and \( d \) is the depth of cut. With this approximation of the average chip thickness, Equation (1.1) can be used to estimate the effective shear angle.

To record the highest quality image/video of the diamond turning process, the following steps should be taken:

1. After securing the workpiece, use a tool with a nose-radius to eliminate any axial (z-axis) run-out from the workpiece. This will eliminate any variation in the z-axis so the workpiece stays in focus throughout an entire rotation.
2. Set the tool even with the front of the workpiece, as shown in Figure 3-9. The fine focus on the microscope mount can be used to focus on the side face of the diamond tool.
3. The workpiece can be moved into focus by jogging the spindle z-axis with the jog pendant. Set the jogging feedrate to 1 mm/min.

By following these steps, the chip, workpiece and tool should remain in focus during the image capture. The best images were recorded at this front location on the tool. High-quality images of the chip formation have not been captured when cutting takes place away from the edge of the tool.

**Figure 3-9.** Workpiece, diamond tool and camera location during image capture.
Table 3-3 shows the best settings for the high-speed camera. Motion blur can be reduced by lowering the cutting speed (0.1-1 m/s) or decreasing the exposure time. The Phantom v7.3 camera is capable of 1 μs exposure times, but image brightness became an issue at 1-2 μs. 3 μs exposure time is a good starting point.

**Table 3-3.** Phantom v7.3 camera settings for high-quality DT images.

<table>
<thead>
<tr>
<th>Camera</th>
<th>Phantom v7.3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Exposure time</strong></td>
<td>3-5 μs (depending on cutting speed)</td>
</tr>
<tr>
<td><strong>Frame rate (images per second)</strong></td>
<td>6000 fps</td>
</tr>
<tr>
<td><strong>Bit depth</strong></td>
<td>14-bit (maximum)</td>
</tr>
<tr>
<td><strong>Sensitivity</strong></td>
<td>64 (maximum)</td>
</tr>
<tr>
<td><strong>Gain</strong></td>
<td>0.20-0.30</td>
</tr>
<tr>
<td><strong>Gamma</strong></td>
<td>0.75-0.85</td>
</tr>
</tbody>
</table>

From Table 3-3, the exposure time is the length of time that the shutter remains during a single image. During the exposure time, photons generate a voltage on the camera’s sensor. The camera frame rate is the number of images recorded every second.

The bit depth corresponds the number of bits used to record the brightness (or color) of a single pixel. The number of grayscale shades that can be recorded by the sensor is the exponential of the bit depth. In the 8-bit setting, a single pixel can take on $2^8$ or 256 colors or brightness levels. At the maximum bit depth of 14-bit, a single pixel can take on $2^{14}$ or 16,384 colors or brightness levels.

The apparent camera sensitivity can be adjusted using the sensitivity slide bar when images are recorded with a bit depth greater than 8. When converting the images back to 8-bits, the software can take the most significant 8 bits, the least significant 8 bits, or an intermediate value. The sensitivity affects the pixel values by
\[ x_{ij} = S \left[ \frac{2^8}{2^b} \right] x_{ij,0}, \]  

(3.3)

where \( x_{ij} \) is the output pixel value, \( S \) is the sensitivity factor, \( b \) is the recorded bit depth and \( x_{ij,0} \) is the input pixel value.

The gain adjustment changes the contrast of the image by multiplying the value of each pixel by a constant number called the gain. If the gain value is greater than 1, all the pixel values are increased causing the image brightness to increase. Similarly, if the gain is less than 1, all the pixel values are decreased causing the brightness to decrease. If the gain is 1, then the pixel values do not change. The mathematical function is

\[ x_{ij} = \alpha x_{ij,0}, \]  

(3.4)

where \( x_{ij} \) is the output pixel value, \( \alpha \) is the gain and \( x_{ij,0} \) is the input pixel value. In the Phantom Camera Control, the gain has a range from 0.1 to 10.

The gamma adjustment is another brightness control function that is not as intuitive as the gain adjustment. The mathematical function for the gamma adjustment is given by

\[ x_{ij} = P_{\text{max}} \left( \frac{x_{ij,0}}{P_{\text{max}}} \right)^\gamma, \]  

(3.5)

where \( x_{ij} \) is the output pixel value, \( \gamma \) is gamma, \( x_{ij,0} \) is the input pixel value and \( P_{\text{max}} \) is the maximum pixel value (255 at a bit depth of 8). In the Phantom Camera Control, the gamma value has a range from 0.1 to 10.

### 3.2.1 Microscope Flexure Design

Flexural bearings or blade flexures are a common device in precision applications to generate accurate and repeatable short-range motion [32]. The imaging system (microscope mount, objective, and camera) has a total weight of 17.6 lb with a center of gravity at 7.16” from the front of the objective. The flexure design uses a cantilever flexure that is shown in Figure 3-10. Displacement of the flexure is controlled by a differential adjuster screw (Thorlabs DAS110). The differential screw’s fine adjustment has a lead of 25 μm/rev.
The free body diagram for the flexure mount is shown in Figure 3-11. $Y$ is the vertical offset from the top of the aluminum mounting plate to the focal point of the reflective objective and $A$ is the horizontal distance from the flexure to the differential screw. By maximizing the ratio of distance $A$ to the offset $Y$, a greater mechanical advantage can be achieved, which results in a finer adjustment of the focal point.
The sum of moments about the flexure ($L$ in Figure 3-11) is

$$\sum M = M_0 - WB + F_s A,$$  \hspace{1cm} (3.6)

where $W$ is the weight of the camera and mount, $F_s$ is the force of the differential screw and $M_0$ is the internal moment of the flexure. The internal moment in the flexure is given by

$$M_0 = \frac{EI}{L} \theta = k_t \theta,$$  \hspace{1cm} (3.7)

where $k_t$ is the torsional stiffness of the flexure, $E$ is the elastic modulus, $I$ is the moment of inertia, and $L$ is the length of the flexure. By making the small angle assumption, the following relationship can be approximated between the displacement of the adjuster screw, $x_s$, and the angle of the cantilever, $\theta$:

$$x_s \approx \theta.$$  \hspace{1cm} (3.8)

Using Equations (3.8), (3.7) and (3.6) the force on the adjuster screw, $F_s$, can be calculated as a function of the screw displacement, $x_s$. 

**Figure 3-11.** Free body diagram for the flexure design.
\[ F_s = \frac{WB + k_s x_s}{A} \]  

(3.9)

Figure 3-12 shows the plot of the screw force and focal point displacement as a function of the screw displacement. It shows that the screw force goes to zero after 3500 μm of screw displacement, which means the entire weight of the camera is supported by the flexure. With approximately 1000 μm of focal point displacement, the system has a mechanical advantage of approximately 3.5.

![Screw Force and Focal Point Displacement](image)

**Figure 3-12.** Screw force and focal point displacement as a function of screw displacement.

The stress in the flexure was analyzed to make sure the yield stress was not reached in the flexure at maximum displacement of the screw. The stress in the flexure is calculated by
\[
\sigma = \frac{M_0 y}{I} = \frac{M_0 h}{2I},
\]

where \(M_0\) is the internal moment of the flexure, \(h\) is the flexure thickness and \(I\) is the moment of inertia. The yield stress of 6061-aluminum is approximately 40000 psi. The flexure stress is plotted as a function of screw displacement in Figure 3-13 along with yield stress. It is shown that at maximum displacement (most negative) of the adjuster screw, the stress in the flexure is approximately 16000 psi. A stress analysis was also performed in ANSYS to check the stress at maximum loading. The results confirmed a maximum stress of approximately 16000 psi (15757 psi).

![Graph of stress in flexure as a function of screw displacement.](image)

**Figure 3-13.** Stress in flexure as a function of screw displacement.

### 3.2.2 Cover Window Design

A cover window was placed over the objective to prevent debris from damaging the mirror surfaces. The window is a 1” diameter float glass with a thickness of 1 mm from Edmund
Optics. The window is coated with a high-efficiency anti-reflective coating that increases the transmittance to 99% for visible light. The holder was manufactured using the 3D printer at the NCSU Hunt Library. The printer uses ABS thermoplastic in 0.254 mm layers to create 3D parts from CAD models. The design was a beveled snap-fit for easy cleaning and replacement of the window. The cover window assembly is shown in Figure 3-14.

![Diagram of holder for objective cover window.](image)

**Figure 3-14.** Design of holder for objective cover window.

The Edmund Optics reflective objective has a correction for the back focal length and cover glass thickness. It is important to verify the objective is set to the correct setting prior to attaching the objective cover. For this experimental setup, there is an infinite back focal length with a 1 mm thick cover glass.

---

5 The back focal length is the distance from the last optical surface to the image plane.
3.3 Temperature Measurement

Several different measurement techniques and devices were considered to monitor the temperature of the diamond tool. An initial design concept was a pyrometer system that used the diamond as a waveguide for infrared light. The infrared light emitted at the cutting edge due to machining would be transferred to an infrared detector to monitor temperature. More detail on this design is included in Appendix E. Pyrometer Design.

The high thermal conductivity of the diamond allows surface temperatures to be measured with fast response times due to the efficient heat transfer through the diamond tool. Measuring the surface temperature with RTDs or thermocouples was determined to be more feasible for this research. Precision thermocouples, 100 Ω thin-film RTDs and 1000 Ω thin-film RTDs were purchased and used to measure surface temperatures. The final temperature sensor selection was the 1000 Ω thin-film RTD from Measurement Specialties (previously RTD Company, Inc.). RTDs have better sensitivity and stability when compared to thermocouples. The thin-film RTD is manufactured by depositing a thin layer of platinum on a ceramic substrate then coating the element with glass. The change in resistance exhibits good linearity, as shown in Figure 3-15.
**Figure 3-15.** European curve for 1000 Ω platinum RTD resistance vs temperature.

A CAD diagram of the setup and thin-film RTD size is shown in Figure 3-16 (a) and (b). The RTD leads are soldered to the pins of a PCB connector. The PCB connector (shown in Figure 3-17) allows the leads to be attached after the diamond tool is in place. The RTD is secured to the diamond tool surface using thermally conductive epoxy (TC-2810 from 3M). More details of the assembly can be found in Appendix B. Securing RTD to Diamond Tool.
Figure 3-16. (a) RTD measurement setup and (b) RTD size.

A picture of the final assembly is shown in Figure 3-17.

Figure 3-17. Thin film RTD mounted on diamond tool.

Figure 3-18 shows the Wheatstone bridge circuit used to measure the RTD temperature. The current passing through the thin-film RTD needs to remain under 1 mA to prevent errors from
self-heating. An excitation voltage of 1.75 V was supplied to the bridge circuit. This keeps the current passing through the RTD under 1 mA (0.875 mA at 0°C).

![Wheatstone bridge circuit for RTD.](image)

**Figure 3-18.** Wheatstone bridge circuit for RTD.

The bridge voltage $V_0$ from Figure 3-18 is measured during the cutting experiments. As the RTD temperature increases, the resistance increases. This causes a positive increase in the bridge voltage, $V_0$, for the configuration shown in Figure 3-18. Since the all the resistors have started with the same resistance, the sensitivity of the bridge voltage is the following:

$$
\Delta V_0 = V_s \left[ \frac{\Delta R_{RTD}}{R} \right] \left[ \frac{4 + 2(\Delta R_{RTD}/R)}{} \right],
$$

(3.11)

where $\Delta R_{RTD}$ is the change in resistance of the RTD, $R$ is the other resistance values and $V_s$ is the supply voltage. Increasing the RTD temperature from 0°C to 100°C increases the resistance by 380 Ω. With a supply voltage of 1.75 V, the sensitivity of the temperature measurement is 1.397 mV/°C, using the change in bridge voltage from Equation (3.11).
The temperature measurements from the thin-film RTD will be used to make predictions on the peak temperature at the cutting edge. The low thermal mass of the RTD and high thermal conductivity of the diamond creates a fast response time for surface temperature measurements. The prediction of the peak temperature will be based on the voltage measurements and are discussed in Chapter 5.

### 3.4 Wear Measurements

One of the greatest difficulties in analyzing diamond tool wear is quantifying the small volume or area of wear that occurs during machining. The wear is often on the sub-micrometer level and cannot be measured using standard equipment, such as an optical microscope. A technique previously developed at the PEC uses an electron beam-induced deposition (EBID) line in a scanning electron microscope (SEM) to quantify the diamond tool wear. The greatest benefit from this technique is the characterization of the tool edge. The EBID measurement gives the shape of the cutting edge, which can be extremely useful in analyzing the mechanisms behind the tool wear. Shi et al. provides a full review of the technique [33]. More information on the development of the technique can be found in Lane’s thesis [16]. A summary of the SEM settings used in this research are given in Table 3-4.

#### Table 3-4. SEM settings for EBID measurement on diamond tool.

<table>
<thead>
<tr>
<th>Setting</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scanning Electron Microscope</strong></td>
<td>JEOL JSM-6400F FESEM</td>
</tr>
<tr>
<td><strong>Beam energy</strong></td>
<td>2 keV</td>
</tr>
<tr>
<td><strong>Beam current</strong></td>
<td>3 pA</td>
</tr>
<tr>
<td><strong>Working distance</strong></td>
<td>13 mm</td>
</tr>
<tr>
<td><strong>Air pressure during deposition</strong></td>
<td>&lt; 2x10⁻⁶ Torr</td>
</tr>
<tr>
<td><strong>Scan Rate at 10,000x</strong></td>
<td>182 µm/ms (Superfast scan mode)</td>
</tr>
<tr>
<td><strong>EBID line deposition time</strong></td>
<td>10-240 s (depending on tool condition)</td>
</tr>
<tr>
<td><strong>Objective aperture</strong></td>
<td>30 µm</td>
</tr>
<tr>
<td><strong>Imaging dwell time</strong></td>
<td>8 µs</td>
</tr>
<tr>
<td><strong>Image pixel count</strong></td>
<td>1000 x 800</td>
</tr>
</tbody>
</table>
The EBID method uses hydrocarbon contamination growth to form a line perpendicular to the diamond cutting edge. The hydrogen contamination line is produced when the high energy electron beam dissociates hydrocarbon contaminates found in the SEM chamber and on the sample surface [3]. When in line scan mode, a stripe of contamination is formed and can be used as a contrasting agent. The line is deposited from the flank face to the rake face of the cutting tool as the cutting edge is vertical. This process is shown in Figure 3-19.

![Figure 3-19. Depositing EBID strip on diamond tool edge [16].](image)

The EBID line acts as a contrasting source once the tool is rotated 45° and allows for the 2D cross-section of the tool to be evaluated. The final imaging process is shown in Figure 3-20.
After the final SEM image is obtained, Figure 3-21 details the steps taken to calculate the worn tool area and get the tool profile. The procedure is as follows:

1. Stretch the digital image by a ratio of approximately $1/\cos(45\pm2^\circ)$ to accommodate for the $45^\circ$ tilt and the $\pm1-2^\circ$ errors in the mechanical tilt of the SEM sample stage [Figure 3-21 (a) to (b)].

2. Trace the EBID line with at least 8 points on the flat sections of the flank and rake face using the digitize11.m Matlab program [Figure 3-21 (c)].

3. The program determines the worn area by creating two interpolated lines along the rake and flank face and then calculating the area between the lines and the EBID points [Figure 3-21 (d)].

4. The clearance angle is assumed to be known and constant ($6^\circ$ in this research) from the manufacturer’s specifications. The tool edge angle is also calculated during the wear area calculation. The stretching process from (a) to (b) must be iterated until the tool edge angle matches the manufacturer’s specification ($84^\circ$ in this research). The following equation can be used to determine the stretch ratio, $R_s$, for the image:
\[ R_s = \frac{\tan(\theta_m/2)}{\tan(\theta_t/2)} \]  

where \( \theta_m \) is the measured angle and \( \theta_t \) is 84° (90° - clearance angle).

5. After the angle is sufficiently close to the specification \((\approx 0.1°)\), the program `EBIDautorot.m` is used to rotate the tool profile so the theoretical sharp edge is located at the origin and the rake face is on the y-axis.

**Figure 3-21.** EBID measurement process from (a) original SEM image of EBID line (b) stretched image (c) traced EBID line using `digitize11.m` (d) calculation of worn area with verification of rake/relief angle and (e) rotation of tool profile using `EBIDautorot.m`. 
The sample preparation procedure can be found in Appendix A.1 Sample Preparation for EBID Measurement.
4 PRELIMINARY EXPERIMENTS WITH 360 BRASS

UNS C36000 brass (360 brass) was used to perform initial experiments during the development of the experimental setup. 360 brass or free-machining brass has a 100% machinability rating [34]. The brass alloy has an increased lead content (2.5-3.7%). In free-machining materials, the incorporation of inclusions or second phase particles typically reduce the shear strength in the shear zones, reducing the cutting forces [9]. A complete list of material properties for the 360 brass is given in Appendix G (Table 0-6).

Minimal material pickup was noticed when machining 360 brass with diamond. Multiple preliminary experiments were performed with negligible tool wear during the development of the experimental procedure. Large DoCs (20 μm) were also performed at low speeds (0.1 m/s) to capture clear videos of the chip formation process. The FE software AdvantEdge from Third Wave systems was used to compare temperature and cutting force results.

4.1 FORCE MEASUREMENTS

Initial experiments were performed at multiple DoCs to compare with simple cutting models and simulation results. A Vickers hardness test was done on the 360 brass material. The results of the Vickers hardness test and experimental parameters are summarized in Table 4-1.

<table>
<thead>
<tr>
<th>Material</th>
<th>UNS C36000 brass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vickers Hardness (MPa)</td>
<td>136</td>
</tr>
<tr>
<td>Hardness (MPa)</td>
<td>1339</td>
</tr>
<tr>
<td>Cutting Speed (m/s)</td>
<td>1</td>
</tr>
<tr>
<td>Depth of Cut (μm)</td>
<td>2, 5, 10, 15, 20, 25</td>
</tr>
<tr>
<td>Workpiece Thickness (mm)</td>
<td>0.8</td>
</tr>
</tbody>
</table>
An approximation of the cutting force can be made by multiplying the hardness by the uncut chip area.

\[ F_c \approx H A_c \]  \hspace{1cm} (3.13)

For the orthogonal cutting conditions used in this research, the uncut chip area is simply the workpiece thickness multiplied by the depth of cut. The experimental cutting forces and the hardness approximation are shown in Figure 4-1 for a cutting speed of 1 m/s.

**Figure 4-1.** Cutting forces vs. DoC for 360 brass at 1 m/s cutting speed.

Figure 4-1 shows that the experimental cutting force and the approximation from Equation (3.13) give comparable magnitudes. The cutting force increases linearly with DoC. The thrust forces increased from 2 to 4.5 N from 2 to 5 μm DoC then stayed approximately constant with DoC.
4.2 Temperature Measurements

The temperature measurement system was being developed during the experiments with 360 brass. Tool temperature measurements were captured using a type-K thermocouple secured to the top surface of the diamond using aluminum tape. The temperature measuring system is shown in Figure 4-2.

![Thermocouple secured to top of diamond](image)

Figure 4-2. Preliminary setup for thermocouple measurements during C36000 brass.

The parameters for the experiments are summarized in Table 4-2. Multiple cutting speeds from 0.5 m/s to 4 m/s were used to observe the effect on temperature measurements. No cutting oil was used due to possible interference with surface temperature measurements. The output of the thermocouple fluctuated when cutting oil was used, likely due to intermittent contact with the fluid.
Table 4-2. Parameters for experiments measuring surface temperature during 360 brass machining.

<table>
<thead>
<tr>
<th>Material</th>
<th>UNS C36000 brass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting Speed (m/s)</td>
<td>0.5, 1, 2, 4</td>
</tr>
<tr>
<td>Depth of Cut (μm)</td>
<td>2, 5, 10</td>
</tr>
<tr>
<td>Total Cutting Time (s)</td>
<td>8-10</td>
</tr>
<tr>
<td>Workpiece Thickness (mm)</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Figure 4-3, Figure 4-4 and Figure 4-5 show the temperature measurements for 2, 5 and 10 μm DoC, respectively.

**Figure 4-3.** Thermocouple measurements for 2 μm DoC for C36000 brass at multiple speeds.
From Figure 4-3 and Figure 4-4, the faster cutting speeds have greater initial slopes with respect to time and reach higher temperatures. Cutting is stopped after 12 s in Figure 4-3 and 11 s in Figure 4-4.

**Figure 4-4.** Thermocouple measurements for 5 μm DoC for C36000 brass at multiple speeds.
Figure 4-5. Thermocouple measurements for 10 μm DoC for C36000 brass at multiple speeds.

The rise in temperature in Figure 4-5 for the 4 m/s cutting speed experiment at 6 s is due to cutting chips getting underneath the tape that secured the thermocouple to the diamond surface. The cutting chips increased the temperature measurement from the thermocouple. The peak recorded cutting temperatures from the thermocouple are plotted as a function of cutting speed in Figure 4-6 for all three DoCs. The tool temperature appears approximately linear with cutting speed for the three DoCs.
4.3 IMAGING RESULTS

The highest quality images can be recorded at large DoCs and slow cutting speeds. The larger DoC gives more pixels from the camera to view the chip formation process. At slower cutting speeds, the workpiece and chip move shorter distances during the exposure time so less motion blur occurs. Figure 4-7 shows process of tracking chip and workpiece features to calculate velocities and shear angle. Figure 4-7 has four consecutive video frames (1-4) during a 20 μm DoC with 360 brass at 0.1 m/s cutting speed. The downward arrow tracks a feature on the chip while the horizontal arrow tracks a feature on the workpiece. By knowing the pixel spacing (0.5578 μm/pixel) and frame rate (4000 frames/sec), the velocity of the workpiece surface and chip can be calculated using the distance moved by the features between frames. With the velocities calculated, Equation (1.1) can be used to approximate the average chip thickness and shear angle.
Figure 4-7. Calculating chip speed and cutting speed for 20 μm DoC. Frame rate of 4000 fps and exposure time of 4 μs.

Figure 4-8 shows images from 0.1 and 1 m/s cutting speeds for 20 μm DoC. The chip (v_c) and workpiece velocities (v) are given in Table 4-3 with calculations for the shear angle.
Figure 4-8. Chip formation during machining of 360 brass with 20 μm DoC at (a) 0.1 and (b) 1 m/s cutting speed with exposure time of 4 μs.

Table 4-3. Calculation of shear angle from high-speed video for 360 brass.

<table>
<thead>
<tr>
<th>Depth of Cut (μm)</th>
<th>20</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting Speed (m/s)</td>
<td>0.1</td>
<td>1</td>
</tr>
<tr>
<td>Calculated Chip Speed (m/s)</td>
<td>0.067</td>
<td>0.411</td>
</tr>
<tr>
<td>Calculated Workpiece Speed</td>
<td>0.11</td>
<td>0.958</td>
</tr>
<tr>
<td>Shear Angle</td>
<td>26.1</td>
<td>23.2</td>
</tr>
<tr>
<td>Average Chip Thickness (μm)</td>
<td>40.8</td>
<td>46.6</td>
</tr>
</tbody>
</table>

From the video analysis in Table 4-3, the shear angle for 360 brass was 26.1° and 23.3° for 0.1 and 1 m/s cutting speeds. An SEM image of a brass chip is shown in Figure 4-9 from the experiment performed in Figure 4-8(a). A shear angle of 26.5° was measured from the visible shear bands in the SEM image. This agrees with the shear angle result from the video analysis in Table 4-3.
AdvantEdge is a commercial FE program from Third Wave Systems that calculates forces, temperatures, stresses, pressures and several other machining parameters. AdvantEdge simulations were run to compare results with the preliminary experiments. The simulations were run in standard (non-‘micro’) mode with a larger cutting radius (1 μm) that is 20x the actual tool edge radius. The standard mode has larger time steps and faster computation times (8-16 hours depending on minimum element size and number of nodes). The model overview is shown in Figure 4-10. The top and right tool BCs are 20°C isothermal. The other tool faces are adiabatic with frictional heating and conduction heating input from the workpiece and chip.
Figure 4-10. AdvantEdge simulation for 10 μm DoC with C3770 brass at 1 m/s.

Complete list of tool parameters, process options and workpiece mesh are located in Appendix I. Large Depth of Cut Simulations AdvantEdge (Table 0-11, Table 0-12 and Table 0-13). The AdvantEdge material library did not include C36000 brass, so C37700 forging brass was selected due to similarities in material properties, shown in Table 4-4. More details on the AdvantEdge software is discussed in Chapter 9.

Table 4-4. C36000 and C37700 brass comparison [34].

<table>
<thead>
<tr>
<th>Material</th>
<th>UNS C36000</th>
<th>UNS C37700</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus of Elasticity (GPa)</td>
<td>97</td>
<td>105</td>
</tr>
<tr>
<td>Machinability</td>
<td>100%</td>
<td>80%</td>
</tr>
<tr>
<td>Thermal Conductivity (W/m-K)</td>
<td>115</td>
<td>120</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>8.49</td>
<td>8.44</td>
</tr>
<tr>
<td>Specific Heat (J/g·°C)</td>
<td>0.38</td>
<td>0.38</td>
</tr>
</tbody>
</table>

4.4.1 Forces

The steady-state cutting forces from the AdvantEdge simulations were compared to the experimental measurements. The frictional factor in AdvantEdge was modified until the
cutting force matched the experimental cutting force. Figure 4-11 shows effect of the friction factor on the cutting and thrust forces for 10 μm DoC. The friction factor was decreased from 0.5 (default) to 0.08. From the slopes of the regression lines in Figure 4-11, the friction factor had larger effect on the thrust force ($\Delta 1.76$ N / $\Delta 0.1$ coefficient) than the cutting force ($\Delta 1.48$ N / $\Delta 0.1$ coefficient).

![Graph showing effect of friction factor on cutting and thrust forces](image)

**Figure 4-11.** Effect of AdvantEdge friction factor on cutting forces for C3770 brass.

A friction factor of 0.08 resulted in similar experimental and simulation cutting forces, shown in Figure 4-12(a). The thrust forces in Figure 4-12(b) were underestimated for a friction factor of 0.08.
Figure 4-12. Comparison of AdvantEdge (a) cutting and (b) thrust forces to experimental data for 360 brass at a cutting speed of 1 m/s.

Differences in the experimental workpiece material and AdvantEdge material may be the cause of the low friction factor. C36000 brass has a greater machinability than C3770 brass (100% to 80%) and a higher lead content. The hardness of the C36000 was determined using a Vickers hardness test, but no sample of C3770 was tested. The simulation material (C3770) had a lower machinability, so the friction factor had to be lowered to match the cutting forces of the free-machining material. As shown in Figure 4-11, the friction factor has a greater effect on the thrust force. This resulted in the thrust forces to be underestimated.

4.4.2 TEMPERATURES

The simulation peak tool temperature is the highest temperature from the tool nodes during the simulations. The simulation peak tool temperatures are shown in Figure 4-13 as a function of cutting speed for multiple DoCs.
Figure 4-13. Peak tool temperatures from AdvantEdge for multiple DoCs and cutting speeds for C3770 brass.

Figure 4-14. Peak thermocouple measurements and peak simulation tool temperature vs. cutting speed for (a) 5 and (b) 10 μm DoC.
In Figure 4-14, the peak tool temperatures are compared to the peak thermocouple measurements from Figure 4-6. Figure 4-14 shows that the peak temperatures measured by the thermocouple exceeded the peak tool temperatures predicted by the AdvantEdge simulations. This is caused by the high thermal conductivity of the diamond and isothermal boundary conditions used by the simulations. This issue is discussed in more detail in Section 9.2.

4.4.3 CHIP FORMATION

The effective shear angle from AdvantEdge can be approximated by measuring the angle of maximum strain rate. Using the AdvantEdge Quick Analysis toolbar in Tecplot, the contour can be changed to plastic strain rate. This will modify the contour plot to show the plastic strain rate. Figure 4-15 shows the angle measurement for 0.5, 1 and 4 m/s cutting speeds with C3770 brass at a 20 μm DoC.
Figure 4-15. Effective shear angle from AdvantEdge for (a) 0.5, (b) 1 and (c) 4 m/s cutting speed for 20 μm DoC with C3770 brass.

Figure 4-15 shows effective shear angles of 26.1°, 26.3° and 26.3° for 0.5, 1 and 4 m/s cutting speeds, respectively. These results compare well to the experimental values in Table 4-3 for 0.1 and 1 m/s cutting speeds. Both the simulation and experimental results show little variation in the effective shear angle with cutting speed for the brass materials.
4.5 Conclusions

Preliminary experiments used C36000 or 360 brass during the development of the experimental setup. The free-machining brass has a high machinability and lead content. For free-machining materials, inclusions or second phase particles typically reduce the shear strength in the shear zones, reducing the cutting forces. Larger DoCs were able to be performed, which aided in the analysis of high-speed images.

Cutting forces matched predictions using the hardness and uncut chip area. The tool forces were also compared against results from the AdvantEdge software. Cutting forces matched the AdvantEdge predictions, but the AdvantEdge thrust forces were low. This was the result of a low friction factor. The simulation friction factor was lowered to match cutting forces, but caused an underestimation of the thrust forces. The difference in the experimental and simulation materials is thought to be the reason the friction factor had to be lowered significantly to match cutting forces. The AdvantEdge tool temperatures were lower than thermocouple measurements. This issue is discussed in more detail in Section 9.2. The results for shear angle from SEM imaging, calculations from high-speed images and AdvantEdge predictions compared well for the 20 μm DoC.
5 PREDICTION OF PEAK TEMPERATURE

The hardness of the diamond and small DoCs prevent temperature devices, such as a thermocouple, from being embedded in the tool to directly measure the chip-tool contact region. The peak temperature at the cutting edge will be predicted from the temperature measurements with the thin-film RTD. Two approaches were taken to predict the peak temperatures at the cutting edge: simplified analytical model and 3D ANSYS model. The thermal properties of the experimental materials are given in Table 5-1. The thermal diffusivity is calculated using Equation (5.1).

Table 5-1. Thermal properties of experimental materials [34].

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Conductivity 20°C (W/m-K)</th>
<th>Density (g/cm³)</th>
<th>Specific Heat (J/g.-°C)</th>
<th>Thermal Diffusivity (mm²/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synthetic Diamond</td>
<td>2000</td>
<td>3.20-3.52</td>
<td>0.508</td>
<td>1157.9</td>
</tr>
<tr>
<td>UNS C36000 Brass</td>
<td>115</td>
<td>8.49</td>
<td>0.38</td>
<td>35.6</td>
</tr>
<tr>
<td>6061 Aluminum</td>
<td>167</td>
<td>2.7</td>
<td>0.896</td>
<td>69.0</td>
</tr>
<tr>
<td>AISI 1215 Steel</td>
<td>59.1</td>
<td>7.87</td>
<td>0.472</td>
<td>15.9</td>
</tr>
<tr>
<td>Tungsten Alloy⁶</td>
<td>113</td>
<td>17.7</td>
<td>0.13⁷</td>
<td>49.1</td>
</tr>
<tr>
<td>TC-2810 Epoxy [35]</td>
<td>0.8-1.4</td>
<td>1.27</td>
<td>0.793⁸</td>
<td>0.11</td>
</tr>
<tr>
<td>RTD (Glass)⁹</td>
<td>1.38</td>
<td>2.18</td>
<td>0.75</td>
<td>0.84</td>
</tr>
</tbody>
</table>

⁶ Mi-Tech Metals Super Chatter Free HD17.7 Tungsten-Based Metal from MatWeb.com
⁷ Not given on MatWeb.com, using specific heat of tungsten
⁸ Not given on 3M data sheet, using specific heat of boron nitride from MatWeb.com
⁹ Using Silica glass from MatWeb.com
5.1 Analytical Model

5.1.1 Heat Input

The thermal diffusivity, $\alpha$, of a material is given by

$$\alpha = \frac{k}{c \rho},$$

where $k$ is the thermal conductivity, $c$ is the specific heat and $\rho$ is the density. Thermal diffusivity is a measure of the thermal inertia of a material. The higher the thermal diffusivity, the faster heat is propagated into a material [36]. The thermal diffusivity of the experimental materials is given in Table 5-1. Diamond has a thermal diffusivity that is one to two orders greater than the other experimental materials (16x greater than 6061 aluminum and 72x greater than 1215 steel). If the diamond tool is approximated as a single mass with a uniform volumetric temperature, the data curves from the thermocouple measurements can be used to approximate the heat input entering the diamond tool. Figure 5-1 shows the diagram for the approximation.

![Diagram for heat input approximation.](image)

In Figure 5-1, $Q$ is the heat input into the diamond, $m$ is the mass of the diamond, $A_s$ is the surface total area, $T$ is the temperature of the diamond approximated as a uniform volumetric temperature, $h$ is the convective coefficient and $T\infty$ is the ambient temperature. The approximate surface area and mass of the diamonds used in this research is shown in Table 5-2.
Table 5-2. Dimensions, surface area and mass of diamond.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Length, Width, Height (mm)</strong></td>
<td>4, 3.7, 1.5</td>
</tr>
<tr>
<td><strong>Surface Area, ( A_s ) (m^2)</strong></td>
<td>0.00045</td>
</tr>
<tr>
<td><strong>Mass, ( m ) (g)</strong></td>
<td>0.063</td>
</tr>
</tbody>
</table>

Deriving an expression for the diamond temperature gives the following:

\[
T(t) = \frac{Qmc}{hA_s} \left( 1 - e^{-\frac{hA_s}{mc}} \right).
\]  \hspace{1cm} (5.2)

Using Matlab’s curve-fitting tool, `cftool`, the Equation (5.3) was fit to the temperature data.

\[
T(t) = a(1 - e^{-bt})
\]  \hspace{1cm} (5.3)

The constants \( a \) and \( b \) are defined as the following:

\[
a = \frac{Qmc}{hA_s}, \quad b = \frac{hA_s}{mc}
\]  \hspace{1cm} (5.4)

The constant \( a \) from Equation (5.3) is the asymptotic value for the temperature rise. The start time is selected close to the initial temperature rise. It is subtracted from all time points so that the curve-fit data starts at zero time. The temperature at that time (initial temperature) is also subtracted from all temperature points so the \( y \)-values are now temperature rise. An example curve-fit is shown in Figure 5-2 for 5 \( \mu \)m DoC at 0.5 m/s cutting speed with 360 brass from Figure 4-4.
Figure 5-2. Curve-fit for temperature measurement during 360 brass machining at 5 μm DoC and 0.5 m/s cutting speed.

The derivative of Equation (5.3) gives the following:

$$\frac{dT(t)}{dt} = abe^{-bt}.$$  \hspace{1cm} (5.5)

If evaluated at \( t = 0 \), Equation (5.5) will produce a value for the approximate heat input, \( Q \).

$$\frac{dT(0)}{dt} = ab = \left( \frac{Qmc}{hA_S} \right) \left( \frac{hA_s}{mc} \right) = Q$$  \hspace{1cm} (5.6)

This was performed on the 360 brass temperature data in Section 4.2. The constants \( a \) and \( b \), the heat input \( Q \) from Equation (5.6) and convective coefficient \( h \) from Equation (5.4) are given in Table 5-3, Table 5-4 and Table 5-5 for the three DoCs.
Table 5-3. Heat input, temperature rise and growth rate for 2 μm DoC.

<table>
<thead>
<tr>
<th>Speed (m/s)</th>
<th>a, Max ΔT (°C)</th>
<th>Q, slope at t = 0 (W/°C)</th>
<th>b, Growth Rate (1/s)</th>
<th>Time to reach 63.2%</th>
<th>R²</th>
<th>h, (W/m²/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>5.35</td>
<td>1.36</td>
<td>0.254</td>
<td>3.94</td>
<td>0.999</td>
<td>181.3</td>
</tr>
<tr>
<td>1</td>
<td>9.12</td>
<td>2.51</td>
<td>0.276</td>
<td>3.63</td>
<td>0.999</td>
<td>196.8</td>
</tr>
<tr>
<td>2</td>
<td>14.83</td>
<td>4.64</td>
<td>0.313</td>
<td>3.19</td>
<td>0.999</td>
<td>223.6</td>
</tr>
<tr>
<td>4</td>
<td>24.05</td>
<td>8.48</td>
<td>0.353</td>
<td>2.84</td>
<td>0.999</td>
<td>251.8</td>
</tr>
</tbody>
</table>

Table 5-4. Heat input, temperature rise and growth rate for 5 μm DoC.

<table>
<thead>
<tr>
<th>Speed (m/s)</th>
<th>a, Max ΔT (°C)</th>
<th>Q, slope at t = 0 (W/°C)</th>
<th>b, Growth Rate (1/s)</th>
<th>Time to reach 63.2%</th>
<th>R²</th>
<th>h, (W/m²/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>9.67</td>
<td>3.31</td>
<td>0.343</td>
<td>2.92</td>
<td>0.998</td>
<td>244.6</td>
</tr>
<tr>
<td>1</td>
<td>15.46</td>
<td>6.31</td>
<td>0.408</td>
<td>2.45</td>
<td>0.999</td>
<td>291.5</td>
</tr>
<tr>
<td>2</td>
<td>24.13</td>
<td>10.79</td>
<td>0.398</td>
<td>2.52</td>
<td>0.999</td>
<td>283.9</td>
</tr>
<tr>
<td>4</td>
<td>39.15</td>
<td>18.35</td>
<td>0.469</td>
<td>2.13</td>
<td>0.998</td>
<td>334.7</td>
</tr>
</tbody>
</table>

Table 5-5. Heat input, temperature rise and growth rate for 10 μm DoC.

<table>
<thead>
<tr>
<th>Speed (m/s)</th>
<th>a, Max ΔT (°C)</th>
<th>Q, slope at t = 0 (W/°C)</th>
<th>b, Growth Rate (1/s)</th>
<th>Time to reach 63.2%</th>
<th>R²</th>
<th>h, (W/m²/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>14.02</td>
<td>4.50</td>
<td>0.572</td>
<td>1.75</td>
<td>0.984</td>
<td>408.4</td>
</tr>
<tr>
<td>1</td>
<td>22.19</td>
<td>7.34</td>
<td>0.331</td>
<td>3.02</td>
<td>0.999</td>
<td>236.0</td>
</tr>
<tr>
<td>2</td>
<td>34.29</td>
<td>14.16</td>
<td>0.413</td>
<td>2.42</td>
<td>0.999</td>
<td>294.8</td>
</tr>
<tr>
<td>4</td>
<td>70.53</td>
<td>28.00</td>
<td>0.466</td>
<td>2.15</td>
<td>0.999</td>
<td>332.8</td>
</tr>
</tbody>
</table>

5.1.2 APPROXIMATION OF THE PEAK TOOL TEMPERATURE

The peak temperature of the diamond tool can be approximated from the heat flow derived in Section 5.1.1. If the heat input, Q, is assumed to be constant and the location of the temperature measurement is approximately known, an expression for the diamond temperature as a function of radius can be derived. The diagram is shown on the right in Figure 5-3 and relates to the
shape of the diamond tool during orthogonal cutting. Using 2D steady-state conduction relationships in polar coordinates, an expression for the peak temperature is given by

\[ T_1 - T_2 = \frac{Q}{2\pi kw} \ln \left( \frac{r_2}{r_1} \right) \Rightarrow T_1 = \frac{Q}{2\pi kw} \ln \left( \frac{r_2}{r_1} \right) + T_2, \]

(5.7)

where \( T_1 \) is the peak temperature, \( T_2 \) is the steady-state thermocouple temperature, \( Q \) is the heat input, \( k \) is the thermal conductivity of the diamond, \( r_1 \) is the approximate radius of the heat input, \( r_2 \) is the thermocouple radius and \( w \) is the width of the workpiece.

**Figure 5-3.** Expression for peak diamond temperature.

The thermocouple radius/location, \( r_2 \), was approximately 2 mm and the width of the workpiece was 0.8 mm.

The input radius is a limitation of the analytical model. The actual heat input will vary along the cutting edge and rake face as a function of pressure, friction coefficient, velocity and temperature of the contacting material. The input radius, \( r_1 \), was selected so that the area of heat input was matched the cutting edge of the worn tool profiles. The maximum heat input is expected to be concentrated near the cutting edge due to the high pressure and sliding velocity of the workpiece. The sensitivity of \( T_1 \) with respect to \( r_1 \) is small because of the high
conductivity, $k$, of the diamond in Equation (5.7) (i.e. the high conductivity prevents large temperature gradients in the diamond). The heat input area, $A$, is given by the following:

$$A \approx \left(\frac{2\pi r_1}{4}\right)w,$$

where $w$ is the width of the workpiece and $r_1$ is the radius of heat input.

\[ \frac{2\pi (0.7)}{4} \approx 1 \text{ μm} \]

Figure 5-4. Distance of the heat input along worn tool edge (tool profile after 120 m machining 1215 steel).

Figure 5-4 shows the approximate distance along a worn tool edge. The radius of heat input, $r_1$, was selected as 0.7 μm to match the approximate line of contact 1 μm shown in Figure 5-4 \([2\pi(0.7)/4 \approx 1]\). The width of the workpiece for the brass experiments was 0.8 mm so the heat input area from (5.8) is 0.0008 mm².
The peak temperature predictions are calculated from Equation (5.7) with the data for the three DoCs with 360 brass (Table 5-3, Table 5-4 and Table 5-5). Figure 5-5 shows the peak temperatures as a function of cutting speed.

![Figure 5-5. Peak tool temperature predictions for C36000 brass machining.](image)

### 5.2 ANSYS THERMAL MODEL

The analysis in Section 5.1 was used primarily during the experiments with precision thermocouples, where the thermal mass of the temperature measuring device was assumed to be negligible. A 3D FE model was developed in ANSYS to account for the spatial and material effects of the thin-film RTD temperature measuring system. The ANSYS model was used to project the measured temperatures from the thin-film RTD to the diamond edge. A transient thermal model was created to compare the simulation RTD temperature response to the
experimental measurement. Using the same parameters, a steady-state model was used to get the relationships between heat input and peak tool temperature.

The CAD model for the ANSYS thermal model is shown in Figure 5-6. The CAD model used the experimental dimensions of the ¼” shank holder, thin-film RTD, diamond and tool shank. The film-thin RTD has a ceramic substrate and a glass coating. In the ANSYS model, it was approximated as a single mass of glass material. The tool shank material is a high-density tungsten alloy\textsuperscript{10}. The ¼” shank holder is 6061 aluminum. The thickness of the TC-2810 epoxy is approximated as 0.1 mm. The model used isotropic values for the thermal conductivity, specific heat and density from the properties presented in Table 5-1.

![Figure 5-6](image)

**Figure 5-6.** (a) Isometric (b) side and (c) top view of the CAD model for thermal analysis.

\textsuperscript{10} Mi-Tech Metals Super Chatter Free HD17.7 Tungsten-Based Metal
### 5.2.1 Boundary Conditions

**Figure 5-7.** (a) Convective ($h = 10 \text{ W/m}^2\text{-K}, T = 20^\circ\text{C}$) and (b) isothermal boundary condition surfaces.

Figure 5-7 shows the surfaces for the convective and isothermal boundary conditions. In Figure 5-7(b), the back surface of the tool shank holder was selected as a 20°C isothermal boundary. All other open surfaces were selected for convective boundaries, shown in Figure 5-7(a). The magnitude of the convective film coefficient had little effect on the RTD and peak temperature. Increasing the film coefficient by an order of magnitude resulted in a 3°C decrease in the RTD and a 1°C decrease in peak temperature a 4.95 W input (example for 1 m/s with 1215 steel). A common range value (10 W/m²-K) for free convection was selected [37]. This indicated that the heat transfer from the diamond edge is driven mainly by conduction through the tool shank. Figure 5-8 shows the transient response for film coefficients of 10 and 100 W/m²-K with a 5 W heat input.
5.2.2 **HEAT INPUT TO DIAMOND TOOL**

The heat was input to the tool over a 1 mm (1215 steel) and 0.8 mm width (6061 aluminum) to match the experimental workpieces. Although 3 different locations were used to cut, there was little variation in the relationship between RTD and peak temperatures in the model when the heat input changed locations. Similar to the analytical model (Figure 5-4), the input radius was selected so that the area of heat input was matched the cutting edge of the worn tool profiles. To match this heat input area, the radius of the diamond edge was set to 0.7 μm in the thermal model. This gave a model heat input area of 0.001 mm² for the steel workpiece, shown in Figure 5-9, and 0.008 mm² for the aluminum workpiece.

**Figure 5-8.** Effect of increasing convective coefficient on transient response in ANSYS.
5.2.3 Meshing

The meshing engine in ANSYS Workbench generated the model mesh. The mesh was refined at the tool edge near the heat input and on the top surface of the diamond to increase nodes near the heat input and RTD. The minimum element size at the cutting edge was 0.2 μm. The final mesh is shown in Figure 5-10.

Figure 5-10. (a) Model overview and (b) diamond mesh for ANSYS thermal model.
5.2.4 Process Diagram

(1) Iteratively adjust tool heat input, $Q$, so transient ANSYS RTD temperature matches the experimental RTD temperature curve for each cutting velocity, $v$.

(2) Curve-fit power relationship between tool heat input, $Q$, and the cutting velocity, $v$.

(3) Use steady-state to find relationship between the max tool temperature rise, $\Delta T_{peak}$, and the tool heat input, $Q$.

(4) Plug in relationship from (2) to solve for $\Delta T_{peak}(v)$.

$$\Delta T_{peak} = 32.611v^{0.8146}$$

Figure 5-11. Process diagram for determining the relationship between the ANSYS peak temperature and the cutting velocity (steel at 1 m/s shown as example).
Figure 5-11 shows the process diagram for determining the peak temperature and cutting speed relationship with the ANSYS model. The heat input, $Q$, was modified iteratively until the asymptotic value for the transient ANSYS RTD temperature matched the experimental measurement in Figure 5-11(1). The steady-state relationship between the peak temperature and the heat input was determined in a steady-state analysis, shown in Section 5.2.5.

### 5.2.5 Steady-State Relationships

Using the boundary conditions and meshing parameters from the transient model, a steady-state analysis was performed in ANSYS to get the relationship between the peak temperature rise and the heat input for the (a) steel and (b) aluminum workpiece widths. The relationships are shown in Figure 5-12.

![Figure 5-12](image)

**Figure 5-12.** Peak RTD temperature rise vs. heat input for (a) steel and (b) aluminum workpiece widths (1 and 0.8 mm, respectively).

### 5.3 Discussion

An analytical and a 3D FE model were to estimate the peak tool temperatures at the wear region based on the temperature measured at the back of the tool. The limitations of the analytical
model are the 2D spatial approximation and the thermal response of the temperature measuring device. Both methods have limitations with modeling the heat input from machining. The actual heat input will not be constant and not uniform over the area of application. Both models also use steady-state relationships to project the temperature to the cutting edge. However, the close match of the ANSYS transient RTD temperatures and the experimental RTD measurements provide some support of the ANSYS model. The ANSYS model was used to estimate the peak temperatures for the aluminum and steel tool wear experiments.
6 ALUMINUM 6061 WEAR EXPERIMENTS

Aluminum 6061-T6 will used to get a baseline for the expected level of abrasive wear. Shi [3] showed that the 6061 aluminum had a similar distribution and size of inclusions when compared to 1215 steel. The aluminum should give a baseline for the level of abrasive wear. Using a similar orthogonal cutting technique as Lane [19] in his wear comparison of 1215 steel and 6061 aluminum, thin aluminum discs 0.813 mm wide will be machined down in radius at a known location on the diamond tool. Due to the thin nature of the discs, multiple locations are available on the 3.7 mm diamond cutting edge for different cutting experiments. The material properties for 6061 aluminum (Al6061) are given in Table 6-1.

<table>
<thead>
<tr>
<th>Material</th>
<th>Aluminum 6061-T6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness (MPa)</td>
<td>1185(^{11})</td>
</tr>
<tr>
<td>Machinability</td>
<td>50%(^{12})</td>
</tr>
<tr>
<td>Thermal Conductivity (W/m-K)</td>
<td>167</td>
</tr>
<tr>
<td>Workpiece Thickness (mm)</td>
<td>0.813</td>
</tr>
</tbody>
</table>

6.1 DETERMINING MACHINING PARAMETERS FOR AVERAGE CUTTING SPEED

Because the tool wear cutting aluminum is mainly abrasive, kilometers of cutting distance is needed for the tool wear to be measureable with the EBID technique. The wear experiments were programmed to be performed at an average cutting speed since the tool temperature is predicted to be dependent on the cutting speed (see Figure 5-3). For a constant spindle speed

\(^{11}\) Determined by Lane [19] using Vickers hardness test.

\(^{12}\) Based on 0-100 scale for aluminum alloys.
and feedrate, the cutting speed decreases as the workpiece radius decreases. The instantaneous cutting speed is the product of the spindle rotational speed and the workpiece radius. Equation (6.1) defines the cutting speed (outer surface workpiece velocity) as a function of time for a workpiece with a decreasing radius:

\[ v(t) = RPM \left( \frac{2\pi}{60} \right) \left[ R_0 - \frac{f}{(60)(1000)} t \right], \quad (6.1) \]

where \( f \) is the feedrate (mm/min), \( R_0 \) is the initial radius (m) and \( RPM \) is the spindle rotational speed (rev/min). For a constant depth of cut, the spindle speed is related to the feedrate as follows:

\[ RPM = \frac{1000 f}{DoC} \quad (6.2) \]

where \( DoC \) is the depth of cut (μm/rev). Substituting Equation (6.2) into Equation (6.1) and integrating gives the cutting distance as a function of time assuming the initial cutting distance is zero.

\[ d(t) = \int v(t) dt = \frac{1000 f}{DoC} \left( \frac{2\pi}{60} \right) \left[ R_0 t - \frac{f}{2(60)(1000)} t^2 \right] \quad (6.3) \]

Substituting in the total experimental time, \( t_f \), gives an expression for the total cutting distance \( d_f \).

\[ d(t_f) = d_f = \frac{1000 f}{DoC} \left( \frac{2\pi}{60} \right) \left[ R_0 t_f - \frac{f}{2(60)(1000)} t_f^2 \right] \quad (6.4) \]

The average cutting velocity can be expressed by performing the following integral:

\[ \bar{v} = \frac{1}{t_f} \int_{0}^{t_f} v(t) dt = \frac{1000 f}{DoC} \left( \frac{2\pi}{60} \right) \left[ R_0 - \frac{f}{2(60)(1000)} t_f \right]. \quad (6.5) \]

Solving for \( t_f \) gives the following expression:

\[ t_f = \frac{(2)(60)(1000)R_0}{f} - \frac{\bar{v}DoC(60)^2}{\pi f^2}. \quad (6.6) \]
Equation (6.6) can be substituted into Equation (6.4) to find the feedrate. From the feedrate, the spindle RPM, and radius removed can be calculated. The Matlab program `Wear_Distance.m` is programmed to calculate all the cutting parameters based on the depth of cut, desired average cutting speed, cutting distance and initial radius. Table 6-2 gives a summary of the inputs and outputs for the program.

### Table 6-2. Inputs and outputs from `Wear_Distance` program.

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial radius</td>
<td>Spindle RPM</td>
</tr>
<tr>
<td>Average cutting speed</td>
<td>Feedrate</td>
</tr>
<tr>
<td>Cutting distance</td>
<td>Total cutting time</td>
</tr>
<tr>
<td>Depth of cut</td>
<td>Radius removal</td>
</tr>
<tr>
<td></td>
<td>Starting velocity</td>
</tr>
<tr>
<td></td>
<td>Ending velocity</td>
</tr>
<tr>
<td></td>
<td>End diameter</td>
</tr>
</tbody>
</table>

During the analysis, it was determined that total time $t_f$ contains the following relationship with cutting distance and average cutting speed for orthogonal cutting with constant feedrate and spindle speed.

$$
t_f = \frac{d_f}{v}
$$

(6.7)

The `Wear_Distance` program was used to set the spindle speed, feedrate and radius removal for all wear experiments with Al6061 and 1215 steel.

### 6.2 Force Measurements

For the 6061 aluminum experiments, large cutting distances (kilometers) are required to get significant levels of wear. The experiments were performed in 250 m cutting distance
increments while force and temperature data was collected. Multiple 250 m increments were performed at each wear location across the face of the tool (Figure 3-4) to reach a certain cutting distance. The tool was then removed from the machine and prepared for EBID measurements. Figure 6-1 shows the tool forces during a 2 μm DoC during the first wear interval (0-250 m total cutting distance).

![Graph showing tool forces during 2 μm DoC with Al 6061 at 1 m/s.]

**Figure 6-1.** Tool forces during 2 μm DoC with Al 6061 at 1 m/s.

To track the changes in tool forces during the wear process, the average and standard deviation of the tool forces were calculated for the center half of each data set, as shown in Figure 6-1. This was done to remove the plunge and exit data points, which could contain spikes. The average cutting forces are shown in Figure 6-2 and the average thrust forces in Figure 6-3 for the 2 μm DoC. The bars are one deviation in either direction.
Figure 6-2. Average cutting forces for 2 μm DoC with Al6061 at 1 m/s cutting speed.

As the cutting distance increases, the tool will begin to wear. Figure 6-2 and Figure 6-3 show that the average tool forces increase as the cutting forces increase.

Figure 6-3. Average thrust forces for 2 μm DoC with Al6061 at 1 m/s cutting speed.
The same procedure was used for the 5 μm DoC experiments. Figure 6-4 shows the tool forces during the 5 μm DoC at a cutting speed of 1 m/s.

![Graph showing tool forces during 5 μm cut with Al 6061 at 1 m/s.](image)

**Figure 6-4.** Tool forces during 5 μm cut with Al 6061 at 1 m/s.

A summary of the averages and standards deviations for the 5 μm DoC is shown in Figure 6-5. Similar to the 2 μm experiments, the cutting forces increase as the cutting distance increases. The average cutting and thrust forces are shown in Figure 6-5 and Figure 6-6 with the bars representing one standard deviation.
**Figure 6-5.** Average cutting forces for 5 μm DoC with Al6061.

**Figure 6-6.** Average thrust forces for 5 μm DoC with Al6061.
Material pickup occurred on the tool during the aluminum experiments. This may have contributed to some of variation in the tool forces shown in Figure 6-2 through Figure 6-5. The long distance wear experiments caused a significant generation of cutting chips. If the cutting chips get caught on the tool and rotating workpiece, they interfere with the dynamometer forces. Improvements to the chip vacuum system helped to alleviate this issue, but cutting chips still periodically affected the tool forces measurements.

![Average Flank Force Graph](image-url)

**Figure 6-7.** Average flank force for 2 and 5 μm DoC with Al6061.

The flank force is needed to determine the Archard wear coefficient, defined in Section 2.3. Equation (2.6) is used to calculate the average flank force, \( F_f \), from the average tool forces in Figure 6-2, Figure 6-3, Figure 6-5 and Figure 6-6. Figure 6-7 shows the results for both 2 and 5 μm DoC. In Figure 6-7, the 2 μm DoC has an average of 1.93 N (standard deviation of 0.61 N) and the 5 μm DoC has an average of 5.74 N (standard deviation of 0.78 N). The high standard deviations are caused by the variation in average tool forces in Figure 6-2 through Figure 6-5.
6.3 Temperature Measurements

Diamond tool temperatures were measured with the 1000 Ω thin-film RTD discussed in Section 3.3. No coolant was used during the experiments due to its interference with the surface temperature measurements. The coolant/cutting oil would contact the RTD and cause variations in the output, shown in Figure 6-8.

![Figure 6-8](image)

**Figure 6-8.** Effect of cutting oil/coolant on surface temperature measurement for 2 μm DoC with Al6061 at 1 m/s cutting speed.

The temperature measurements for the 2 μm DoC experiments are shown in Figure 6-9.
Figure 6-9. RTD temperature for multiple cutting speeds at 2 μm DoC during Al6061 machining.

The temperature curves from Figure 6-9 are used to get the heat input using the ANSYS temperature model. The heat input and model predictions are shown in Figure 6-10.
Figure 6-10. Peak temperature predictions for Al6061 at 2 μm DoC and cutting speeds of 1, 2 and 4 m/s.

The heat inputs from Figure 6-10 (located on top of each individual graph) are used to get a power-law relationship between cutting speed and heat input. A power law is curve-fitted to the data with a strong correlation ($R^2 = 0.9997$), shown in Figure 6-11.
Combining results from Figure 6-11 and the ANSYS steady-state relationships from Figure 5-12(b) produces the approximate peak temperature rise as a function of cutting speed in Equation (6.8), shown in Figure 6-12.

\[ Q = 3.666v^{0.5968} \]
\[ \Delta T_{\text{peak}} = 6.680Q \]
\[ \Delta T_{\text{peak}}(v) = 24.49v^{0.5968} \]
Figure 6-12. Peak tool temperature prediction for 2 μm DoC with Al6061.

The temperature comparison for three DoCs (2, 5 and 10 μm) with Al6061 is shown in Figure 6-13. The temperature rise (steady-state temperature minus initial temperature) compared to the 2 μm DoC is approximately 1.9x greater for the 5 μm DoC and 2.5x greater for the 10 μm DoC.
Figure 6-13. RTD temperature for multiple DoCs at 1 m/s cutting speed during Al6061 machining.

6.4 Imaging Results
A high-speed image of the chip formation during the diamond turning of 6061 aluminum is shown in Figure 6-14. The image was captured at an exposure time of 3 μs and frame rate of 6006 frames per second (fps).
The smaller DoC and higher cutting speed for the conditions in Figure 6-14 makes distinguishing chip features more difficult. The aluminum chip in Figure 6-14 is more continuous than the 360 brass images in Figure 4-8.

**Table 6-3.** Calculation of shear angle from high-speed video for Al6061.

<table>
<thead>
<tr>
<th>Depth of Cut (μm)</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting Speed (m/s)</td>
<td>1</td>
</tr>
<tr>
<td>Calculated Chip Speed (m/s)</td>
<td>0.200</td>
</tr>
<tr>
<td>Calculated Workpiece Speed (m/s)</td>
<td>1.008</td>
</tr>
<tr>
<td>Shear Angle (degrees)</td>
<td>11.2</td>
</tr>
<tr>
<td>Average Chip Thickness (μm)</td>
<td>10.1</td>
</tr>
</tbody>
</table>
6.5 Wear Results

The primary wear experiments with Al6061 used two different depths of cut: 2 and 5 μm. The wear distances for the 2 μm DoC were 3, 5 and 7.5 km. The distances for the 5 μm DoC were 2.5 and 5 km. Figure 6-15 shows the tool profiles from the EBID measurements and Table 6-4 gives the results for the edge radius, wear area, wear volume and average flank force during the specific wear increment experiments for the 2 μm DoC. Figure 6-16 and Table 6-5 give the results for the 5 μm DoC. The wear volume is the wear area multiplied by the workpiece thickness. The average flank force is calculated using Equation (2.6) and the average cutting forces during the 250 m experiments. The flank forces for the wear intervals in Table 6-4 and Table 6-5 are averaged from the data in Figure 6-7 for the range of cutting distances.

**Figure 6-15.** (a) EBID line on worn tool after cutting 7.5 km and (b) wear profiles for multiple cutting lengths for Al6061 at 2 μm DoC at average cutting speed of 1 m/s.
Figure 6-15 shows the progression of tool wear for the 2 μm DoC. As the cutting distance increases, flank wear develops on the diamond tool. The wear consists of a larger edge radius and a flatter flank surface. No wear is observed on the rake face from EBID measurements.

Table 6-4. Experimental wear results for 2 μm DoC with Al6061.

<table>
<thead>
<tr>
<th>Cutting Distance (m)</th>
<th>Edge Radius (μm)</th>
<th>Wear Area (μm²)</th>
<th>Wear Volume (μm³)</th>
<th>Average Flank Force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.050</td>
<td>0.001</td>
<td>0.813</td>
<td>-</td>
</tr>
<tr>
<td>3000</td>
<td>0.1039</td>
<td>0.0558</td>
<td>45.36</td>
<td>1.65</td>
</tr>
<tr>
<td>5000</td>
<td>0.1527</td>
<td>0.1278</td>
<td>103.86</td>
<td>1.75</td>
</tr>
<tr>
<td>7500</td>
<td>0.1944</td>
<td>0.2431</td>
<td>197.60</td>
<td>2.25</td>
</tr>
</tbody>
</table>
Figure 6-16. (a) EBID line on worn tool after cutting 2.5 km and (b) 5 km with (c) tool profile comparison for 5 μm DoC at average cutting speed of 1 m/s.

Figure 6-16 shows a similar tool wear progression for the 5 μm DoC as Figure 6-15. As the cutting distance increases, a wear land develops that is approximately parallel to the cutting direction and the edge radius increases. The change in wear area from 2.5 to 5 km is shown in Figure 6-16(c). No wear is observed on the rake face for the 5 μm DoC, similar to the 2 μm DoC.
Table 6-5. Experimental wear results for 5 μm DoC with Al6061.

<table>
<thead>
<tr>
<th>Depth of Cut (μm)</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Cutting Speed (m/s)</td>
<td>1</td>
</tr>
<tr>
<td>Workpiece Thickness (mm)</td>
<td>0.813</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cutting Distance (m)</th>
<th>Edge Radius (μm)</th>
<th>Wear Area (μm²)</th>
<th>Wear Volume (μm³)</th>
<th>Average Flank Force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.050</td>
<td>0.001</td>
<td>0.813</td>
<td>-</td>
</tr>
<tr>
<td>2500</td>
<td>0.0929</td>
<td>0.0374</td>
<td>30.37</td>
<td>5.39</td>
</tr>
<tr>
<td>5000</td>
<td>0.1604</td>
<td>0.1443</td>
<td>117.34</td>
<td>6.08</td>
</tr>
</tbody>
</table>

The data from Table 6-4 and Table 6-5 is plotted in Figure 6-17 and Figure 6-18 to show the wear volume and edge radius as the cutting distance increases.

![Graph showing wear volume and edge radius vs. cutting distance](image)

**Figure 6-17.** Wear volume from EBID measurements for 2 and 5 μm DoC with Al6061.

The wear area was measured at each wear increment using the MATLAB program *digitize11* and is used to calculate the wear volume shown in Figure 6-17. For abrasive wear under a
constant normal force, the wear volume increases linearly from Archard’s wear equation in Equation (2.5). However, as shown in Figure 6-7, the average flank force increased as the cutting distance increased. This led to the nonlinearity in the wear volume and cutting distance in Figure 6-17.

Figure 6-18. Edge radius from EBID measurements for 2 and 5 μm DoC with Al6061.

Figure 6-18 indicates that the edge radius increased linearly with cutting distance (0.02 nm/m). Lane [19] showed similar magnitudes and trends for the cutting edge radius. To obtain the Archard wear coefficient, the worn volume is plotted as function of the product of the average flank force and cutting distance, shown in Figure 6-19. The slope of the linear regression gives the Archard coefficient.
Figure 6-19. Archard coefficients for 2 \((0.0116 \, \text{μm}^3\text{N}^{-1}\text{m}^{-1})\) and 5 \(\mu\text{m} \,(0.0036 \, \text{μm}^3\text{N}^{-1}\text{m}^{-1})\) depths of cut with Al6061. 

In Figure 6-19, different values of the Archard coefficients are given for the 2 and 5 \(\mu\text{m}\) DoCs. The Archard wear coefficients are 0.0116 and 0.0036 \(\text{μm}^3\text{N}^{-1}\text{m}^{-1}\), respectively. Figure 6-17 and Figure 6-18 show that the two depths have similar wear rates. The increased cutting forces and calculated flank forces for the 5 \(\mu\text{m}\) DoC cause the slope to decrease in Figure 6-19. Section 6.5.1 discusses this result in more detail.

### 6.5.1 Effect of Depth of Cut

Multiple DoCs were used to investigate the effect on the tool wear. Figure 6-20 shows the tool profiles after 5 km of machining for 2 and 5 \(\mu\text{m}\) DoCs with the results summarized in Table 6-6.
Figure 6-20. EBID lines after 5 km cutting Al6061 at 1 m/s average cutting speed with (a) 2 μm and (b) 5 μm depth of cut with (c) tool profile comparison.

The tool profiles in Figure 6-20 show similar tool geometries for the two DoCs after 5 km of machining. The average flank force calculated from Equation (2.6) is approximately 3.5x greater for 5 μm DoC. The wear volume after 5 km of machining was 12% greater for the 5 μm DoC. Again, neither profile has wear on the rake face.
Table 6-6. Comparison of wear results for 2 and 5 μm DoC with Al6061 at 1 m/s.

<table>
<thead>
<tr>
<th>Cutting Distance (m)</th>
<th>5000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Cutting Speed (m/s)</td>
<td>1</td>
</tr>
<tr>
<td>Workpiece Thickness (mm)</td>
<td>0.813</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Depth of Cut (µm)</th>
<th>Edge Radius (µm)</th>
<th>Wear Area (µm²)</th>
<th>Wear Volume (µm³)</th>
<th>Average Flank Force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.1527</td>
<td>0.1278</td>
<td>103.86</td>
<td>1.75</td>
</tr>
<tr>
<td>5</td>
<td>0.1604</td>
<td>0.1443</td>
<td>117.34</td>
<td>6.08</td>
</tr>
</tbody>
</table>

6.5.2 Effect of Cutting Speed

To evaluate the effect of temperature on the wear rate, a higher cutting speed of 4 m/s was used to compare the wear results. Figure 6-21 shows the tool profile comparison between 1 and 4 m/s after 5 km of machining with the EBID results in Table 6-7.
Figure 6-21. EBID lines after 5 km cutting Al6061 with 2 μm depth of cut at (a) 1.0 m/s and (b) 4.0 m/s average cutting speed with (c) tool profile comparison.

Figure 6-21 shows that the worn tool geometry for the two cutting speeds are nearly identical. From Table 6-7, the wear volume for the 4 m/s cutting speed is approximately 12% less than the 1 m/s wear volume. From Equation (6.8), the predicted peak temperature for 1 m/s is 44.5°C and 76.0°C for 4 m/s cutting speed at 2 μm DoC with Al6061. The increased temperature does not increase the wear rate for the Al6061 machining.
Table 6-7. Comparison of wear results for 2 μm DoC with Al 6061 at 1 and 4 m/s.

<table>
<thead>
<tr>
<th>Cutting Distance (m)</th>
<th>5000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth of Cut (μm)</td>
<td>2</td>
</tr>
<tr>
<td>Workpiece Thickness (mm)</td>
<td>0.813</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cutting Speed (m/s)</th>
<th>Edge Radius (μm)</th>
<th>Wear Area (μm²)</th>
<th>Wear Volume (μm³)</th>
<th>Average Flank Force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1527</td>
<td>0.1278</td>
<td>103.86</td>
<td>1.75</td>
</tr>
<tr>
<td>4</td>
<td>0.1291</td>
<td>0.1143</td>
<td>92.89</td>
<td>1.37</td>
</tr>
</tbody>
</table>

6.6 COMPARISON TOUEDA TEMPERATURE RESULTS

To compare this temperature measuring technique with previous results, cutting parameters similar to those used by Ueda [15] were employed. He used a two-color pyrometer to measure the rake face temperature of a single crystal diamond tool during the dry machining of aluminum and copper at high speeds (6.87-15.61 m/s). The setup had a chalcogenide optical fiber that would accept infrared radiation emitted from the rake face and transmitted through the diamond. The cutting tool had a rake angle of -5° and a clearance angle of 5°. The DoC was 10 μm with a workpiece width of 1 mm. For aluminum, his rake face temperature results increased from approximately 166°C at 6.87 m/s to 221.8°C at 15.61 m/s.

Due to the increased DoC, the location of the RTD on the diamond had to be modified. The larger chips from the 10 μm DoC knocked the RTD loose when it was placed on the top surface of the diamond. Mounting the RTD on the side of the diamond tool (Figure 6-22) prevented this from occurring. However, the adjustment decreased the contact surface between the RTD and diamond. The effect is a decrease in the response time of the RTD measurement as shown in Figure 6-23.
**Figure 6-22.** CAD diagram of RTD location for side-mounting.

**Figure 6-23.** Response time comparison of two RTD locations for 10 μm DoC at 0.5 m/s with Al6061.
Figure 6-23 shows that the top location for the RTD has a slightly faster response than the side location, but that the temperature measurement gets disrupted by the cutting chips. Changing the location of the RTD to the side of the diamond prevented cutting chips from getting underneath the sensor. Table 6-8 summarizes the cutting parameters used for the Ueda comparison. The spindle encoder output and workpiece diameter limited the maximum average cutting speed to 7.86 m/s.

<table>
<thead>
<tr>
<th>Material</th>
<th>Aluminum 6061-T6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth of cut</td>
<td>10 μm</td>
</tr>
<tr>
<td>Workpiece width</td>
<td>0.813 mm</td>
</tr>
<tr>
<td>Average cutting speeds</td>
<td>0.5, 1, 2, 4, 6, 7.86 m/s</td>
</tr>
<tr>
<td>Total cutting time</td>
<td>15 seconds</td>
</tr>
</tbody>
</table>

Figure 6-24 shows the RTD measurements for the cutting parameters from Table 6-8. At the highest average cutting speed of 7.86 m/s, the RTD output reached over 105°C.
Figure 6-24. RTD measurements for 10 μm DoC with Al6061 at multiple cutting speeds.

The ANSYS model in Section 5.2 was modified for the side mount of the RTD. The comparison for all six cutting speeds is shown in Figure 6-25.
Figure 6-25. Summary of experimental RTD, model transient RTD, and model peak temperatures for multiple cutting speeds with Al6061 at 10 μm DoC.
Figure 6-25 shows that the model results for the transient RTD temperature match the shape of the experimental result. The close match of the transient results provides some validation of these predicted peak temperatures. The heat inputs from Figure 6-25 (at the top of individual plots) are plotted as a function of cutting speed in Figure 6-26. A power law fits the data with a strong correlation ($R^2 = 0.9913$). This indicates that as the cutting speed increases, the rate of increase reduces for the heat input into the tool. Shaw’s approximation in Equation (1.2) has a similar power relation with cutting speed.

![Figure 6-26. Heat input from ANSYS model as a function of cutting speed for Al6061 at 10 μm DoC.](image)

A steady-state analysis in ANSYS was performed using the heat inputs from Figure 6-25. Figure 6-27 shows the relationship between the peak temperature rise, $\Delta T_{\text{peak}}$ (defined as $T_{\text{peak}} - 20^\circ\text{C}$), and the heat input, $Q$. Combining results from Figure 6-27 and Figure 6-26 produces Equation (6.9) for the peak temperature rise as a function of cutting speed.
Figure 6-27. Relationship between peak tool temperature and heat input from ANSYS model for 10 μm DoC with Al6061.

\[ Q = 9.613v^{0.4807} \]
\[ \Delta T_{\text{peak}} = 6.6813Q \]
\[ \Delta T_{\text{peak}} (v) = 64.227v^{0.4807} \]

The result from Equation (6.9) is plotted with Ueda’s results and the peak experimental RTD temperatures in Figure 6-28 (dashed line).
Figure 6-28. Peak temperature predictions, RTD measurements and Ueda results.

Figure 6-28 shows the prediction for the peak tool temperature during the machining of Al6061 with a 10 μm DoC. It should be noted that the values after 7.86 m/s are extrapolated from the peak temperature function in Equation (6.9). The peak temperature predictions match the shape of the results published by Ueda et al. [15] but are at 20-30°C greater magnitudes.

The cutting forces were also recorded during these experiments. The average forces are shown plotted as a function of cutting speed in Figure 6-29. The average cutting forces decreased with increases in cutting speed. Marusich [38] from Third Wave Systems published a paper on the effects of cutting speed on cutting force. He used the FE software AdvantEdge and experiments with Al6061-T6 to explain the decreases in cutting force with speed. He claimed the large rise in temperature in the secondary shear zone reduces the flow stress significantly, which reduces the cutting forces and chip thickness.
Ueda plotted the cutting forces for a speed of 8.63 m/s. His measurements showed an average cutting force of 12.4 N and an average thrust force of approximately 8.1 N. These are similar in value to the 7.68 m/s speed shown in Figure 6-29 (12.3 N cut, 10.1 N thrust). The decrease in cutting force may also contribute to the power law relationship for heat flow and tool temperature.

**6.7 DISCUSSION OF ALUMINUM WEAR EXPERIMENTS**

The tool wear profiles for the 2 μm and 5 μm depth of cut were similar as were the wear areas at the same cutting distances. The average flank force calculation from Equation (2.6) was 3x greater for the 5 μm DoC, which would suggest the wear rate should increase significantly from the Archard wear equation. However, Figure 6-17 and Figure 6-20 show that the wear volume and tool geometry are similar after 5 km of machining for 2 and 5 μm DoC. For an average cutting speed of 1 m/s, the Archard coefficient was 0.0116 μm³N⁻¹m⁻¹ for the 2 μm DoC and 0.0036 μm³N⁻¹m⁻¹ for the 5 μm DoC. The difference in the Archard coefficients came...
from the application of the flank force. The normal stress distribution on the flank face for the two DoCs should be investigated to see the effect of increasing DoC. For the 2 and 5 μm DoCs, no wear was observed on the rake face. Material pickup was observed on the tool rake face after both DoCs. The material pickup could prevent wear on the rake face by providing a protective barrier between the chip and tool.

Lane [8] obtained an Archard coefficient of $0.057 \mu m^3 N^{-1} m^{-1}$ for a 2 μm DoC at cutting speeds between 2.66-3.40 m/s using the 6061 aluminum. The large difference was caused by dissimilarities in the flank force from Equation (2.6). The cutting and thrust force measurements were greater than Lane’s [8] measurements for the 2 μm DoC, but the wear volumes were comparable at each cutting distance interval. Dry machining conditions, which were implemented to prevent interference with surface temperature measurements, may have contributed to the increase in tool forces due to the lack of lubrication. Lane [8] used Mobilmet Omicron cutting oil during his tool wear experiments with 6061 aluminum. The increase in both cutting and thrust forces caused the calculated flank force to increase by 63 and 74% at the 2.5 and 5 km cutting distances. The increased flank force caused the Archard wear coefficient to decrease.

Evidence of significant thermal softening during Al6061 machining is shown in Figure 6-29. This implies that less wear per cutting distance may occur at faster cutting speeds due to the decrease in forces. The comparison for 1 and 4 m/s cutting speeds at 2 μm DoC supported this to some extent, with a 10% decrease in worn volume. The worn volumes were 104 and 93 μm$^3$ respectively after 5 km of machining. The average flank force for the 1 m/s cutting speed was 1.75 N compared to the 1.37 N for the 4 m/s speed.
7 STEEL 1215 WEAR EXPERIMENTS

AISI 1215 steel is a low-carbon steel alloyed with sulfur, phosphorous and manganese. 1215 steel has a high machinability of 140% using AISI 1212 as the reference [34]. Shi et al. [3] showed that 6061 aluminum had a similar distribution of inclusions when compared to 1215 steel, so the abrasive contribution to tool wear from machining 1215 steel should be similar in magnitude to 6061 aluminum. Experiments were performed using the same orthogonal cutting geometry as the aluminum experiments. The DoC was held constant at 2 μm by using a constant in-feed and the width of the workpieces was 1 mm. Cutting speeds of 0.5, 1, 2, 4 and 6 m/s were used at different tool locations while the temperature and forces were measured. The 1 m/s cutting speed experiment was repeated to verify results and check experimental technique. Table 7-1 gives the material properties for 1215 steel.

<table>
<thead>
<tr>
<th>Material</th>
<th>AISI 1215 steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness (MPa)</td>
<td>1850&lt;sup&gt;13&lt;/sup&gt;</td>
</tr>
<tr>
<td>Machinability</td>
<td>140%&lt;sup&gt;14&lt;/sup&gt;</td>
</tr>
<tr>
<td>Thermal Conductivity (W/m-K)</td>
<td>51.9</td>
</tr>
<tr>
<td>Workpiece Thickness (mm)</td>
<td>1.0</td>
</tr>
</tbody>
</table>

The cutting distance intervals were varied for different cutting speeds. After performing cutting experiments at each tool location, the tool was removed and measured with the EBID technique to observe the progression of tool wear. For 0.5 m/s cutting speed, the cutting distance intervals were 5, 5, 10, 20 and 20 m for a total cutting distance of 60 m. For 1 and 2 m/s cutting speed,

<sup>13</sup> Determined by Lane [19] using Vickers hardness test.

<sup>14</sup> Based on 0-100 scale with AISI 1212 steel as the reference material.
the cutting distance intervals were 10, 10, 20, 40 and 40 m for a total cutting distance of 120 m. For 4 m/s, 6 m/s and the second 1 m/s cutting speed experiments, the cutting distance intervals were 20, 60 and 40 m for a total cutting distance of 120 m.

The 1215 steel workpieces were machined from round stock with a starting diameter of 3 inches. After machining the 1 mm fins to center the cylindrical surface, the machining surface had a diameter of approximately 2.9 inches. The time to reach the DoC and spindle speed for the 5 cutting speeds is shown in Table 7-2 for a 2.9 inch starting diameter. As the radius of the workpiece decreases, the required spindle speed will increase and the time to establish the DoC will decrease.

Table 7-2. Time to reach DoC and spindle speed for the steel wear experiments.\(^{15}\)

<table>
<thead>
<tr>
<th>Cutting speed (m/s)</th>
<th>Time to establish DoC (s)</th>
<th>Spindle speed (RPM)</th>
<th>Feedrate (mm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.46</td>
<td>130</td>
<td>0.26</td>
</tr>
<tr>
<td>1</td>
<td>0.23</td>
<td>260</td>
<td>0.52</td>
</tr>
<tr>
<td>2</td>
<td>0.12</td>
<td>520</td>
<td>1.04</td>
</tr>
<tr>
<td>4</td>
<td>0.06</td>
<td>1040</td>
<td>2.08</td>
</tr>
<tr>
<td>6</td>
<td>0.04</td>
<td>1560</td>
<td>3.12</td>
</tr>
</tbody>
</table>

\(^{15}\) Based on starting workpiece diameter of 2.9 inches.
7.1 Force Measurements

Figure 7-1. Cutting forces during 1215 steel machining for 0-10 m cutting distance at 2 m/s and 2 μm DoC.

Force measurements were recorded during each experiment. An example measurement is shown in Figure 7-1 for 2 m/s cutting speed.

Similar to the aluminum experiments, the average and standard deviation of the tool forces were calculated for the center half of each data set (Ex. 1.25-3.75 s in Figure 7-1). Figure 7-2 shows the average cutting forces as function of cutting distance for each cutting speed. The bars are one standard deviation in each direction. All the force measurements are given in Appendix L. Force Measurements for 1215 Steel.
Figure 7-2. Cutting forces over cutting distances for multiple speeds with 1215 steel at 2 μm DoC.
Due to the rapid tool wear, the cutting forces increase for each speed, as shown in Figure 7-2. To observe the effect of cutting speed, the average cutting forces from Figure 7-2 were plotted as a function of cutting speed in Figure 7-3.

![Figure 7-3. Average cutting forces vs. cutting speed for 2 μm DoC with 1215 steel.](image)

At each cutting speed in Figure 7-3, the effect of tool wear can be seen on the cutting forces. The cutting and thrust forces increase with increased tool wear for each speed and is indicated by the arrows in Figure 7-3 for one of the cutting speeds. However, another trend can be observed from Figure 7-3. Both the average cutting and thrust forces increase as a function of cutting speed. This is the opposite trend as seen with aluminum in Figure 6-29. Korket et al. [39] saw an increase in cutting force with cutting speed while face milling AISI 1040 steel with steel grade cemented carbide inserts. They predicted that at low and intermediate cutting speeds, the material will have a tendency to form a built-up edge (BUE). The BUE increases the effective rake angle, which reduces the cutting forces. At higher cutting speeds, the BUE
becomes unstable and is removed, which increases the cutting forces. However, little
difference was noticed in the pickup pattern between cutting speeds from the high-speed
videos. Another possibility is a strain-rate sensitivity effect increasing the flow stress of the
steel. AdvantEdge results in Section 7.5.1 show a similar trend in cutting and thrust forces.

7.2 TEMPERATURE MEASUREMENTS

Temperatures were measured using the 1000 Ω thin-film RTD. Unlike for the aluminum
experiments, the total cutting distance for the steel experiments was not held constant. This
was done to observe the wear rate in the first several meters of cutting and also after a more
significant distance (>100 m). The maximum cutting distance for a single wear interval was
much less for steel due to the rapid tool wear. This prevented the RTD temperature
measurements from reaching a steady-state value, especially at the faster speeds. This is shown
for the three wear intervals for 4 m/s cutting speed in Figure 7-4.

![Figure 7-4. Temperature during three wear intervals with 1215 steel at 4 m/s cutting speed.](image-url)
Figure 7-4 shows how the longest cutting interval 20-80 m reached the highest temperature. The shapes of the curves vary slightly, but the temperature plot from the longest length of cut was used to make peak temperature predictions from the ANSYS model. The RTD temperatures from the longest wear interval for each cutting speed are shown in Figure 7-5.

![Figure 7-5. RTD measurements for 2 μm DoC with 1215 steel at multiple cutting speeds.](image)

Figure 7-5 shows the RTD temperature measurements for each cutting speed with temperature data from the experiment with the longest cutting distance. Using the ANSYS model detailed in Section 5.2, transient temperatures are fit to the experimental measurements in Figure 7-6.
Figure 7-6. Summary of experimental RTD, model transient RTD, and model peak temperatures for multiple cutting speeds with 1215 steel at 2 μm DoC.
Figure 7-6 shows the comparison between the experimental and model temperatures. The RTD measurements rise at a slow rate until the cutting is completed (no steady-state). This temperature growth is demonstrated clearer in Figure 7-7 and may be caused by the thermal mass of the steel workpiece. The low thermal conductivity of the steel may prevent the heat from dissipating between rotations. This would cause the heat input to slowly rise until the cutting is stopped.

![Graph of RTD temperature during 1215 steel machining at 0.5 m/s and 2 μm DoC.](image)

**Figure 7-7.** RTD temperature during 1215 steel machining at 0.5 m/s and 2 μm DoC.

The heat inputs from Figure 7-6 are used to get a power-law relationship between cutting speed and heat. A power law is fitted to the data with a $R^2$ value of 0.9979, shown in Figure 7-8.
Combining results from Figure 7-8 and the ANSYS relationships from Figure 5-12 produces an equation for the approximate peak temperature rise as a function of cutting speed in Equation (7.1). The relationship in Equation (7.1) is plotted in Figure 7-9.

\[
Q = 5.354v^{0.8146}
\]
\[
\Delta T_{\text{peak}} = 6.091Q
\]
\[
\Delta T_{\text{peak}}(v) = 32.611v^{0.8146}
\]
The power required to perform a machining operation is the product of the cutting force and cutting speed [40]. This product is known as the cutting power. Figure 7-10 shows the cutting power and the ANSYS tool heat input from Figure 7-6 as a function of cutting speed.
**Figure 7-10.** Cutting power (cutting force times cutting speed) and ANSYS heat input as a function of cutting speed for 1215 steel at 2 μm DoC.
7.3 Imaging Results

Figure 7-11. Image of chip formation machining 1215 steel at 0.5 m/s and 2 μm DoC, 4 μs exposure time.
High speed images of the chip formation during the diamond turning of 1215 steel are shown in Figure 7-11 and Figure 7-12. The images were captured at a frame rate of 6006 fps and exposure times of 4 and 3 μs, respectively. Like aluminum, the steel chip is more continuous than the brass chips. The high-speed images have less evident shear bands when compared to the 360 brass images in Figure 4-8. The smaller DoC and higher cutting speed for the conditions made distinguishing chip features more difficult. Table 7-3 gives the results for the two cutting speeds recorded.

**Figure 7-12.** Image of chip formation machining 1215 steel at 1 m/s and 2 μm DoC, 3 μs exposure time.
Table 7-3. Calculation of shear angle from high-speed video for 1215 steel at 0.5 and 1 m/s.

<table>
<thead>
<tr>
<th>Depth of Cut (μm)</th>
<th>2</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting Speed (m/s)</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>Calculated Chip Speed (m/s)</td>
<td>0.20</td>
<td>0.39</td>
</tr>
<tr>
<td>Calculated Workpiece Speed (m/s)</td>
<td>0.506</td>
<td>0.982</td>
</tr>
<tr>
<td>Shear Angle</td>
<td>21.4</td>
<td>21.8</td>
</tr>
<tr>
<td>Average Chip Thickness (μm)</td>
<td>5.1</td>
<td>5.0</td>
</tr>
</tbody>
</table>

The chips from the cutting experiments were imaged using the SEM. Figure 7-13 and Figure 7-14 show the SEM images for the 0.5 m/s cutting speed. Figure 7-15 and Figure 7-16 show the SEM images for the 1 m/s cutting speed. The SEM measurements show a much more continuous chip (non-segmented) than brass (Figure 4-9); no shear bands could be distinguished. The chip thickness was measured to be 8.6 μm at 0.5 m/s and 8.7 μm at 1 m/s. Grooves can be seen on the back side of the cutting chips, which were also observed by Shi [3]. Shi proposed that the grooves were generated by the buildup of hard particles near the cutting edge.
**Figure 7-13.** SEM image of 1215 steel chip cut at 0.5 m/s.

**Figure 7-14.** Higher magnification SEM image of 1215 steel chip edge cut at 0.5 m/s.
Figure 7-15. SEM image of 1215 steel chip cut at 1 m/s.

Figure 7-16. Higher magnification SEM image of 1215 steel chip edge cut at 1 m/s.
From the SEM images, the average chip thickness was approximately 8.6 μm. From Equation (1.1), the shear angle for the 2 μm DoC was 13.1°. The high-speed video images analyzed in Table 7-3 underestimated the chip thicknesses when compared to the SEM measurements.

### 7.4 Wear Results

Diamond turning 1215 steel results in a unique wear pattern, first documented by Lane et al. [19], which consists of a slanted wear land not parallel to the cutting direction (shown in Figure 2-2). Figure 7-17 and Figure 7-18 show SEM images from the EBID measurements for the different cutting parameters.
Using the EBID technique described in Section 3.4, the tool profiles are measured at multiple cutting intervals to show the progression of tool wear. Figure 7-17 shows the SEM images of the tool edge after the final experiment for 0.5, 1 and 2 m/s cutting speeds at distances of 60, 120 and 120 m, respectively. The SEM magnification for the images in Figure 7-17 is 20000X (scale bar at bottom right is 1 μm). The EBID lines trace the tool profiles along the cutting edge from the rake face to the flank face. The 2D tool profiles measured from Figure 7-17 are
shown in Figure 7-19 (after applying the measurement procedure in Figure 3-21) with the profiles from the wear intervals.

![SEM images](image)

**Figure 7-18.** SEM images at 25 kX of tool wear after (a) 120 m at 1 m/s (b) 120 m at 4 m/s and (c) 120 m at 6 m/s with 1215 steel, 2 μm DoC.

Figure 7-18 shows the tool edge after the 120 m cutting for 1, 4 and 6 m/s cutting speeds. The SEM magnification for the images in Figure 7-18 is 25000X (scale bar at bottom right is 1 μm). The 2D tool profiles measured from Figure 7-18(b) and Figure 7-18(c) for 4 and 6 m/s are shown in Figure 7-20 with the profiles from the wear intervals.
Figure 7-19. Worn tool profiles for 1215 steel for 0.5, 1 and 2 m/s cutting speeds and 2 μm DoC.
Figure 7-19 shows the tool profiles from the EBID measurements for 0.5, 1 and 2 m/s cutting speeds at a 2 μm DoC. The profiles show the tool edge at increasing cutting distances to observe the tool wear progression. The shaded regions in Figure 7-19 illustrate the tool wear that occurred between two cutting distances (5-10 m for 0.5 m/s, 10-20 m for 1 m/s and 2 m/s).

The tool profiles for 4 and 6 m/s cutting speeds are shown in Figure 7-20. The shaded regions in Figure 7-20 illustrate the tool wear that occurred between 20-80 m of cutting. It should be noted that the scale in Figure 7-20 is double the scale from Figure 7-19.

The 2D wear area is measured at each cutting distance interval from Figure 7-19 and Figure 7-20 are summarized in Figure 7-21 as a function of distance and in Figure 7-22 as a function of time. Also, the data for all EBID measurements is given in Appendix J. Wear Measurements for 1215 Steel. A linear regression is fit to each data set and is shown as a dotted line with equation and fitting statistics. Although the wear is expected to be non-linear versus cutting speeds.
distance, i.e. the rate should increase as the tool wear becomes more pronounced, the slope of the regression lines provide an estimate of the average wear rate (2D Wear Area/Cutting Distance or 2D Wear Area/Cutting Time). The slopes from Figure 7-21 will be used to evaluate the temperature dependency of the diamond tool wear.

![Graph showing 2D wear area vs. cutting distance for all cutting speeds for 1215 steel. Linear regression (dotted) is also shown for each cutting speed.](image)

**Figure 7-21.** 2D wear area vs. cutting distance for all cutting speeds for 1215 steel. Linear regression (dotted) is also shown for each cutting speed.
Figure 7-22. 2D wear area vs. cutting time for all cutting speeds for 1215 steel. Linear regression (dotted) is also shown for each cutting speed.

Figure 7-23. 2D wear area vs. cutting distance for two separate experiments with 1215 steel at a cutting speed of 1 m/s and 2 μm DoC.
To evaluate the repeatability of the experimental procedure and measurement technique, the 1 m/s cutting parameter was repeated. Figure 7-23 shows the comparison of the 2D wear areas as a function of cutting distance. Figure 7-23 shows similar results for the two experiments. At cutting distances of 80 and 120 m, the 2D wear areas for the second run were 0.0055 and 0.0035 μm² less than the first run (difference of 18% and 6.7%).

The profiles at different cutting speeds are shown at equal cutting distances in Figure 7-24. This helps to visualize the data presented in Figure 7-22. It should be noted that the scaling is increasing for each cutting distance in Figure 7-24. The approximate angle of the wear land is shown in each plot in Figure 7-24 (using 4 m/s cutting speed). The wear land develops at angle between 19-24°, which is similar in magnitude to the calculated shear angle from the high-speed video analysis in Table 7-3 (22°). The relationship between the shear angle and wear land angle should be investigated further to verify any connection.
Figure 7-24. Tool profiles at 20, 80 and 120 m cutting distances for 1215 steel at 2 µm DoC.
7.4.1 Crater Wear

Figure 7-25. Zygo NewView SWLI surface measurement of diamond rake face after 120 m machining 1215 steel at 1 m/s (37 nm PV).
Figure 7-26. Zygo NewView SWLI surface measurement of diamond rake face after 120 m machining 1215 steel at 4 m/s (20 nm PV).
Figure 7-27. Zygo NewView SWLI surface measurement of diamond rake face after 120 m machining 1215 steel at 6 m/s (20 nm PV).
The tool rake face was measured using a Zygo NewView Scanning White Light Interferometer (SWLI). The rake face showed small levels of crater wear (20 – 37 nm PV) in Figure 7-25, Figure 7-26 and Figure 7-27. A sharp diamond tool is shown in Figure 7-28 for reference (7 nm PV on surface profile line and no sign of cratering). The crater wear extends approximately 200 μm back from the cutting edge. The chip must be contacting the tool at these locations for the wear to occur. Figure 7-12 shows that for the 1 m/s cutting speed, the chip appears to be contacting the surface for approximately 150-200 μm. Drescher [2] also observed crater wear when diamond turning plated copper. After 28 km of machining, he measured a crater depth of 3 μm that extended approximately 1 mm from the start of the crater. He showed that the
crater wear started approximately 15 μm from the cutting edge for both 1.25 and 0.16 μm DoCs.

Figure 7-29 shows the comparison of the length and depth of the crater wear from the line profile in Figure 7-27. It should be noted the x-axis is in μm and the y-axis is in nm. The crater wear begins to occur at a length of approximately 2-3 μm from the cutting edge (2 μm DoC), shown in Figure 7-29. The approximate crater area (using one half the product of the crater depth, 18 nm, and crater length, 180 μm) in Figure 7-29 is 1.6 μm². This is 4x the flank wear area (0.40 μm²) for the 6 m/s cutting speed.

![Figure 7-29. Crater wear for 1215 steel at 6 m/s cutting speed (x-scale in μm, y-scale in nm).](image)

**7.5 AdvantEdge Simulation Results for Steel**

FE simulations were performed using AdvantEdge to provide a comparison with the 1215 steel experimental results. The low temperature results discussed in Sections 4.4.2 and 9.2 were corrected by using a custom tool with isothermal boundary conditions set to a higher temperature based on RTD temperature measurements. Figure 7-30 shows the first zone of the simulation with the custom isothermal boundary conditions on the top and right tool faces. This results in a higher steady-state temperature distribution that is comparable to predictions from the temperature measurements in Section 7.2.
The steel simulations were run in standard mode to shorten the computation time, but this mode requires a minimum workpiece element size of 0.001 mm. Therefore, the starting radius of the diamond tool needs to be increased to prevent size issues at the cutting edge. The custom tool radius was set to 500 nm. The complete set of simulation parameters are given in Appendix M. AdvantEdge Simulations for Steel. The AdvantEdge material library does not contain 1215 steel. AISI 1118 steel was used instead, due to the similarities in material properties, which are compared in Table 7-4.

<table>
<thead>
<tr>
<th>Material</th>
<th>AISI 1215</th>
<th>AISI 1118</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus of Elasticity (GPa)</td>
<td>200</td>
<td>205</td>
</tr>
<tr>
<td>Hardness, Brinell</td>
<td>167</td>
<td>149</td>
</tr>
<tr>
<td>Thermal Conductivity (W/m-K)</td>
<td>51.9</td>
<td>49.8</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>7.85</td>
<td>7.87</td>
</tr>
<tr>
<td>Specific Heat (J/g-°C)</td>
<td>0.472</td>
<td>0.472</td>
</tr>
</tbody>
</table>

Figure 7-30. AdvantEdge simulation with adjusted isothermal boundary conditions.
Figure 7-31 shows the final temperature contour for the 1 m/s simulation with the cutting forces and temperature plot underneath the temperature contour. The same cutting speeds and DoC used in the steel machining experiments were used in the AdvantEdge simulations. The data for the simulation results is given in Table 0-25.

**Figure 7-31.** Final temperature contour plot with cutting forces and temperature plotted vs. time for 2 μm DoC at 1 m/s with 1118 steel.
Figure 7-32. Tool temperature contour for 2 μm DoC at 1 m/s with 1118 steel.

The AdvantEdge temperature distribution for the 1 m/s simulation compared with the projection from the ANSYS model in Figure 7-33. The distance variable in Figure 7-33 is defined in Figure 7-36.
Figure 7-33. AdvantEdge and ANSYS temperature distributions along the cutting edge and rake face.

Figure 7-33 shows that the predicted temperature distributions from AdvantEdge match the temperature projections from the RTD measurements for the 1 m/s cutting speed within 3°C.
7.5.1 FORCES

Figure 7-34. Comparison of AdvantEdge and experimental tool forces as a function of cutting speed for a 2 μm DoC with 1118 and 1215 steel.

Figure 7-34 shows the comparison of average experimental and simulation tool forces. The average simulation tool forces increase with cutting speed similar to the pattern noticed with the experimental data. The thrust forces are underestimated by the simulations for the higher cutting speeds (approximately 10-25% for 2-6 m/s cutting speeds). The cutting and thrust simulation forces can be increased by increasing the friction factor in AdvantEdge. For a friction factor of 0.4, the simulation cutting forces matched the experimental cutting forces to within 7%. The 1118 steel has a Brinell hardness of 149 and the 1215 steel has a Brinell hardness of 167 (12% greater). The difference in simulation and experimental material properties may prevent the balance of both the cutting and thrust forces, similar to the brass materials in Section 0.
7.5.2 TEMPERATURES

The simulations were performed using custom tools in AdvantEdge. As shown in Figure 7-30, the top and right tool faces had increased isothermal boundary conditions. The boundary temperatures were selected by using the predicted temperature from the ANSYS models at 25 μm from the cutting edge (size of AdvantEdge tool). The boundary temperatures for the steel simulations are given in Table 0-25. Figure 7-35 shows the comparison between peak temperature predictions from Equation (7.1) and the AdvantEdge peak temperatures.

![Figure 7-35](image)

**Figure 7-35.** Peak tool temperature projections and peak AdvantEdge temperatures vs. cutting speed.

Figure 7-35 shows that the peak temperatures from the AdvantEdge simulations closely match the projections made from the RTD measurements. To observe the temperature distribution along the cutting edge and rake face, the rake and relief data from AdvantEdge was extracted using the procedure detailed in Appendix H. Extracting AdvantEdge Rake and Relief Tool
Data. This gives parameters such as temperature and process along the tool perimeter. The data is plotted against the distance variable, which is shown in Figure 7-36.

![Graph showing the orientation of the distance variable](image)

**Figure 7-36.** Orientation of distance variable from rake/relief data extraction in AdvantEdge.

The origin of the distance variable is at the lowest point on the tool as shown in Figure 7-36. The distance increases to the left towards the tool rake face. The negative distance is towards the flank face. The temperature distribution along the cutting edge and rake face for all the simulations is shown in Figure 7-37. Because of the high thermal conductivity, the temperature gradient for each speed is very low. It should be noted that the x-axis in Figure 7-37 is reversed to match the orientation presented in Figure 7-36.
Figure 7-37. (a) Tool perimeter distance and (b) temperature distribution along the cutting edge and rake face for each cutting speed.

The steady-state temperature contour plot for the diamond tool at a cutting speed of 1 m/s is shown in Figure 7-32. The high thermal conductivity of diamond reduces the gradient in the tool to approximately 5° (≈ 50° - 45°) in the overall dimensions of the 1 m/s simulation.
7.5.3 CHIP FORMATION

The plastic strain rate contour plot was generated in Tecplot for the 1 m/s cutting speed. The effective shear angle was measured and is shown in Figure 7-38 (experimental comparison given in Table 7-5).

**Figure 7-38.** Effective shear angle (22.4°) from AdvantEdge for 1 m/s cutting speed for 2 μm DoC with 1118 steel using strain rate.

During the machining process, the workpiece material will split and some material flows up the rake face forming a chip and other materials flows under the edge to become the new workpiece surface. At the separation or ‘stagnation’ point, there will be a minimum speed where no material flows. This is shown in Figure 7-39 with the AdvantEdge velocity contour for the 1 m/s cutting speed with 1118 steel. Underneath the minimum speed, the flow quickly tapers back to the approximate cutting speed.
Figure 7-39. Workpiece material velocity distribution along the tool cutting edge for 1 m/s cutting speed with 1118 steel.

Table 7-5 gives the comparison between the experimental and AdvantEdge results for chip speed and shear angle for the 1 m/s cutting speed. The experimental values are from the high-speed analysis in Table 7-3 and the AdvantEdge values are shown in Figure 7-38 and Figure 7-39.

Table 7-5. Comparison of chip speed and shear angle for experimental and AdvantEdge for 2 μm DoC, 1 m/s cutting speed with steel.

<table>
<thead>
<tr>
<th></th>
<th>Experimental (1215)</th>
<th>AdvantEdge (1118)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting Speed (m/s)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Chip Speed (m/s)</td>
<td>0.39</td>
<td>0.41 (25 m/min)</td>
</tr>
<tr>
<td>Shear Angle (degrees)</td>
<td>21.8</td>
<td>22.4</td>
</tr>
</tbody>
</table>
7.6 Steel and Aluminum Comparison

The results for temperature, cutting forces and wear patterns varied between the 1215 steel and 6061 aluminum. As shown in Figure 6-29 and Figure 7-3, the level of tool wear and cutting speed will affect the tool forces for both materials. Table 7-6 shows the comparison of the cutting force, thrust force, flank force and specific cutting energy during the first wear interval (non-worn tool) for both materials at the same cutting speed of 1 m/s. The specific cutting energy is calculated using Equation (1.3) and the flank force is calculated using Equation (2.6)\(^6\).

Table 7-6. Comparison of specific cutting energy for steel and aluminum at 1 m/s cutting speed.

<table>
<thead>
<tr>
<th>Material</th>
<th>Aluminum 6061-T6</th>
<th>AISI 1215 Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth of Cut (μm)</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Hardness (MPa)</td>
<td>1185</td>
<td>1850</td>
</tr>
<tr>
<td>Workpiece Thickness (mm)</td>
<td>0.813</td>
<td>1.0</td>
</tr>
<tr>
<td>Cutting Speed (m/s)</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Cutting Distance (m)</td>
<td>0-250</td>
<td>0-10</td>
</tr>
<tr>
<td>Average Cutting Force (N)</td>
<td>3.54 (± 0.22)</td>
<td>6.80 (± 0.40)</td>
</tr>
<tr>
<td>Average Thrust Force (N)</td>
<td>3.18 (± 0.21)</td>
<td>3.292 (± 0.34)</td>
</tr>
<tr>
<td>Average Flank Force (N)</td>
<td>1.92</td>
<td>0.62</td>
</tr>
<tr>
<td>Specific Cutting Energy (N/m²)</td>
<td>2.17×10⁹</td>
<td>3.40×10⁹</td>
</tr>
</tbody>
</table>

Table 7-6 shows that for these cutting conditions, 1215 steel has a 56% greater cutting energy than 6061 aluminum. This means 56% more energy is consumed per volume removal of 1215 steel when compared to 6061 aluminum for these cutting conditions (1 m/s, 2 μm DoC). This corresponds to the difference in hardness between the steel and aluminum (the 1215 steel has

\(^6\) Approximated using the same rake and flank friction coefficients for aluminum and steel.
a 56% greater hardness than the 6061 aluminum). It should be noted that the average cutting forces were affected by cutting speed for both materials. For the 1215 steel, the average cutting forces increased with cutting speed. For the 6061 aluminum, the cutting forces decreased with speed. The change in cutting force would affect the magnitude of the specific cutting energy. The 1 m/s cutting speed in Table 7-6 was selected as an example to compare the steel and aluminum.

Figure 7-40. Worn tool profile comparison for 6061 aluminum and 1215 steel.

Figure 7-40 shows the tool profiles for aluminum after 3 km of machining and steel after 120 m of machining. Both have a larger edge radius, but the aluminum profile has a wear land that is more parallel to the cutting distance (-X direction in Figure 7-40), characteristic of abrasive diamond tool wear. The steel wear land develops at an angle from the cutting direction, as seen by Lane [8]. The 2D wear areas in Figure 7-40 are comparable (0.056 μm² for aluminum and
0.052 μm² for steel), although the aluminum cutting distance is 25x greater. Using the average flank force from Table 7-6 and the Archard coefficient determined for 2 μm DoC with aluminum at 1 m/s (0.0116 μm³N⁻¹m⁻¹), the abrasive wear volume from Equation (2.5) is 0.86 μm³ after 120 m cutting distance. This corresponds to a 0.00086 μm² wear area for the 1 mm wide steel workpiece in orthogonal cutting. This accounts for 1.65% of the wear area of the worn tool profile shown in Figure 7-40 (0.00086 μm²/0.052 μm²).

![Graph showing wear area vs. cutting distance for steel and aluminum](image)

**Figure 7-41.** Average wear rate comparison for steel and aluminum at 1 m/s and 2 μm DoC.

In Figure 7-41, a linear regression is performed on the wear areas and cutting distances for aluminum and steel at 1 m/s cutting speed to get an *average* wear rate over the cutting distances. It shows that the average wear rate for steel at 1 m/s was approximately 11x as much as the wear rate for aluminum. This ratio is even greater for other steel cutting speeds, since the 1 m/s cutting speed had the lowest wear rate for steel. This shows that even at the approximate optimal cutting speed, there is a significantly greater wear rate for steel diamond machining than aluminum.
7.6.1 **Temperature Comparison for Steel and Aluminum**

**Figure 7-42.** Temperature comparison between steel and aluminum for 1, 2 and 4 m/s cutting speeds and 2 μm DoC.
Shaw’s prediction for mean rake face temperature rise from dimensional analysis\textsuperscript{17} predicted a much greater temperature rise (approximately 4x) for steel than aluminum, mainly due to differences in thermal conductivity and specific cutting energy\textsuperscript{18}. Figure 7-42 compares the RTD temperatures for steel and aluminum at 1, 2 and 4 m/s. Figure 7-42 shows that tool temperatures were significantly greater for steel than aluminum machining at the same cutting speeds and DoCs. At 1 m/s cutting speed, the temperature rise was 1.23x (16°C/13°C) greater for steel than aluminum. At 2 m/s cutting speed, the steel temperature rise was 1.9x (32°C/17°C) greater and 2x (60°C/30°C) greater at 4 m/s. Figure 7-42 also shows that for steel experiments, no steady-state temperatures were achieved. The temperatures are slowly increasing until cutting is stopped. It is thought that this is caused by the thermal mass of the steel workpiece. The low thermal conductivity of the steel may prevent the heat from dissipating in the orthogonal cutting configuration used.

**7.7 DISCUSSION**

1) The 1215 steel showed an increase in the initial average cutting and thrust forces (Figure 7-3) with cutting speed. This could be a result of strain rate sensitivity having a greater effect on the yield stress of the material than thermal softening. The opposite trend is observed for 6061 aluminum, where cutting forces decreased with cutting speed (Figure 6-29).

2) The thin-film RTD measurements were used to estimate the peak tool temperatures. A summary of all peak temperature predictions is given in Figure 7-43. Figure 7-43 is a summary of the peak temperature predictions as a function of cutting speed. It includes 2 \(\mu\)m DoC with steel from Equation (7.1), 2 \(\mu\)m DoC with aluminum from Equation (6.8), 10 \(\mu\)m DoC with aluminum from Equation (6.9) and Ueda’s results for 10 \(\mu\)m DoC with aluminum. For the 2 \(\mu\)m DoC, the peak temperature predictions for 1215 steel are

\textsuperscript{17}Equation (1.2) \cite{10}.

\textsuperscript{18} Energy consumed in removing a unit volume of material \cite{9}.
approximately 2x greater than 6061 aluminum. This is likely due to the low thermal conductivity and high specific cutting energy of the steel.

3) 

**Figure 7-43.** Comparison of peak temperature predictions for aluminum and steel as a function of cutting speed.

4) AdvantEdge simulations were performed using a larger radius tool in standard mode to decrease computation time to approximately 20 hours. The tool thermal boundary conditions were set to higher values based on values from temperature measurements and ANSYS projections. This method produced peak temperature values in AdvantEdge that matched predictions. The approximate temperature distribution along the cutting edge and rake face was also extracted using AdvantEdge. The extracted data showed a low temperature gradient along the cutting edge and rake face. The simulation force data
followed the same trend from the experiments. Both the cutting and thrust force increased with cutting speed after 1 m/s.

5) The worn tool geometries for steel exhibit a unique profile were the wear land is angled from the cutting direction, first observed by Lane et al. [8]. The angle is approximately 20° between the wear land and cutting direction (19-24° in Figure 7-24). The angle of the wear land is similar in magnitude to the shear angle calculated from the high-speed video analysis, 21.8°, and the AdvantEdge shear angle, 22.4°.

6) A minimum experimental wear rate was observed at 1 m/s. This minimum wear rate for 1215 steel is 11 times greater than at the same DoC and cutting speed with 6061 aluminum. The data from this section will be used to evaluate the temperature dependency of the steel wear rate in Chapter 8.
8 AVERAGE TEMPERATURE DEPENDENCY OF TOOL WEAR

8.1 TEMPERATURE DEPENDENCY OF TOOL WEAR

A minimum experimental wear rate was observed at 1.0 m/s cutting speed. This suggests an active thermo-chemical wear mechanism. Multiple researchers have explored the chemical aspects of diamond tool wear. Paul et al. [22] reviewed numerous possible physical and chemical mechanisms including diffusion, catalytic reactions and the formation of several intermediary reaction complexes. Most of the proposed mechanisms followed an Arrhenius-type equation with an activation energy, pre-exponential constant and temperature. Lane used an Arrhenius-type model using modified forms presented by Takeyama and Jiang [41,42]. The peak temperature projections and wear geometry examined in Chapter 7 are used to evaluate the temperature dependency of the diamond tool wear during the machining of 1215 steel.

The Arrhenius function relates the rate of a reaction to the temperature (i.e. it gives the temperature dependency). It was discussed in Section 2.2.1 in more detail, but Equation (8.1) shows both the wear/distance and wear/time forms [16].

\[
\frac{dW}{dt} = A \exp \left( \frac{-E_a}{RT} \right) \quad \iff \quad \frac{dW}{ds} = \frac{A}{v} \exp \left( \frac{-E_a}{RT} \right)
\]  \tag{8.1}

Table 8-1 gives the required data for calculating a chemical-type Arrhenius model. The predicted peak temperatures are calculated using Equation (7.1). The average distance wear rates, dW/ds, are the slopes of the regression lines in Figure 7-21.
Table 8-1. Data for Arrhenius-type model for 2 μm DoC with 1215 steel.

<table>
<thead>
<tr>
<th>Cutting Speed (m/s)</th>
<th>Expected Peak Temperature (°C)</th>
<th>T⁻¹ (K⁻¹)</th>
<th>dW/ds, Average 2D Worn Area/distance (μm²/m)</th>
<th>ln(dW/dt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>38.54</td>
<td>0.00324</td>
<td>0.00155</td>
<td>-7.163</td>
</tr>
<tr>
<td>1</td>
<td>52.61</td>
<td>0.00312</td>
<td>0.00043</td>
<td>-7.752</td>
</tr>
<tr>
<td>2</td>
<td>77.36</td>
<td>0.00292</td>
<td>0.00073</td>
<td>-6.529</td>
</tr>
<tr>
<td>4</td>
<td>120.88</td>
<td>0.00264</td>
<td>0.00149</td>
<td>-5.123</td>
</tr>
<tr>
<td>6</td>
<td>160.36</td>
<td>0.00242</td>
<td>0.00325</td>
<td>-3.937</td>
</tr>
</tbody>
</table>

From Table 8-1, the natural log of the time wear rate, dW/dt, is plotted as a function of the inverse temperature, shown in Figure 8-1. The slope, intercept and R² values are shown in Figure 8-1 and Table 8-2.

Figure 8-1. Arrhenius plot of for average 2D wear areas vs. peak temperature predictions.
Using Equation (2.3), the activation energy, $E_a$, and pre-exponential constant, $A$, are calculated from the slope and intercept and given in Table 8-2.

Table 8-2. Arrhenius coefficients from peak temperature predictions and average wear rates.

<table>
<thead>
<tr>
<th>Arrhenius Coefficients</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope (- $\alpha$)</td>
<td>-4015.2</td>
</tr>
<tr>
<td>Intercept</td>
<td>5.1224</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.9235</td>
</tr>
<tr>
<td>Universal gas constant (kJ/mol-K)</td>
<td>0.008314462</td>
</tr>
<tr>
<td>Activation Energy (kJ/mol)</td>
<td>33.4</td>
</tr>
<tr>
<td>Activation Energy (eV/atom)</td>
<td>0.346</td>
</tr>
<tr>
<td>Constant, A ($\mu$m$^2$/s)</td>
<td>167.7</td>
</tr>
</tbody>
</table>

Inserting the equation for temperature rise from Equation (7.1) into Equation (8.1) gives the wear rate as a function of cutting speed:

$$
\frac{dW}{ds} = \frac{A}{v} \exp\left(\frac{-E_a}{R(32.611v^{0.8146} + 293.15)}\right),
$$

where $v$ is cutting speed, $R$ is the universal gas constant, $E_a$ is the activation energy and $A$ is the pre-exponential constant. Equation (8.2) is plotted in Figure 8-2(a) and the wear/time form in Figure 8-2(b).
Figure 8-2. (a) Distance wear rate and (b) time wear rate as a function of cutting speed with logarithmic x-scale for 2 μm DoC with 1215 steel.

Figure 8-3 shows Equation (8.2) without the logarithmic x-axis scale. It shows a minimum wear rate at 1.0 m/s cutting speed. The wear rate increases with cutting speed after the minimum due to increased tool temperatures. As the cutting speed is reduced below the optimal cutting speed, the wear rate (wear per distance) increases due to the longer time for reactions to take place.
Figure 8-3. Wear rate per distance as a function of cutting speed for 2 μm DoC with 1215 steel.

The least-squares line fit in Figure 8-1 resulted in a high correlation coefficient for the Arrhenius function. The activation energy was determined from single values for predicted peak temperatures and an average rate of wear for each cutting speed. Both the temperature and wear rate will have a distribution along the perimeter of the tool. Nevertheless, the results indicate a strong correlation with an Arrhenius-type exponential function for chemical reaction rates, shown in Figure 8-2(b).
The EBID measurement in Figure 8-4 shows a high wear rate at the cutting edge and the development of an angled wear land for 1215 steel. Minimal wear occurs along the tool rake face even though it is in contact with the workpiece material and chip. Small levels of crater wear (18-37 nm) were observed on the rake face, but were located past the 2 μm DoC. For the 6 m/s cutting speed shown in Figure 8-4, the maximum crater depth was approximately 18 nm (Figure 7-27). This is approximately 0.9 nm/s at the maximum crater depth. The recession at the cutting edge is significantly greater. In Figure 8-4 for the 6 m/s cutting speed, a maximum recession of 0.56 μm is shown from the sharp cutting edge to the normal of the cutting edge surface after 120 m of machining 1215 steel (31x than the maximum crater depth). This corresponds to a maximum wear distance per time of 28 nm/s from the sharp tool edge.
AdvantEdge simulations show a low temperature gradient along the cutting edge and rake face caused by the high thermal conductivity of the diamond (Figure 7-33). The low temperature gradient presents an issue in predicting the accelerated wear occurring at the cutting edge, which is discussed more in Chapter 9.

**8.2 CONCLUSIONS**

This research provides strong evidence of a temperature-dependency in the wear rate of diamond tools during ferrous machining. Lane’s [17] experiments with 1215 steel included low speed (0.002-0.008 m/s), mid-speed (0.071-0.284 m/s) and high-speed (1-4 m/s) experiments. The low and mid-speed experiments had a significantly greater wear rate than the high-speed experiments. Lane did not directly observe a minimum wear rate as a function of cutting speed for his 1215 steel experiments. He proposed an Arrhenius-type chemical model where the wear rate would reach a minimum at an intermediate cutting speed then increase. The results from the tool wear measurements verified an optimal cutting speed for the diamond machining of 1215 steel.

The activation energy is low compared to the reaction pathways discussed by Paul et al. [22] for graphitization and diffusion. Static diffusion tests produced an activation energy of 100 kJ/mol for the erosion of diamond in pure iron and 130 kJ/mol for stainless steel [21]. These were performed at temperatures from 600 to 900°C. No diffusion was observed for the iron or stainless steel at 600°C. At 900°C, pure iron removed the diamond surface at 3.7 nm/s. The activation energy for the uncatalyzed graphitization of diamond is 730 kJ/mol for the dodecahedral face and 1060 kJ/mol for the octahedral face [22]. Seal [23] analyzed the static graphitization tests of diamond powder samples at 1200, 1600 and 2000°C without the presence of an iron catalyst. No graphite was formed at the 1200°C temperature.

---

19 Lane’s DoC was 1 μm and cutting oil was used. Both would reduce the cutting temperature and possibly increase the optimal cutting speed. He observed the increase wear rate with cutting speed for Stavax stainless steel.
Measurements predict peak temperatures on the order of 40 to 160°C for cutting speeds from 0.5 to 6 m/s for the 2 μm DoC with 1215 steel. The temperatures from static diffusion and graphitization tests are much greater than the predicted peaks from the temperature measurements and FE simulations. The freshly generated workpiece in is contact with the tool edge under high pressure and elevated temperatures. This could provide a catalyst for the specific reaction, e.g. graphitization through the formation of metal complexes followed by diffusion into the workpiece material [22], reducing the activation energy. Regardless of the reaction pathway, the carbon atoms get removed from the diamond lattice and enter the workpiece or chip.
9  FINITE ELEMENT MODELING FOR TOOL WEAR

Finite element modeling (FEM) was used for comparison of experimental cutting forces, tool temperatures, chip formation and wear rate. Commercial finite element programs for modeling machining processes include MSC.Marc, Deform2D, AdvantEdge and Abaqus/Explicit. Bil et al. [43] reviewed MSC.Marc, Deform2D and AdvantEdge comparing the results to experimental values. He noted that none of the reviewed program could predict forces, chip thickness/shear angle, and temperatures to within 50% of experimental values. Despite inaccuracies, finite element analysis allows the prediction of parameters that would otherwise be difficult to measure, such as normal pressure and temperature along the cutting edge. By making discrete elements and time steps, the finite element programs can also take into account the connection between thermal and material properties.

9.1 THIRD WAVE ADVANTEdge

Third Wave AdvantEdge is a commercial FEM program that calculates forces, temperatures, stresses, pressures and several other machining parameters. AdvantEdge has a 2D turning mode that can be used to model the orthogonal cutting system used in this research. It should be noted that the terminology differs between AdvantEdge and the parameters defined in Figure 1-1. Figure 9-1 shows the geometry for a 2D turning simulation in AdvantEdge. In this chapter, the AdvantEdge terminology will be used followed by the original definition in parentheses.
AdvantEdge simulations consist of a stationary tool and a deformable workpiece that moves at a constant speed and feed (DoC) into the tool. A plane-strain condition is assumed for the 2D simulations so that the depth of cut (width) is large compared to the feed (DoC). AdvantEdge uses six-noded quadratic triangular elements for both workpiece and tool meshing [43]. The workpiece and chip is regenerated after each time step.

Heat is generated by plastic work and Coulomb frictional heating. The rate of specific volumetric heat flux from plastic work is obtained by multiplying the rate of plastic work (stress times strain rate) by a constant fraction and dividing by the density. The specific volumetric heat flux from friction is calculated through the dot product of the surface traction vector and the relative velocity between the tool and workpiece. The heat from friction is partitioned between the tool and workpiece by a comparison of their densities, thermal capacities and conductivities. The relationship is given as

\[
\frac{h_1}{h_2} = \frac{k_1 \rho_1 c_1}{\sqrt{k_2 \rho_2 c_2}},
\]

(9.1)
where $\rho$ is the density, $k$ is the thermal conductivity and $c$ is the specific heat [8]. The heat generated from plastic work is transferred to the tool by conduction through the workpiece and chip.

AdvantEdge models the complex material behaviors occurring during machining by accounting for changes in yield stress caused by strain hardening, strain rate sensitivity and thermal softening. For custom materials, AdvantEdge offers two constitutive models: Power Law and Drucker Prager. For non-custom materials, the constants and models are predetermined by Third Wave using elastic and plastic deformation experiments and cutting tests.

The Power Law is defined as

$$\sigma(\varepsilon^p, \varepsilon^r, T) = g(\varepsilon^p) \times \Gamma(\dot{\varepsilon}) \times \Theta(T),$$

where $g(\varepsilon^p)$ is the strain hardening term, $\Gamma(\dot{\varepsilon})$ is the strain rate sensitivity term and $\Theta(T)$ is the thermal softening term. Similarly, the Drucker Prager law is defined as

$$\sigma(\varepsilon^p, J, \varepsilon^r, T) = G(\varepsilon^p, J) \times \Gamma(\dot{\varepsilon}) \times \Theta(T),$$

where $G(\varepsilon^p, J)$ is strain hardening plus the hydrostatic pressure given by

$$G(\varepsilon^p, J) = g(\varepsilon^p) + DP_0 \times J,$$

where $DP_0$ is the hydrostatic stress coefficient and $J$ is the hydrostatic pressure.

### 9.1.1 Strain Hardening

Strain hardening will increase the yield strength of the material as plastic strain increases. The strain hardening term in AdvantEdge is defined by
\[ g(\varepsilon^p) = \sigma_0 \left(1 + \frac{\varepsilon^p}{\varepsilon_0^p}\right)^{1/n} , \text{if } \varepsilon^p < \varepsilon^p_{\text{cut}} \]
\[ g(\varepsilon^p) = \sigma_0 \left(1 + \frac{\varepsilon^p}{\varepsilon^p_{\text{cut}}}\right)^{1/n} , \text{if } \varepsilon^p \geq \varepsilon^p_{\text{cut}} \]

where \( \sigma_0 \) is the initial yield stress, \( \varepsilon^p \) is the plastic strain, \( \varepsilon_0^p \) is the reference strain, \( \varepsilon^p_{\text{cut}} \) is the cut off strain and \( n \) is the strain hardening component.

### 9.1.2 Strain Rate Sensitivity

During machining, extreme strain rates are achieved as workpiece material is removed at high cutting speeds. In most materials, increases in the strain rate will cause the yield stress of the material to increase. In AdvantEdge the strain rate sensitivity effect is given by

\[ \Gamma(\dot{\varepsilon}) = \left(1 + \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^{1/m_1} , \text{if } \dot{\varepsilon} \leq \dot{\varepsilon}_t \]
\[ \Gamma(\dot{\varepsilon}) = \left(1 + \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^{1/m_2} \left(1 + \frac{\dot{\varepsilon}_t}{\dot{\varepsilon}_0}\right)^{1/m_1-1/m_2} , \text{if } \dot{\varepsilon} > \dot{\varepsilon}_t \]

where \( \dot{\varepsilon} \) is the strain rate, \( \dot{\varepsilon}_0 \) is the reference plastic strain rate, \( \dot{\varepsilon}_t \) is the transition between low \((m_1)\) and high \((m_2)\) strain rate sensitivity.

### 9.1.3 Thermal Softening

The thermal softening effect will reduce the yield strength as the temperature increases. The thermal softening effect in Advantage is given by

\[ \Theta(T) = c_0 + c_1T + + c_2T^5, T < T_{\text{cut}} \]
\[ \Theta(T) = \Theta(T_{\text{cut}}) \left(1 - \frac{T - T_{\text{cut}}}{T_{\text{melt}} - T_{\text{cut}}}\right), T \geq T_{\text{cut}} \]

where the constants are coefficients for the polynomial fit, \( T \) is the temperature, \( T_{\text{cut}} \) is the linear cut off temperature and \( T_{\text{melt}} \) is the melting temperature [44].
9.2 Low Temperature Results Using Isothermal Boundary Conditions

The AdvantEdge software is restricted to isothermal or adiabatic boundary conditions (BCs) for the 2D turning simulations. The high thermal conductivity of diamond combined with ambient isothermal BCs results in the peak tool temperature to be underestimated. The diamond efficiently removes the heat from the cutting edge to the BCs. In reality, the tool shank (typically carbide) will have an insulating effect on the tool. However, only one material type is allowed for the 2D turning simulations.

During the initial development of the experimental setup, free-cutting brass (UNS 36000) was used as the workpiece material. The free-cutting brass allowed larger depths of cut to test the imaging system, load cell, and eventually temperature measurements. Lane’s FE models [17] for diamond turning of steel were for smaller depths of cut (0.5-2 μm) than the present work. Since the depth of cut for these models are increased, the simulations were run in standard (non-‘micro’) mode with a larger cutting radius (1 μm). The standard mode has a larger time step for calculations and allows faster computation times. The model overview is shown in Figure 9-2 with tool parameters, process options and workpiece mesh in Table 0-11, Table 0-12 and Table 0-13. The AdvantEdge material library did not include C36000 brass, so the C3770 forging brass was selected because it has similar material properties (Table 0-6).
The standard tool model has isothermal BCs for the right and top faces of the tool, as shown in Figure 9-2. The other faces of the tool are adiabatic to the environment, but heat is input from the workpiece due to friction and conduction. The end of the length of cut for a 10 μm DoC at a cutting speed of 1 m/s is shown in Figure 9-3 with temperature contours. In this case, a peak temperature of 34.4°C was predicted from the software.

**Figure 9-2.** AdvantEdge model and mesh for large depth of cut (5-20 μm) simulations.

**Figure 9-3.** AdvantEdge cutting simulation for 10 μm DoC, 1 m/s cutting speed with C3770 brass. Peak tool temperature is 34.4°C.
During development of the experimental setup, a thermocouple was secured to the top of the diamond tool and used to monitor surface temperature (Appendix C. Thermocouple Measurement). The diamond was located approximately 2 mm from the cutting edge and secured with aluminum tape. This was done to provide a comparison for the FE results. Figure 9-4 shows the comparison between the peak temperature recorded with the thermocouple and the peak temperature predicted by AdvantEdge. The peak temperature from AdvantEdge is at the cutting edge. Although the thermocouple was not placed directly at the cutting edge, the temperature measured by the thermocouple still exceeded the FE predictions.

**Figure 9-4.** Experimental and simulation temperature comparison for (a) 5 μm and (b) 10 μm depth of cut for brass.
The BCs in AdvantEdge’s 2D turning simulations need to be modified for diamond tools due to the high thermal conductivity. This is demonstrated by a simplified 1D steady-state conduction example in Figure 9-5. Figure 9-5 shows two cases where a constant heat flux of 5 W/mm\(^2\) put on the left side of a 1 mm sample with 20°C isothermal boundary, \(T_L\), on the right side. Case 1 is only diamond and Case 2 is a series composite wall of diamond and a tungsten alloy (tool shank material). The temperatures \(T_H\) and \(T_1\) can be solved using Fourier’s law:

\[
T_H = q^* \sum \left( \frac{L_i}{k_i} \right), \tag{9.8}
\]

where \(L\) is the length and \(k\) is the thermal conductivity of the specific material [36]. The composite wall has two terms for the summation, the tungsten alloy and diamond. The lower thermal conductivity of the tungsten alloy greater increases the summation term and therefore the hot temperature, \(T_H\). Case 1 in Figure 9-5 is an example of what happens in the AdvantEdge simulations when ambient isothermal BCs are used. The high thermal conductivity of the diamond creates a small \(\Delta T\). The temperature remains low because the overall thermal resistance of the system is low. In reality, diamond tools are secured to non-diamond tool
shanks, typically carbide or a specialty alloy. The tool shank thermal conductivity will always be at least an order of magnitude less than the diamond. Case 2 requires a larger ΔT to move the heat through the tool shank.

Figure 9-5 also demonstrates the advantage of using a surface temperature measurement technique with diamond tools. As a result of its high thermal conductivity, the diamond has a more uniform temperature throughout its length than the tungsten carbide. The method in Section 7.5 should be the preferred method to model diamond tool temperatures (increased isothermal BCs from projected temperatures near cutting edge). This method requires experimental measurements to project the temperatures near the cutting edge. However, the standard isothermal BCs will cause low temperature predictions for diamond tools.

9.3 MICRO-MACHINING MODE

For machining feeds less than 1 μm, the AdvantEdge software has a micro-machining mode (micro-mode). This mode is necessary to model the sharp cutting edge radius of a new diamond tool (< 50 nm). For accurate results, the AdvantEdge manual suggests setting the minimum element size (workpiece material) smaller than the cutting edge radius or feed, whichever is smaller. For the starting cutting edge radius of 50 nm, this requires that the minimum element size is set to under 50 nm. For standard mode, the minimum element size is 1 μm (over 2x larger). For micro-machining, it is suggested that the tool and workpiece be scaled proportionally to the simulation feed and speed. The manual also suggests that the meshing be changed proportionally with the feed and cutting radius [44]. The micro-machining mode increases the computation time significantly (approximately 15x), but is necessary to model the material flow around a sharp diamond tool. Figure 9-6 shows the size difference for micro-machining and standard mode.
9.4 Previous Tool Wear Modeling Using Finite Element

At this time, the majority of research concerning tool wear uses analytical and experimental approaches to investigate the wear mechanisms. Although these approaches can provide excellent insight to the parameters related to the tool wear, many have inherent limitations, such as single geometries or wear mechanisms. The material properties of workpiece are often held constant. Factors affecting the plastic flow curve such as strain rate hardening and thermal softening are often neglected. This makes determining the stress distribution around the tool edge difficult. Most importantly for analytical models, the analysis and predictions are made for new tool geometries. The effect of tool wear on temperature, pressure and material flow are not considered.

The FE method can help to handle some of these limitations. By using discrete elements and time steps, material properties can be updated using element temperatures and strain rates. Temperature distributions, pressure distributions and material flow at the chip/tool and workpiece/tool interface can be approximated. Finally, the tool wear can be applied to discrete nodes and the geometry updated. As a result, the effects of tool wear to be analyzed with an
iterative process. Experiments can be expensive and time-consuming to perform. The development of more powerful computers has allowed FE analysis to become a practical instrument in tool wear analysis.

Recently, several researchers have used FE analysis to simulate tool wear and compare to experimental results. Xie et al. [45] simulated 2D orthogonal tool wear by integrating ABAQUS/Explicit and ABAQUS/Standard with a custom Python program. The goal was to simulate the crater and flank wear of tungsten carbide tools during the machining of AISI 1045 steel. The ABAQUS/Explicit was used to simulate the chip formation, the ABAQUS/Standard was used to analyze the temperature distribution and the Python program calculates and applies the nodal wear rate using an adhesive wear calculation. The adhesive wear law was derived by Usui et al. [46]. Attanasio et al. [47] used DEFORM-3D to simulate 3D crater wear in tungsten carbide tools using a diffusive wear law. The model showed similar results for maximum flank wear and crater depth, but underestimated crater area. Wassdahl [48] used Huang and Usui wear models to simulate 2D orthogonal wear in carbide tools with temperatures from AdvantEdge software. The built-in Usui wear model in AdvantEdge was also used to compare experimental and simulated values for flank wear. Yen et al. [49] developed a procedure to use commercial FE software DEFORM-2D and the Usui wear model to simulate the wear of carbide tools during carbon steel machining. The simulation results showed the development of crater and flank wear on the carbide tool, although the wear rate was underestimated. The results from these researchers demonstrate the value of the FE approach to tool wear.

9.5 Finite Element Wear Models Using AdvantEdge

AdvantEdge can be used to simulate tool wear during a machining process. The first step of the procedure is a cutting simulation with steady-state analysis applied\textsuperscript{20}. Then, a wear model is applied using different parameters from the tool perimeter nodes. After the wear rate is applied, multiple iterations are performed until the total wear time is reached. The software has

\textsuperscript{20} Cutting conditions near the end of simulation are used to perform steady-state heat transfer analysis from the generated heat. This is used to predict steady-state temperatures and stresses.
four options for wear models (shown in Figure 9-7): standard, custom, Usui and user defined. The standard model has been created by Third Wave systems for cubic-boron-nitride tools machining AISI 52100 and D3 steels.

![Figure 9-7. Wear model options in AdvantEdge.](image)

In Figure 9-7, the common input parameters for the AdvantEdge wear models are shown. The total wear time is the total cutting time, which can be used to set the total cutting distance (multiply by cutting speed). The wear time increment is the time step used in the movement of the nodes for wear. The maximum wear increment is the maximum distance that any node is allowed to move during a wear step. This typically gets automatically set to one-fourth of the minimum tool element size. The new $x$ and $y$ positions of the tool perimeter nodes are calculated using the following equations:

$$
x_{wear,d} = x_{start,d} + \hat{w} \Delta t(-N_{x,d})
$$

$$
y_{wear,d} = y_{start,d} + \hat{w} \Delta t(-N_{y,d})
$$

where $x_{start}$ and $y_{start}$ are the unloaded tool perimeter nodes from the first zone of the iteration, $N$ is the normal direction of the node, $\hat{w}$ is the model wear rate and $\Delta t$ is the timestep. The time step will be equal to the wear time increment; unless the maximum wear increment is
exceeded during the wear rate calculation. Then, the time step is reduced by multiplying it by the ratio of the maximum wear increment to the wear maximum calculated wear rate.

The custom wear model is a temperature-dependent model using Equation (9.10) to calculate the wear rate, \( \dot{w} \):

\[
\dot{w} = K_T \exp \left( -\frac{\alpha}{T + 273.15} \right) v,
\]

where \( \dot{w} \) is the wear rate (volume loss per unit area per unit time), \( T \) is the steady-state nodal temperature and \( v \) is cutting velocity. \( K_T \) and \( \alpha \) are material constants supplied by the user. Equation (9.10) is of the same form as the Arrhenius function, where the \( \alpha \) value would be equivalent to the activation energy, \( E_a \), divided by the universal gas constant (8.314 J/mol-K) with units of temperature (K).

\[
\alpha = \frac{E_a}{R}
\]

AdvantEdge also contains the Usui wear model, which is discussed in Section 9.5.1. The last wear model in AdvantEdge is the user defined model. This allows the user to define custom models using a FORTRAN dynamic library. The models will be dependent on the pressure, sliding velocity and temperature.

**9.5.1 Usui Wear Model**

The Usui wear model in AdvantEdge is based on the analytical predictions of the cutting tool wear from E. Usui [46]. The predictions were derived to predict crater and flank wear in tungsten carbide tools during steel machining from an adhesive wear mechanism\(^{21}\). The model combines the Archard type of equation from Shaw and Dirke [50] with temperature effects for

---

\(^{21}\) Adhesive wear is also referred to as attrition wear. The tool material is removed due to micro-welding with the workpiece and chip.
the material strength and diffusion. The method uses wear data from orthogonal cutting experiments to determine two material constants. The Usui wear equation is

$$\frac{dV}{\sigma_t dL} = C_1 \exp \left( -\frac{C_2}{T} \right)$$  \hspace{1cm} (9.12)

where $dV$ is the change in wear volume for sliding distance $dL$, $\sigma_t$ is the normal stress on the contact surface, $T$ is the temperature of the chip surface, and $C_1$ and $C_2$ are the two material constants. The wear rate in the Usui model includes the same temperature-dependency exponential term as Equation (9.10). The constant $C_2$ represents the combined effects of thermal softening and diffusion of wear asperities into the workpiece. The weld formation is a thermally-activated event, so the probability increases with temperature. The normal pressure is included outside the exponential term. The model is empirical in nature, requiring data from controlled experiments to determine the characteristic equation constants $C_1$ and $C_2$.

A limitation of Usui’s analytical model is the changing tool geometry. As the tool wears, the pressure, temperature and material flow distributions will change. In the original Usui analytical model, the stresses and temperatures are derived for a tool with no wear. The AdvantEdge FE software allows the varying tool geometry to be taken into account.

The Usui model in AdvantEdge is given by

$$\dot{w} = K_U \exp \left( -\frac{\alpha}{T + 273.15} \right) p v_s$$  \hspace{1cm} (9.13)

where $\dot{w}$ is the wear rate (volume loss per unit area per unit time), $T$ is the steady-state nodal temperature, $p$ is the pressure and $v_s$ is sliding velocity. The constant $K_U$ has units (1/Pa). The $\alpha$ value would be equivalent to the activation energy, $E_a$, divided by the universal gas constant (8.314 J/mol-K) with units of temperature (K).

### 9.5.2 Calculating Perimeter Wear Rates

The Matlab function `tw_wearestimate` was written to analyze the wear rate along the tool perimeter for the temperature and Usui wear models in AdvantEdge. The program performs
the AdvantEdge FE wear calculations from the extracted relief and rake data using Equations (9.10) and (9.13). Instructions on how to extract the rake and relief data from AdvantEdge is given in Appendix H. Extracting AdvantEdge Rake and Relief Tool Data.

The inputs to the function are the first simulation zone (where no cutting has begun), last zone (last zone in simulation or zone where values have approximately reached steady-state values), the cutting speed and time step:

\[
\text{tw\_wearestimate (filename1, filename2, vel, time)}
\]

where filename1 is the first zone data, filename2 is the last zone data, vel is the cutting speed and time is the time step. Inside the function the material constants \(a, K_U\) and \(K_T\) can be changed for the temperature and Usui model. The sliding velocity for the Usui model is not available in the AdvantEdge rake/relief data extraction for the tool perimeter. It is approximated in the Matlab function by assuming the sliding velocity along the flank face and edge radius is the cutting speed and the sliding velocity along the rake face is the chip speed. The start of the rake face is approximated by using the chip speed for tool \(X\)-values (see Figure 7-36) under 0.01 \(\mu\)m. After calculating all the wear rates along the perimeter, the \text{tw\_wearestimate} function applies the rates to the first zone nodes using Equation (9.9) and then plots both the first zone and the tool after the wear rate has been applied.

An example of the program is given for a 6 m/s cutting speed with 1118 steel from Section 7.5. Figure 9-8 shows the temperature contour plot and the cutting forces from AdvantEdge. The tool parameter data from the first and last zone (shown in Figure 9-8) is extracted using the rake/relief extraction tool. The \text{tw\_wearestimate} function is then used on the extracted data.
Figure 9-8. Final temperature contour plot with cutting forces and temperature plotted vs. time for 2 μm DoC at 6 m/s with 1118 steel.

Figure 9-9 shows the Usui wear rate plotted as a function of the distance variable against the perimeter temperature, pressure and sliding velocity. A shear angle of 22° was used from the AdvantEdge simulations. The activation energy determined in Section 8.1 is used to calculate α, AdvantEdge’s temperature constant.
Figure 9-9. Usui wear rate plotted with temperature, pressure and sliding velocity for 2 \( \mu \)m DoC, 6 m/s cutting speed with 1118 steel.

The program also calculates the change in tool area, \( dW \), during the time step to approximate the wear rate, \( dW/dt \). This is done by subtracting the area of the tool after the wear rate has been applied from the area of the first zone tool, shown in Figure 9-10. This is an initial
estimate since the pressure, temperatures and material flow are expected to change as the tool wears. However, this will provide an approximation for the material constants if the average wear rate is known from experimental values. The function also calculates the maximum wear increment, which is the maximum distance any node moves for the specified time step. This can be an important parameter for setting up a wear simulation in AdvantEdge because the wear increment should not exceed ¼ of the tool element size.

The wear rate from Figure 9-9 is applied to the original tool nodes and plotted in Figure 9-10. The time step, wear area, approximate wear rate and material constants are shown above the graph. In Figure 9-10, the simulation wear rate with a $K_U$ value of $1.5E-14 \text{ l/Pa}$, $0.0189 \mu\text{m}^2/\text{s}$, matched the average experimental wear rate, $0.01951 \mu\text{m}^2/\text{s}$, for the 6 m/s cutting speed. From Figure 9-9, the maximum nodal wear rate (distance/time) at the cutting edge is 12 nm/s. Along the rake face, the nodal wear rate (distance/time) is approximately 2 nm/s. From Figure 8-4 in Section 8.1, the maximum distance/time wear rate along at the cutting edge is approximately 0.9 nm/s. This maximum takes place 90 μm above the cutting edge on the rake face where the maximum crater depth was observed (Figure 7-29).
Figure 9-10. Application of the Usui wear rate for 2 μm DoC, 6 m/s cutting speed with 1118 steel ($K_U = 1.5E-14$ 1/Pa, $\alpha = 4015.2$ K).

The AdvantEdge temperature wear rate from Equation (9.10) is also calculated in the `tw_wearestimate` function. Figure 9-11 shows the AdvantEdge temperature wear rate plotted as a function of the distance variable against the temperature. The low temperature gradient along the cutting edge and rake face produces a consistent wear rate. Due to the high thermal conductivity, a temperature difference of only 8°C is predicted along the cutting edge and rake face.
The wear rate is applied to the original tool nodes and plotted in Figure 9-12. Figure 9-12 shows the wear from the AdvantEdge temperature model does not increase at the cutting edge. For a $K_T$ value of $3.1E-5$, the wear rate (area/time) is $0.0195 \, \mu m^2/s$, which matches the experimental average of $0.01951 \, \mu m^2/s$. However, the nodes along the rake face and cutting edge in contact with the workpiece/chip have similar wear rates of approximately $6 \, \text{nm/s}$. This wear rate profile does not correspond to the experimental results where a greater wear rate is observed at the cutting edge with minimal wear observed along the rake face. The experimental maximum distance/time wear rate along the rake face was approximately $0.9 \, \text{nm/s}$, which took place $90 \, \mu m$ above the cutting edge at the maximum crater depth (Figure 7-29). The maximum wear rate (distance/time) at the cutting edge in Figure 8-4 was approximately $31x$ greater than the maximum rake face wear rate for the $6 \, \text{m/s}$ cutting speed with 1215 steel.
Figure 9-12. Application of the temperature wear rate for 2 μm DoC, 6 m/s cutting speed with 1118 steel ($K_T = 8.5E-6$, $\alpha = 4015.2$ K).

9.6 MICRO-MODE SIMULATION RESULTS

The micro-machining mode in AdvantEdge is necessary to model the precision turning process with sharp diamond tools, which can have edge radii under 50 nm. Standard-mode in AdvantEdge does not allow element sizes under 1 μm. Due to the time for a simulation (approximately 2 weeks), only one cutting simulation was done.
Figure 9-13 shows the temperature contour with the cutting forces and peak tool temperature plotted against simulation time. A complete list of simulation parameters is given in Appendix N. Micro-mode AdvantEdge Simulations for Steel.

![Temperature Contour Plot](image)

**Figure 9-13.** Micro-mode temperature contour plot with cutting forces and temperature plotted vs. time for 2 μm DoC at 0.5 m/s with 1118 steel.

The peak tool temperature of the simulation is 37.5 °C which matches the projection from the RTD measurements (38.4°C). In Figure 9-14, the temperature contour scale from Figure 9-13 is adjusted to show the tool temperature distribution. For the 0.5 m/s cutting speed, the distribution has a low temperature difference of approximately 1.5 °C.
Figure 9-14. Tool temperature contour for micro-mode simulation at 0.5 m/s cutting speed.

To accurately model the material flow and stress around the 50 nm edge radius, the minimum element size was reduced to 20 nm. This reduces gaps in the contact area between the workpiece and tool. Figure 9-15 shows the mesh around the cutting edge.

Figure 9-15. Mesh for micro-mode simulation with 50 nm tool edge radius.
The effective shear angle is measured by the angle of the maximum strain rate and is shown in Figure 9-16. The micro-mode simulation predicts a shear angle of 24°.

Figure 9-16. Effective strain rate for 2 μm DoC at 0.5 m/s with 1118 steel (24°).

The perimeter wear rate was analyzed for the 0.5 m/s simulation shown in Figure 9-13. Figure 9-17 shows the Usui wear rate plotted with pressure, temperature and sliding velocity for the micro-machining AdvantEdge simulation.
Figure 9.17. Usui wear rate plotted with temperature, pressure and sliding velocity for 2 μm DoC, 0.5 m/s cutting speed from micro-mode simulation.

Figure 9-17 shows a large increase in pressure (over 2x from the pressure on the rake face) at the cutting edge from the AdvantEdge perimeter data. The large pressure at the cutting edge increases the Usui wear rate locally at the edge. The Usui nodal wear rate (distance/time) at the cutting edge is approximately 7x greater than the wear rate along the rake face. The
application of the wear rate is shown in Figure 9-18. In Figure 9-18, the wear rate (area/time), 0.00077 μm²/s, matched the experimental average of 0.00077 μm²/s for the 0.5 m/s cutting speed with a \( K_U \) value of 3.7E-13 1/Pa.

Figure 9-18. Application of the Usui wear rate for 2 μm DoC, 0.5 m/s cutting speed from micro-mode simulation (\( K_U = 3.7E-13 \) 1/Pa, \( \alpha = 4015.2 \) K).

The low temperature gradient along the cutting edge and rake face produces a constant wear rate from the AdvantEdge temperature model. Figure 9-19 shows the AdvantEdge wear rate and tool temperature along the cutting edge and rake face.
Figure 9-19. Wear rate from AdvantEdge temperature model in micro-mode (0.5 m/s).

9.7 WORN TOOL SIMULATION

A worn tool profile from Section 7.4 for 6 m/s and 120 m cutting distance (Figure 7-20) was imported into AdvantEdge. This was done to observe the wear rate with a worn tool. The AdvantEdge simulation parameters are identical to the parameters in Section 7.5 with the exception of a worn tool profile. Figure 9-20 shows the temperature contour for the simulation. The tool temperature distribution and peak temperature location is shown in Figure 9-21.
Figure 9-20. AdvantEdge temperature contour for worn tool (6 m/s after 120 m), 2 μm DoC at 6 m/s cutting speed.

Figure 9-21. AdvantEdge tool temperature distribution for worn tool (6 m/s after 120 m), 2 μm DoC at 6 m/s cutting speed.

Figure 9-22 shows the Usui wear rate plotted with pressure, temperature and sliding velocity for the worn tool.
Figure 9-22. Usui wear rate plotted with temperature, pressure and sliding velocity for 2 μm DoC, 6 m/s cutting speed with a worn tool profile.

Figure 9-23 shows the application of the Usui wear rate from Figure 9-22. The wear rate is the greatest along the wear land on the flank face due to the sliding velocity and pressure.
Figure 9-23. Application of the Usui wear rate for 2 μm DoC, 6 m/s with worn tool profile

\( K_U = 1.1E-14 \text{ 1/Pa}, \alpha = 4015.2 \text{ K} \).

Figure 9-24. Temperature model wear rate plotted with temperature, 2 μm DoC, 6 m/s cutting speed with worn tool profile.
The temperature model wear rate and tool temperature are plotted in Figure 9-24. Again, the low temperature gradient along the cutting edge and rake face produces a constant wear rate from the temperature model.

9.8 Accelerated Diffusion from Nanocrystalline Grain Boundaries

Figure 9-25. AdvantEdge strain rate for 2 μm DoC, 1118 steel at (a) 0.5 m/s in micro-mode, (b) 6 m/s in standard mode and (c) 6 m/s worn tool in standard mode.
Subramanian et al. [51] described the engineering of inclusions in steel materials to reduce chemical wear in tungsten tools. They added glassy oxide inclusions to 1215 steel to provide \textit{in situ} lubrication at the chip-tool interface. The lubrication reduced the occurrence of seizure\textsuperscript{22} at the chip-tool interface. They contributed the accelerated chemical wear to the high diffusivity of nanocrystalline grain boundaries, which are generated at areas of high strain rate or shear localization (e.g. seizure in the secondary shear zone). Figure 9-25 shows the strain rate contour for three AdvantEdge simulations: 0.5 m/s cutting speed in micro-mode, 6 m/s in standard mode and 6 m/s with a worn profile. The maximum strain rate location in each contour plot in Figure 9-25 coincides with the location of the accelerated tool wear at the cutting edge. Further studies would be needed to verify the formation of the grain boundaries and their effect on the diffusivity of the carbon atoms from the diamond tool.

\textbf{9.9 DISCUSSION OF ADVANTEdge WEAR MODELS}

There are two major benefits of using FE software to model machining processes. One is the ability to vary the material properties during the deformation process, e.g. the yield stress of a material will depend on the temperature, plastic strain and strain rate. The AdvantEdge software updates the material properties based on the strain, strain rate and temperature values from the previous time step. The second is the ability to update tool geometry. The pressure, temperatures and material flow will change as the tool wears, which analytical models cannot take into account.

Ambient isothermal BCs can cause low temperature results when using a diamond tool in AdvantEdge. The high thermal conductivity of the diamond creates a low resistance for the heat flow. In a manufacturing setting, the tool will be attached to a tool shank that has a much lower conductivity in comparison. The tool shank will have an insulating effect on the diamond. This can be simulated by using a custom tool in AdvantEdge with modified

\textsuperscript{22} Concept discussed in [51] as the tribological phenomenon that occurs when the normal pressure exceeds the flow stress of the asperities, forcing the asperities to make atomic contact. Trent [52] first introduced the concept of seizure.
temperatures at the BCs. These BC temperatures can be predicted from the projection of surface temperature measurements. Another solution would be the addition of convective BCs in AdvantEdge.

There is also an inherent drawback from using AdvantEdge for modeling diamond turning. The initial edge radius of a precision diamond tool requires the use of micro-mode for modeling the conditions around the edge radius. Decreasing the element size causes quadratic increases in the computation time [44]. Therefore, a single-pass\textsuperscript{23} cutting simulation can take more than 175 hours to finish. Combined with a wear model that performs multiple iterations, a wear simulation could take an enormous amount of time to complete. Although wear models are not feasible in micro-mode, data extracted at the end of single micro-mode cutting simulations can provide insight on parameters at the cutting edge. Tool perimeter data can be extracted and used to make predictions of the factors contributing the tool wear. This type of analysis does not have to be limited to the two models given in the AdvantEdge software. Custom wear equations can be made in AdvantEdge using the FORTRAN dynamic library.

\textbf{9.9.1 ADVANTEDGE TEMPERATURE AND USUI WEAR MODEL}

Both the temperature and Usui wear model in AdvantEdge contain the exponential temperature term from the Arrhenius function. The experimentally determined activation energy was input to the models to calculate wear rates. The wear rates from the AdvantEdge temperature model do not produce the localized wear at the cutting edge observed in the experiments. The high thermal conductivity of the diamond causes a low temperature gradient that produces a more uniform wear rate along the cutting edge and rake face.

The Usui model was developed for an adhesive wear mechanism and includes a pressure term in the wear rate calculation with the exponential temperature dependent term. The increase in pressure around the cutting edge causes the wear rate to increase locally at the edge, as seen with the experimental tool profiles. However, the model is not for a specific thermo-chemical

\textsuperscript{23} Simulation without tool wear model.
wear mechanism, such as diffusion or graphitization. It was developed to model flank and crater wear of carbide tools, combining an Archard-type of equation with temperature effects for the material strength and diffusion. Other parameters, with temperature, should be investigated further to see the effect on the tool wear.
CONCLUSIONS

Rapid tool wear limits the use of diamond tools in the ultra-precision machining of ferrous materials. This research provided a quantitative study of the parameters contributing to the diamond tool wear, including force, temperature and material flow. An apparatus was designed and constructed to allow the simultaneous measurement of tool forces and diamond surface temperature while capturing high-speed images of the cutting process. The tool forces were measured by mounting the tool to a three-axis dynamometer. A thin-film RTD measured the surface temperature on the rake face. The RTD temperature measurements were extrapolated to estimate the peak temperature at the tool edge. An imaging system was developed to capture high-speed images of the cutting process. The high-speed images allowed the analysis of the material flow (i.e. chip and workpiece speed) at the cutting edge. The finite element software AdvantEdge was used to model the cutting process and provide a comparison for tool forces, temperatures and material flow.

The cutting and thrust forces for a 2 μm depth of cut with 1215 steel ranged from approximately 6.8-8.8 N and 3.2-5.7 N, respectively. For 1215 steel, both the cutting and thrust force increased with cutting speed and tool wear/cutting distance. AdvantEdge simulations were performed to compare tool forces. The 1215 steel used in experiments was not in the AdvantEdge library, so 1118 steel was chosen due to similarities in material properties. The 1118 steel has nearly identical thermal properties (thermal conductivity, specific heat and density) and the hardness is 12% less than the 1215 steel. The cutting and thrust forces increased with cutting speed in AdvantEdge as observed with the experimental forces. Simulation cutting forces were within 5% of the experimental measurements for 1215 steel. Thrust forces were underestimated from 0.4 to 1.2 N using a simulation friction factor of 0.4. The difference between the simulation and experimental hardness may prevent the balance of cutting and thrust forces.

Peak temperature predictions ranged from 40 to 160°C for cutting speeds of 0.5 to 6 m/s with 1215 steel at 2 μm depth of cut. The high thermal conductivity of diamond and ambient (20°C) isothermal boundary conditions resulted in low tool temperatures in AdvantEdge. The tool
shank has a thermal conductivity that is an order of magnitude less than diamond. This insulates the diamond and increases the tool temperature during machining. The boundary condition temperatures in AdvantEdge were increased based on measurement predictions. This produced comparable results for the peak temperatures between the simulations and measurement projections.

Using the chip and cutting speeds from the high-speed images, a shear angle of 21.4° and 21.8° was calculated for 1215 steel at cutting speeds of 0.5 and 1 m/s, respectively. The shear angle from AdvantEdge was measured using the plastic strain rate contour plot. For the 1 m/s cutting speed with 1118 steel, the shear angle was 22.4° with the friction factor value of 0.4. From the high-speed video, the experimental chip speed for the 1 m/s cutting speed was 0.39 m/s for 1215 steel. The chip speed in AdvantEdge was 0.41 m/s for the 1118 steel. The shear angle and chip speed from AdvantEdge matched the experimental values within 6%.

The cutting edge of the diamond tool was measured using the EBID technique in the SEM at multiple wear intervals. This quantified the progression of tool wear for each cutting speed with 1215 steel by measuring the 2D wear areas and cutting edge profiles at multiple cutting distances. The wear land developed at angle of approximately 20° (19-24°) from the cutting direction. This angle is similar in magnitude to the calculated shear angle of 22° from the high-speed video analysis. Further studies are needed to verify the connection between the two angles. The wear profiles from the EBID measurements showed localized wear at the cutting edge. Crater wear was also measured on the tool rake face using a Zygo NewView SWLI. Crater depths were approximately 18-37 nm (after 120 m machining) with the maximum crater depth taking place around 90 µm from the cutting edge. The crater wear started 2-3 µm from the cutting edge and extended approximately 200 µm from the cutting edge. The cutting chips contact the tool for this distance along the rake face, which is verified by the high-speed videos.

For the 6 m/s cutting speed with 1215 steel, the maximum crater depth was approximately 18 nm after 120 m of machining. The cutting edge recessed a maximum distance of 560 nm (taken as the distance from the sharp edge to the normal of the cutting edge surface) after 120 m of machining. The maximum recession at the cutting edge is over 30x greater than the maximum
crater depth on the rake face for the 6 m/s cutting speed. The 2D wear area at the cutting edge/flank face was 0.40 μm² after machining 120 m from the EBID technique. The crater area was approximated as one half the product of the crater depth (18 nm) and the crater length (180 μm). This gave an area of 1.6 μm², which is 4x greater than the flank wear area from the EBID measurement. However, the large recession at the cutting edge has a greater effect on the cutting process (surface finish and tool forces) than the crater wear.

The cutting speeds in this research were chosen to test the Arrhenius-type, thermo-chemical wear model. In the model, a minimum wear rate occurs at an intermediate cutting speed, which is the balancing point between increased time for reaction (low speed) and increased tool temperatures (high speed). An experimental minimum in the wear rate was observed at a cutting speed of 1 m/s for 1215 steel. An activation energy of 33.4 kJ/mol was calculated using the peak temperature predictions and average wear rates. This activation energy is lower than results from uncatalyzed static diffusion or graphitization tests. The fresh surfaces generated during machining must provide lower reaction pathways for the diamond carbon atoms to break from the diamond lattice and enter the workpiece material.

Wear experiments were performed with 6061 aluminum to compare the tool wear, surface temperatures and forces. The 6061 aluminum contains a similar distribution of hard particles as the 1215 steel, so the contribution from abrasive wear should be comparable. EBID measurements show the aluminum profile has a wear land that is approximately parallel to the cutting distance with an increased edge radius. Using the 2D wear areas from the EBID measurements, the average wear rate (area/cutting distance) for 1215 steel was over 11x greater than 6061 aluminum for the 2 μm DoC and 1 m/s cutting speed. This ratio was greater for other cutting speeds with 1215 steel, since the minimum wear rate was observed at 1 m/s for 1215 steel. Using the Archard coefficient determined from the 6061 aluminum at a 2 μm DoC (0.0116 μm³N⁻¹m⁻¹), only 1.65% of the tool wear is attributed to abrasive wear with 1215 steel at the 1 m/s optimal cutting speed.

The RTD temperature rise for 1215 steel was approximately 2x greater than 6061 aluminum for cutting speeds 2 m/s and 4 m/s and 1.2x greater at 1 m/s for a 2 μm DoC. At 1 m/s cutting
speed and 2 μm DoC, specific cutting energy (energy consumed per volume removal) was 56% greater for 1215 steel than 6061 aluminum. The ratio of specific cutting energy is affected by cutting speed, since the cutting forces for 1215 steel increased with increasing speed and decreased for 6061 aluminum.

The temperature and Usui wear models in AdvantEdge were analyzed to observe the wear rates. The temperature model produced little variation in the wear rate due to the low temperature gradient in the diamond. For this wear model in AdvantEdge, similar magnitudes of wear would occur on the cutting edge and rake face. The AdvantEdge Usui wear model included normal pressure, sliding velocity and an exponential temperature term in the wear rate calculation. The predicted pressure spike at the cutting edge resulted in localized wear rate at the cutting edge.

**10.1 Future Work**

Experiments with another steel, (preferably one contained in the AdvantEdge material library, e.g. AISI 1118 or AISI 4140), would be beneficial to provide a comparison with the worn tool profiles and temperatures from the 1215 steel experiments.

A complete set of micro-mode simulations (without applying a wear model) in AdvantEdge using the cutting parameters (speeds and DoC) in this research would help to provide more information and comparisons about the conditions at the diamond cutting edge. Time limited the results obtained from the micro-mode simulations. The process of raising the isothermal boundary conditions based on temperature measurements should be performed when simulating diamond turning in AdvantEdge.

The temperature predictions from measurements and simulations from should be compared against flash temperatures using tribology analysis. These predictions could represent a nominal surface temperature. Flash temperatures from asperity contacts could result in greater temperature rises.
Molecular dynamics (MD) simulations may be helpful to differentiate between the thermo-chemical wear mechanisms (i.e. if graphitization has occurred at the cutting edge). Data from this research such as peak temperature predictions and cutting forces could be useful data for MD simulations. Raman spectroscopy could be used to see if graphite has formed at the diamond cutting edge.

Workpiece surface modifications should be investigated. Although steel is desired for its high wear-resistance, non-ferrous coatings or materials should be examined to compare the performance (wear-resistance, strength, etc.) with respect to steel. Emphasis also needs to be placed on the surface finish of the workpiece.
REFERENCES


APPENDIX A. SEM IMAGING

APPENDIX A.1 SAMPLE PREPARATION FOR EBID MEASUREMENT

The following steps should be taken to prepare the sample for the EBID measurement.

1. After machining is completed, blow off debris and oil with compressed air.
2. Remove RTD or temperature measuring device.
3. Rinse with acetone and wipe with Kim Wipe.
4. Used tool-cleaning holder (Figure 0-1) to suspend the tool cutting edge in Keller’s solution for approximately 15 minutes. This will remove any material pickup that has occurred during machining.

5. Rinse with de-ionized (DI) water and wipe with acetone soaked Kim Wipe.
6. Using tool-cleaning holder, suspend the tool edge in acetone and use ultrasonic cleaner to sonicate the tool for 5 minutes.
7. Remove the tool and place on the SEM holder.
8. Using an acetone-soaked optical wipe, gently brush the cutting edge as a final cleaning step. This should help to remove any residue left after the ultrasonic bath.

Figure 0-1. Tool-cleaning holder for diamond preparation procedure.
9. Since diamond is an electrical insulator, it will tend to charge during SEM imaging. To mitigate this effect, place a strip of carbon tape close to the diamond cutting edge that contacts the tool shank (Figure 0-2).

![Image of diamond tool with carbon tape.]

**Figure 0-2.** SEM image of diamond tool with carbon tape near cutting edge.

**APPENDIX B. SECURING RTD TO DIAMOND TOOL**

To secure the RTD to the diamond the following steps were taken:

1) Cut away 2 pins from a standard 2.54 mm pitch PCB connector

2) Wrap the leads around the 2-pin PCB connector and solder.

3) Using superglue, secure the 2-pin PCB connector on the carbide shank at the back of the diamond (shown in Figure 3-17).
4) After the connector is secured, the RTD can easily be situated on the top surface of the diamond. Use a thermally conductive epoxy, such as TC-2810 from 3M, to secure the diamond on the diamond surface (shown in Figure 0-3).

![Figure 0-3. Thin-film RTD secured to top of diamond.](image)

Note: The TC-2810 epoxy will cure completely after approximately 8 hours. After it cures completely, it becomes more difficult to remove. Ideally, epoxy the RTD to the diamond around 4 hours before cutting to let the epoxy begin to cure. After the cutting experiments are completed remove, the RTD should be removed and the surface prepared for SEM imaging. Use acetone to soften the epoxy if it has cured.

**APPENDIX C. THERMOCOUPLE MEASUREMENT**

To measure the temperature using a thermocouple, the voltage data must be acquired and converted to a corresponding temperature. The (Seebeck) voltage from the thermocouple cannot be measured directly from a voltmeter and converted. The voltmeter leads create a new thermoelectric circuit that can impact the measurement. The temperature of the reference junction must be established. Traditionally, the reference junction is an ice bath, making the reference temperature 0°C. If the reference junction temperature is measured, the voltage corresponding to this reference temperature, $V_{ref}$ can be added to the measured voltage $V_{meas}$.
The temperature of the hot junction, \( T_H \), is determined from the sum of the two voltages. This is referred to as cold-junction compensation.

\[
V_1 = V_{\text{ref}} + V_{\text{meas}} \\
T_H = f(V_1)
\]  

(11.1)

The cRIO data acquisition system has two options: use thermocouple modules that automatically applies cold-junction compensation or measure the voltage (9205 module) and convert using a polynomial approximation of the curve in Figure 1-6. LabView also has an existing block for the voltage-to-temperature conversion. Table 0-1 shows the three thermocouple modules for the cRIO from National Instruments.

**Table 0-1. cRIO thermocouple modules.**

<table>
<thead>
<tr>
<th>Module</th>
<th>Channels</th>
<th>Sample Rate</th>
<th>Minimum time between samples</th>
<th>Resolution</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>9213</td>
<td>16</td>
<td>1200 S/s</td>
<td>0.013</td>
<td>24-bit</td>
<td>$1,065.00</td>
</tr>
<tr>
<td>9219</td>
<td>4</td>
<td>75 S/s/Ch</td>
<td>0.020</td>
<td>24-bit</td>
<td>$1,065.00</td>
</tr>
<tr>
<td>9211</td>
<td>4</td>
<td>50 S/s/Ch</td>
<td>0.286</td>
<td>24-bit</td>
<td>$351.00</td>
</tr>
</tbody>
</table>

Another option is to construct a thermocouple amplifier circuit. Figure 0-4 shows a circuit designed for K-type thermocouples that has a 5 mV/°C output signal using the AD8495 chip from Analog Devices. Data about the precision thermocouples used is shown in Table 0-2.
Figure 0-4. Thermocouple amplifier circuit using AD8495 chip [53].

Table 0-2. Thermocouple data.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Omega Engineering Inc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part Number</td>
<td>5TC-TT-K-40-80</td>
</tr>
<tr>
<td>Type</td>
<td>K</td>
</tr>
<tr>
<td>Insulation</td>
<td>PFA</td>
</tr>
<tr>
<td>AWG Gauge</td>
<td>40</td>
</tr>
<tr>
<td>Diameter (mm)</td>
<td>0.08</td>
</tr>
<tr>
<td>Lead Length (m)</td>
<td>2</td>
</tr>
</tbody>
</table>
APPENDIX D. MATLAB CODE

Table 0-3. Summary of MATLAB codes.

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>digitize11</td>
<td>-Function inputs stretched SEM image file and allows user to select pixels along the EBID line in a GUI. Need at least 8 points on both the rake and flank face line. Outputs the 2D wear area and angle between the rake and flank face.</td>
</tr>
<tr>
<td>EBIDautorot</td>
<td>-Function takes XY points from digitize11, interpolates two lines through the rake and flank, and then rotates the points for a 0° rake. It places the origin at the intersection of the rake and flank lines.</td>
</tr>
<tr>
<td>toolprofile</td>
<td>-Function plots the XY points from EBIDautorot with equal axes and x/y scale in μm.</td>
</tr>
<tr>
<td>tw_wearestimate</td>
<td>-Function calculates the wear rate along the tool perimeter for the temperature and Usui wear models in AdvantEdge. Inputs the first zone, last zone, cutting speed and time step.</td>
</tr>
<tr>
<td>twperimetergrab</td>
<td>-Converts rake/relief .tec files from AdvantEdge into .mat files</td>
</tr>
<tr>
<td>tw_toolface</td>
<td>-Function plots different parameters from AdvantEdge as a function of perimeter distance.</td>
</tr>
<tr>
<td>Wear_Distance</td>
<td>-Calculates the machining set points for orthogonal machining experiments for constant feedrate and constant spindle RPM. The function inputs the starting diameter, desired average cutting speed, total cutting distance and DoC. The function outputs the required RPM, feedrate and radius removal for the cutting experiments. Also, it calculates the total cutting time, start/end velocity and end workpiece diameter.</td>
</tr>
</tbody>
</table>
APPENDIX E. PYROMETER DESIGN

In spectral radiation thermometry (SRT) applications, IR radiation is transferred to the spectrometer or detector via an optical fiber guide. These fiber optic radiation thermometers are useful when a clear field of view to the object is difficult to achieve. Ueda [15] and Lane [54] both had designs for measuring the temperature at the cutting interface using custom diamond tools and fiber-optic guides. For IR radiation to be transmitted into the optic fiber, the incident light must be within the numerical aperture for the fiber optic. This depends on the index of refraction of both the fiber and the medium of the incident light. Natural diamond has a large index of refraction at 2.4 ($n_{\text{air}} = 1.0$). When light is traveling from a medium with a higher index of refraction to a medium with a lower index, there is a phenomenon known as total internal reflection where no light passes through the first medium. The process occurs when the angle of incident angle is greater than the critical angle. Figure 0-5 shows the process as light undergoes total internal reflection. For the diamond-to-air boundary, the critical angle is 24.6°.

![Total internal reflection for diamond-to-air](image)

**Figure 0-5.** Total internal reflection for diamond-to-air.

With this property, the diamond tool used in the DT process could be used as an optical guide in an infrared radiation system that is used to measure the peak tool temperature. Jonas [55] demonstrated the benefits of using a diamond rod to couple a blackbody source to an optical fiber. Substantial reflective losses occur when light from air ($n_{\text{air}} = 1$) is incident onto a
chalcogenide optic fiber \( (n_{\text{chal}} = 1.5-3) \). The close match of the indices of refraction reduces the reflective losses [55]. By optically designing the shape of the diamond tool, the throughput of an optic radiation thermometer could potentially be maximized.

A continuous parabolic shape for the diamond tool would theoretically maximize the transfer of infrared radiation. If the cutting edge was placed at the focal point, the emitted infrared radiation would be totally internally reflected to the back of the diamond. For manufacturing purposes, the parabolic edge was segmented with 4 flat faces as shown in Figure 0-6. The final acceptance ratio was 56% from the MATLAB program.

![Figure 0-6. Diamond tool IR-Fiber Raytrace for the manufactured segmented parabola.](image)
An infrared fiber optic cable would be connected to the back of the diamond to capture the infrared radiation. The final manufactured diamond tool is shown in Figure 0-10. Table 0-4 gives the list of the equipment chosen in the design with the corresponding process diagram in Figure 0-7.

Table 0-4. Equipment for the diamond tool pyrometer design.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Manufacturer</th>
<th>Product Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber Optic Cable</td>
<td>JT Ingram</td>
<td>CIR-Fiber, 500 μm core</td>
</tr>
<tr>
<td>Phase-matching fluid</td>
<td>Cargille</td>
<td>Series M: 1815X</td>
</tr>
<tr>
<td>Refocusing Coupler</td>
<td>JT Ingram</td>
<td>ZnSe lens, SMA-connector</td>
</tr>
<tr>
<td>Infrared Detector</td>
<td>Infrared Associates, Inc.</td>
<td>IS-1.0</td>
</tr>
<tr>
<td>Dewar</td>
<td>Infrared Associates, Inc.</td>
<td>MSL-12</td>
</tr>
<tr>
<td>Preamp</td>
<td>Infrared Associates, Inc.</td>
<td>INSB-1000</td>
</tr>
<tr>
<td>Optical Chopper</td>
<td>Thorlabs</td>
<td>MC2000</td>
</tr>
<tr>
<td>Lock-in Amplifier</td>
<td>Signal Recovery</td>
<td>7270</td>
</tr>
<tr>
<td>Diamond Tool</td>
<td>Chardon Tool Inc.</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Figure 0-7. Process diagram for the diamond tool pyrometer system.
Figure 0-7 shows the process of transferring the infrared radiation to the infrared detection system. The emissivity of the diamond material used in the diamond tool was tested using a MIR 8000 Fourier Transform InfraRed (FT-IR) spectrometer. The results showed a peak emissivity of approximately 0.3 occurring at a wavelength of 5 μm (wavenumber of 2000 cm$^{-1}$). The components in the pyrometer system were designed around the maximum transmission for this wavelength (Chalcogenide glass fiber, ZnSe refocusing lens, and InSb detector). Figure 0-8 shows a CAD diagram of the infrared detection system.

![Figure 0-8. Layout for the infrared detection system.](image)

The coupler focuses the output of the infrared detector unto the InSb detector and is shown in Figure 0-9. It has an SMA connector for the fiber optic cable. The output of the fiber optic cable gets focused with a 15 mm ZnSe lens with a focal length of 10 mm. The coupler clamps onto the Dewar using the clamp screw. The separation between the detector and the lens can be adjusted by turning the focal screw. There are also adjustment screws for angular translation of the objective. Both the angular adjustment and focal distance need to be positioned to maximize the detector output using a constant input signal. Once the detector output is
maximized, the fiber output should be focused on the detector. The refocusing coupler also has a slot for filters that can be used for a chopper wheel.

Figure 0-9. Refocusing coupler from JT Ingram Technologies.

An optical chopper combined with a lock-in amplifier can be used to increase the signal-to-noise ratio (SNR) of the infrared detection system. The lock-in amplifier is a form of phase sensitive detection. It has a switch operated by the chopper output waveform. When the chopper level is high (open slot), the switch is closed completing the circuit. When the chopper level is low (closed slot), the switch is open and no connection is made. The output from the switch goes to a low pass (RC) filter. This generates a DC voltage signal that can be calibrated to the diamond temperature. Noise from the signal gets smoothed or averaged by the RC filter. The combination of the signal modulation from the chopper and phase-sensitive detection from the lock-in can improve the overall SNR of the system by minimizing the detector circuit’s noise bandwidth.
APPENDIX F. INFRARED SPECTROSCOPY OF A DIAMOND SAMPLE

The emissive, absorptive and transmissive properties of materials can be evaluated using a Fourier Transform InfraRed (FT-IR) spectrometer. The spectrometer used is the MIR 8000 FT-IR manufactured by Oriel shown in Figure 0-11.

Figure 0-10. Custom diamond tool for the pyrometer system.
APPENDIX F.1 INTRODUCTION TO FT-IR SPECTROSCOPY

IR radiation refers to the electromagnetic radiation with wavenumbers 13,000 to 10 cm\(^{-1}\), or wavelengths from 0.78 to 1000 µm. It is bounded by the red light of the visible spectrum at high frequencies and the microwaves at the low frequencies. FT-IR spectrometers collect broadband spectra in the near to far infrared (0.7-28 µm). These spectrometers can quickly generate spectra and work with weak input signals when compared to preceding dispersive spectrometers.

All the atoms in molecules are in continuous vibration with respect to another at any temperature above 0 K. The chemical bonds in materials absorb energy from infrared radiation at specific frequencies or wavelengths that coincide with the molecular vibration. FT-IR spectrometers can measure the frequencies of these molecular vibrations, enabling the chemical structure of compounds to be analyzed. This is done by positioning a sample in the path of an IR beam and measuring the absorption across the IR frequency range. The plot of a compound’s IR transmission versus wavelength can be used to identify the materials present.
in the compound. The transmittance, reflectivity, and absorptivity for a material contains the following relationship

\[ \tau + \rho + \alpha = 1 \]  

(11.2)

where \( \tau \) is the transmittance, \( \rho \) is the reflectivity, and \( \alpha \) is the absorptivity [56]. This comes from energy conservation, where all radiation incident upon a surface must be either reflected, transmitted or absorbed by the material.

Exitance, or power per unit area, radiated by a surface can also be measured using FT-IR spectroscopy. All matter above 0 K emits thermal radiation or photons. Radiation emitted from a substance will depend on the temperature, surface condition, and emissivity of the material. Emissivity or emittance, \( \varepsilon \), is the ratio of the radiation emitted by a surface to the radiation emitted by a blackbody at the same temperature. Emissivity is proportional to the absorptivity. Using spectra intensity measurements from the infrared emission, the FT-IR spectrometer can be calibrated to measure the temperature of materials and evaluate the emissivity as a function of wavelength [36].

**APPENDIX F.2 EXPERIMENTAL SETUP**

The emissions of a diamond specimen were measured using the FT-IR spectrometer. The experimental setup is shown in Figure 0-12. A hot plate was heated to various temperatures between 60 to 125°C. A diamond-turned aluminum plate was placed on top of the hot plate. Aluminum was chosen because of its low emissivity (\( \varepsilon = 0.04 \)) and high thermal conductivity (205 W/m-K), so the background noise would be reduced. Black paint (\( \varepsilon = 0.97 \)) was also placed on the aluminum to approximate the emission from a blackbody. A thermocouple was mounted to the aluminum plate using aluminum tape. A close-up of the aluminum plate is shown in Figure 0-13. The hot plate was set to various temperatures. The thermometer from the mounted thermocouple was monitored until the aluminum surface temperature flattened. A lab jack was used to move the diamond into focus of the parabolic mirror. This was approximated by mounting a visible light collimator at the interferometer inlet and viewing the focal point.
Figure 0-12. Experimental setup for spectrum measurements.

Figure 0-13. Close-up of aluminum plate and diamond.
At each temperature set point, a measurement was taken of the diamond, a nearly ideal blackbody radiator, and the background. The diamond was a rectangular prism with 3 mm length, 2 mm width and 1.5 mm height. The temperature fluctuated slightly during the three measurements at each temperature set point, so the initial thermocouple readout was recorded for each measurement. The temperature measurements are shown in Table 0-5.

Table 0-5. Temperature measurements during emissivity experiment.

<table>
<thead>
<tr>
<th>Run</th>
<th>Hot Plate Setpoint (°C)</th>
<th>Diamond Temperature (°C)</th>
<th>Blackbody Temperature (°C)</th>
<th>Background Temperature (°C)</th>
<th>Average (°C)</th>
<th>Average (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>70</td>
<td>63.3</td>
<td>63.3</td>
<td>63.3</td>
<td>63.3</td>
<td>336.5</td>
</tr>
<tr>
<td>2</td>
<td>75</td>
<td>74.9</td>
<td>72.0</td>
<td>76.2</td>
<td>74.4</td>
<td>347.5</td>
</tr>
<tr>
<td>3</td>
<td>80</td>
<td>72.7</td>
<td>76.9</td>
<td>72.5</td>
<td>74.0</td>
<td>347.2</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>90.4</td>
<td>89.8</td>
<td>90.0</td>
<td>90.1</td>
<td>363.2</td>
</tr>
<tr>
<td>5</td>
<td>110</td>
<td>98.8</td>
<td>98.1</td>
<td>98.6</td>
<td>98.5</td>
<td>371.7</td>
</tr>
<tr>
<td>6</td>
<td>120</td>
<td>107.3</td>
<td>107.0</td>
<td>107.5</td>
<td>107.3</td>
<td>380.4</td>
</tr>
<tr>
<td>7</td>
<td>130</td>
<td>116.8</td>
<td>116.7</td>
<td>116.7</td>
<td>116.7</td>
<td>389.9</td>
</tr>
<tr>
<td>8</td>
<td>140</td>
<td>124.2</td>
<td>124.6</td>
<td>124.6</td>
<td>124.5</td>
<td>397.6</td>
</tr>
</tbody>
</table>
Figure 0-14. Non-calibrated response from single crystal diamond.

APPENDIX F.3 CALIBRATING THE SPECTRAL DATA

The measured spectra must be calibrated to remove the offset of the interferometer’s optics and to remove minor nonlinearities in the detector’s responsivity. The blackbody curve measured from the painted surface was used to calibrate the spectrometer and find the spectrometer offset.

The total emissive power of a blackbody, $E_b$, is given by the integral

$$E_b = \int_0^\infty \frac{c_1}{\lambda^5} \exp\left[\frac{c_2}{\lambda T} - 1\right] d\lambda,$$

where $c_1$ and $c_2$ are constants, $T$ is the temperature in Kelvin, and $\lambda$ is the wavelength. This can be considered as the band-integrated radiance or exitance across all wavelengths for a
blackbody. Performing the integration gives the Stefan-Boltzmann power relationship for a blackbody temperature

\[ E_b = \sigma T^4, \]  

(11.4)

where \( \sigma \) is the Stefan-Boltzmann constant \((5.670 \times 10^{-8} \text{W} / \text{m}^2 \cdot \text{K}^4)\), and \( T \) is the temperature in Kelvin. For a real-surface, the emissivity, \( \varepsilon \), will limit the power emitted from its surface. The exitance can also be considered over a certain wavelength interval or emission band. The radiant exitance, or the power emitted from a surface, on the wavelength band \( \lambda_1 \) to \( \lambda_2 \) is given by

\[ M_\varepsilon = \int_{\lambda_1}^{\lambda_2} \frac{\varepsilon(\lambda)c_1}{\lambda^5 \exp[c_2 / \lambda T - 1]} d\lambda, \]  

(11.5)

where \( \varepsilon \) is the emissivity, \( c_1 \) and \( c_2 \) are constants, \( T \) is the temperature in Kelvin, and \( \lambda \) is the wavelength. Inside the integrand is the spectral exitance or spectral power. Spectral exitance is the power emitted from a surface per wavelength \((\text{W} \cdot \text{m}^{-2} \cdot \mu\text{m}^{-1})\) and is given by

\[ M_{\varepsilon,\lambda} = \frac{\varepsilon(\lambda)c_1}{\lambda^5 \exp[c_2 / \lambda T - 1]}. \]  

(11.6)

Equation (11.6) is of the same form as Planck’s distribution for theoretical blackbody intensity [36]. At the measured experimental temperatures (K) the theoretical spectral exitance can be plotted for a single wavelength using Equation (11.6).

The experimental intensity (Arbitrary Units, AU) is plotted at each temperature for the same wavelength (wavenumber) from the experimental data. These relationships shown in Figure 0-15 and Figure 0-16 follow the temperature to the 4th power dependence portrayed in Equation (11.4).
Figure 0-15. Experimental intensity with respect to temperature at 1157 cm\(^{-1}\).

Figure 0-16. Theoretical intensity with respect to temperature at 1157 cm\(^{-1}\).

Combine lot the theoretical exitance (y) curve and the experimental intensity (x) curve into a single curve shown in Figure 0-17.
A linear regression curve for this data was calculated. In this case, the resulting linear equation’s slope represents microflicks per AU while the y-intercept is the instrument’s radiometric offset. The flick is a unit of spectral radiance; e.g. 1 flick = 1 W·sr⁻¹·cm⁻²·µm⁻¹ and 1 microflick = 10⁻⁶ flicks = 10 kW·sr⁻¹·m⁻³. This makes the calibration curve, at this specific wavenumber (wavelength), equal to

\[ M_\lambda = m \cdot V_\lambda + b, \]  

(11.7)

where \( m \) is the responsivity of the detector, \( V_\lambda \) is the detector voltage and \( b \) is the instrument’s radiometric offset. There will be an offset for each wavelength increment to create a correction matrix over all wavenumbers. This correction matrix can now be used to calibrate the experimental data into units of microflicks. Kudenev et al. [57]
Applying the correction matrix to the measured blackbody and diamond spectra gives Figure 0-18 and Figure 0-19. Subtracting the background aluminum measurement from the diamond spectra gives Figure 0-20.

**Figure 0-18.** Calibrated blackbody curve with $\varepsilon = 0.97$. 
Figure 0-19. Calibrated diamond spectra for multiple temperatures with background present.

Figure 0-20. Calibrated diamond spectra with background removed.
Use the calibration curve on the diamond data to determine the effective diamond power intensity at each wavelength and temperature. Compare this intensity with respect to the blackbody intensity to find the emissivity of diamond.

\[
\varepsilon_{\text{diamond}} = \frac{I_{\text{diamond}}}{I_{\text{blackbody}}}
\]  

(11.8)

The result from (11.8) is shown in Figure 0-21.

![Figure 0-21. Emissivity of diamond at varying temperatures.](image)

The values of emissivity are approximately constant with temperature. The emissivity increases from approximately 0.05 to 0.3 on the wavenumber interval from 500 to 2000 cm\(^{-1}\). The peak emissivity (0.3) occurs at approximately 2000 cm\(^{-1}\) (wavelength of 5 µm). The effects
of this peak in emissivity can be seen in Figure 0-14 and Figure 0-20 with an intensity maximum occurring at the same wavenumber.

\[
\varepsilon_{\text{paint}} = 0.97 = \frac{I_{\text{paint}}}{I_{\text{blackbody}}} \rightarrow \varepsilon_{\text{diamond}} = \frac{I_{\text{diamond}}}{I_{\text{paint}} / 0.97}
\]  

(11.9)

The diamond tool pyrometer system will be designed around the peak emission wavelength from the diamond of 2000 cm\(^{-1}\) (5 \(\mu\)m).

**APPENDIX G. MATERIAL PROPERTIES**

Material properties were obtained from Matweb.com [34]. The brass, steel and aluminum alloys used in this research are shown in Table 0-6, Table 0-7 and Table 0-8, respectively.
**Table 0-6. Properties of brass alloys.**

<table>
<thead>
<tr>
<th>Type</th>
<th>UNS C26000</th>
<th>UNS C36000</th>
<th>UNS C3770</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Common Name</strong></td>
<td>260 or Cartridge</td>
<td>360 or Free-Cutting</td>
<td>Forging Brass</td>
</tr>
<tr>
<td><strong>Machinability</strong></td>
<td>30%</td>
<td>100%</td>
<td>80%</td>
</tr>
<tr>
<td><strong>Yield Strength, psi</strong></td>
<td>10900</td>
<td>18000-45000 (depends on temper)</td>
<td>14500-50800 (depends on temper)</td>
</tr>
<tr>
<td><strong>Hardness, Rockwell</strong></td>
<td>B77</td>
<td>B78</td>
<td>B74</td>
</tr>
<tr>
<td><strong>Hardness, Rockwell</strong></td>
<td>54F</td>
<td>-</td>
<td>78F</td>
</tr>
<tr>
<td><strong>Modulus of Elasticity, ksi</strong></td>
<td>16000</td>
<td>14100</td>
<td>15200</td>
</tr>
<tr>
<td><strong>Elongation at break</strong></td>
<td>67%</td>
<td>53%</td>
<td>45%</td>
</tr>
<tr>
<td><strong>Thermal Conductivity (W/m-K)</strong></td>
<td>120</td>
<td>115</td>
<td>120</td>
</tr>
<tr>
<td><strong>Specific Heat (J/g°C)</strong></td>
<td>0.375</td>
<td>0.38</td>
<td>0.38</td>
</tr>
<tr>
<td><strong>Density (g/cm³)</strong></td>
<td>8.53</td>
<td>8.49</td>
<td>8.44</td>
</tr>
<tr>
<td><strong>Approximate Cutting Force</strong></td>
<td>13 N (Width: 0.813 mm, DoC: 5 μm)</td>
<td>3.5 N (Width: 0.813 mm, DoC: 2 μm)</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Specific Cutting Energy (N/m²)</strong></td>
<td>3.198E+09</td>
<td>2.15E+09</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Components</strong></td>
<td>Copper - 68-71%</td>
<td>Copper - 60-63%</td>
<td>Copper - 58-62%</td>
</tr>
<tr>
<td></td>
<td>Lead - &lt;0.07%</td>
<td>Lead - 2.5-3.7%</td>
<td>Lead - 1.5-2.5%</td>
</tr>
<tr>
<td></td>
<td>Zinc - 28-31%</td>
<td>Zinc - 35.5%</td>
<td>Zinc - 39%</td>
</tr>
</tbody>
</table>
### Table 0-7. Properties of steel alloys.

<table>
<thead>
<tr>
<th>Type</th>
<th>UNS G11180</th>
<th>UNS G12150</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Common Name</strong></td>
<td>AISI 1118</td>
<td>AISI 1215</td>
</tr>
<tr>
<td><strong>Machinability</strong></td>
<td>-</td>
<td>120% (Based on 1212)</td>
</tr>
<tr>
<td><strong>Yield Strength, psi</strong></td>
<td>45700</td>
<td>60200</td>
</tr>
<tr>
<td><strong>Hardness, Rockwell</strong></td>
<td>B80</td>
<td>B85</td>
</tr>
<tr>
<td><strong>Hardness, Vickers</strong></td>
<td>155</td>
<td>175</td>
</tr>
<tr>
<td><strong>Modulus of Elasticity, ksi</strong></td>
<td>29700</td>
<td>29000</td>
</tr>
<tr>
<td><strong>Thermal Conductivity (W/m-K)</strong></td>
<td>49.8</td>
<td>51.9</td>
</tr>
<tr>
<td><strong>Specific Heat (J/g°C)</strong></td>
<td>0.472</td>
<td>0.472</td>
</tr>
<tr>
<td><strong>Density (g/cm³)</strong></td>
<td>7.87</td>
<td>7.87</td>
</tr>
<tr>
<td><strong>Approximate Cutting Force</strong></td>
<td>N/A</td>
<td>6.8 N (Width: 1 mm, DoC: 2 μm)</td>
</tr>
<tr>
<td><strong>Specific Cutting Energy (N/m²)</strong></td>
<td>N/A</td>
<td>3.40E+09</td>
</tr>
<tr>
<td><strong>Elongation at break</strong></td>
<td>32%</td>
<td>10%</td>
</tr>
</tbody>
</table>

#### Components

<table>
<thead>
<tr>
<th>Component</th>
<th>UNS G11180</th>
<th>UNS G12150</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.14-0.20%</td>
<td>Carbon - &lt;0.09%</td>
</tr>
<tr>
<td>Iron</td>
<td>98.03-98.48%</td>
<td>Iron - 98.42-98.95%</td>
</tr>
<tr>
<td>Manganese</td>
<td>1.3-1.6%</td>
<td>Manganese - 0.75-1.05%</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.08-0.13%</td>
<td>Sulfur - 0.26-0.35%</td>
</tr>
<tr>
<td>Phosphorous</td>
<td>&lt;0.04%</td>
<td>Phosphorous - 0.04-0.09%</td>
</tr>
</tbody>
</table>
Table 0-8. Properties of 6061-T6 Aluminum.

<table>
<thead>
<tr>
<th>Type</th>
<th>6061-T6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common Name</td>
<td>-</td>
</tr>
<tr>
<td>Machinability</td>
<td>50%</td>
</tr>
<tr>
<td>Yield Strength, psi</td>
<td>40000 (at 75F)</td>
</tr>
<tr>
<td>Hardness, Brinell</td>
<td>95</td>
</tr>
<tr>
<td>Hardness, Vickers</td>
<td>107</td>
</tr>
<tr>
<td>Hardness, Rockwell</td>
<td>60B</td>
</tr>
<tr>
<td>Modulus of Elasticity, ksi</td>
<td>10000</td>
</tr>
<tr>
<td>Thermal Conductivity (W/m-K)</td>
<td>167</td>
</tr>
<tr>
<td>Specific Heat (J/g°C)</td>
<td>0.896</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>2.7</td>
</tr>
<tr>
<td>Approximate Cutting Force</td>
<td>3.54 N (Width: 0.813 mm, DoC: 2 μm)</td>
</tr>
<tr>
<td>Specific Cutting Energy (N/m²)</td>
<td>2.17E+09</td>
</tr>
<tr>
<td>Elongation at break</td>
<td>17%</td>
</tr>
</tbody>
</table>

Components

- Aluminum - 95.8-98.6%
- Chromium - 0.04-0.35%
- Copper - 0.15-0.40%
- Iron - <0.70%
- Magnesium - 0.8-1.2%

**APPENDIX H. EXTRACTING ADVANTEdge RAKE AND RELIEF TOOL DATA**

1) From the main page, load the results by pressing the results tab. This will load the results into Tecplot 360.

2) Once the results are loaded into Tecplot, open the AdvantEdge Quick Analysis toolbars under the Tools Tab.
3) Under the AdvantEdge Quick Analysis toolbar’s Tools tab, click Rake and Relief Face data Extraction.
4) Use the browse tab to select the desired project. Change the extract length to the area of interest (~10x the depth of cut) and change to Rake and Relief to extract perimeter data around the tool.

5) A .TEC file will be generated with the following format in the project folder
Projectname_Zone_rakeface.tec

6) Use the MATLAB function `twperimetergrab.m` to convert the data into a .mat file. The `outfile` is the name of the output file.

```
twperimetergrab(filename,outfile)
```

7) The data will be set up into $n \times 27$ matrix, where the row $n$ depends on the number of nodes on the perimeter. The 27 columns contain the variables in Table 0-9.
The MATLAB function `tw_toolface.m` can be used to plot the different parameters as a function of the perimeter distance. `Line` corresponds to the parameter from the Table 0-9.

\[
\text{tw_toolface(filename, smoothness, number, line)}
\]
## APPENDIX I. LARGE DEPTH OF CUT SIMULATIONS ADVANTEdge

Table 0-10. Tool dimensions and mesh for large depth of cut models.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting radius</td>
<td>0.001 mm</td>
</tr>
<tr>
<td>Rake angle/length</td>
<td>0°/1.5 mm</td>
</tr>
<tr>
<td>Relief angle/length</td>
<td>6°/1.5 mm</td>
</tr>
<tr>
<td>Minimum tool element size</td>
<td>0.001 mm</td>
</tr>
<tr>
<td>Maximum tool element size</td>
<td>1.5 mm</td>
</tr>
<tr>
<td>Mesh grading</td>
<td>0.9</td>
</tr>
<tr>
<td>Tool material</td>
<td>Diamond-Single Crystal</td>
</tr>
</tbody>
</table>

Table 0-11. AdvantEdge process options for large depth of cut models.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width of cut</td>
<td>0.8 mm</td>
</tr>
<tr>
<td>Length of cut</td>
<td>0.4 mm</td>
</tr>
<tr>
<td>Friction coefficient</td>
<td>0.08-0.09</td>
</tr>
<tr>
<td>Workpiece length</td>
<td>0.6 mm</td>
</tr>
<tr>
<td>Workpiece height</td>
<td>0.4 mm</td>
</tr>
<tr>
<td>Workpiece material</td>
<td>Brass C37700</td>
</tr>
<tr>
<td>Simulation mode</td>
<td>Standard</td>
</tr>
</tbody>
</table>

Table 0-12. AdvantEdge mesh parameters for large depth of cut models.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max number of nodes</td>
<td>20000</td>
</tr>
<tr>
<td>Fraction of radius/feed</td>
<td>0.5/0.1</td>
</tr>
<tr>
<td>Mesh refine/coarse</td>
<td>1/8</td>
</tr>
<tr>
<td>Maximum/minimum element size</td>
<td>0.1/0.001</td>
</tr>
<tr>
<td>Approximate computation time</td>
<td>12 hours</td>
</tr>
</tbody>
</table>
Table 0-13. Force and peak temperatures for large depth of cut models.

<table>
<thead>
<tr>
<th>Filename</th>
<th>Depth of Cut (µm)</th>
<th>Cutting Speed (m/s)</th>
<th>Average Cutting Force (N)</th>
<th>Average Thrust Force (N)</th>
<th>Max Tool Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>brass_5um_0.5mps</td>
<td>5</td>
<td>0.5</td>
<td>6.52</td>
<td>1.57</td>
<td>25.2</td>
</tr>
<tr>
<td>brass_5um_1mps</td>
<td>5</td>
<td>1</td>
<td>6.52</td>
<td>1.59</td>
<td>29.6</td>
</tr>
<tr>
<td>brass_5um_2mps</td>
<td>5</td>
<td>2</td>
<td>6.5</td>
<td>1.57</td>
<td>36.3</td>
</tr>
<tr>
<td>brass_5um_4mps</td>
<td>5</td>
<td>4</td>
<td>6.42</td>
<td>1.58</td>
<td>47.4</td>
</tr>
<tr>
<td>brass_10um_0.5mps</td>
<td>10</td>
<td>0.5</td>
<td>11.9</td>
<td>2.03</td>
<td>28.2</td>
</tr>
<tr>
<td>brass_10um_1mps</td>
<td>10</td>
<td>1</td>
<td>11.9</td>
<td>2.15</td>
<td>34.4</td>
</tr>
<tr>
<td>brass_10um_2mps</td>
<td>10</td>
<td>2</td>
<td>11.7</td>
<td>2.03</td>
<td>44.3</td>
</tr>
<tr>
<td>brass_10um_4mps</td>
<td>10</td>
<td>4</td>
<td>11.4</td>
<td>1.99</td>
<td>59.7</td>
</tr>
<tr>
<td>brass_20um_0.5mps</td>
<td>20</td>
<td>0.5</td>
<td>22.1</td>
<td>2.85</td>
<td>32.6</td>
</tr>
<tr>
<td>brass_20um_1mps</td>
<td>20</td>
<td>1</td>
<td>22.2</td>
<td>3.08</td>
<td>41.7</td>
</tr>
<tr>
<td>brass_20um_2mps</td>
<td>20</td>
<td>2</td>
<td>21.5</td>
<td>2.77</td>
<td>55.1</td>
</tr>
<tr>
<td>brass_20um_4mps</td>
<td>20</td>
<td>4</td>
<td>20.3</td>
<td>2.69</td>
<td>73.7</td>
</tr>
</tbody>
</table>
## APPENDIX J. WEAR MEASUREMENTS FOR 1215 STEEL

<table>
<thead>
<tr>
<th>Cutting Speed (m/s)</th>
<th>Depth of Cut (μm)</th>
<th>Cutting Distance, s (m)</th>
<th>Time, t (s)</th>
<th>Edge Radius</th>
<th>Worn Area, A (μm²)</th>
<th>dA/ds</th>
<th>dA/dt</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0.0555</td>
<td>0.013</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>10</td>
<td>0.0654</td>
<td>0.014203</td>
<td>0.0025806</td>
<td>0.0012903</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>20</td>
<td>0.0828</td>
<td>0.027063</td>
<td>0.002572</td>
<td>0.001286</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20</td>
<td>40</td>
<td>0.0805</td>
<td>0.043368</td>
<td>0.0015305</td>
<td>0.00081525</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40</td>
<td>80</td>
<td>0.0936</td>
<td>0.055405</td>
<td>0.00060185</td>
<td>0.00030093</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60</td>
<td>120</td>
<td>0.1102</td>
<td>0.090718</td>
<td>0.00176565</td>
<td>0.00088283</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Average</td>
<td>0.00183012</td>
<td>0.00091506</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cutting Speed (m/s)</th>
<th>Depth of Cut (μm)</th>
<th>Cutting Distance, s (m)</th>
<th>Time, t (s)</th>
<th>Edge Radius</th>
<th>Worn Area, A (μm²)</th>
<th>dA/ds</th>
<th>dA/dt</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0.0555</td>
<td>0.013</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>20</td>
<td>0.062</td>
<td>0.007665</td>
<td>0.0006365</td>
<td>0.0006365</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20</td>
<td>40</td>
<td>0.0698</td>
<td>0.014363</td>
<td>0.0006698</td>
<td>0.0006698</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40</td>
<td>80</td>
<td>0.0839</td>
<td>0.022669</td>
<td>0.0004153</td>
<td>0.0004153</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80</td>
<td>120</td>
<td>0.1092</td>
<td>0.05167</td>
<td>0.000535</td>
<td>0.000535</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Average</td>
<td>0.00048933</td>
<td>0.00048933</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cutting Speed (m/s)</th>
<th>Depth of Cut (μm)</th>
<th>Cutting Distance, s (m)</th>
<th>Time, t (s)</th>
<th>Edge Radius</th>
<th>Worn Area, A (μm²)</th>
<th>dA/ds</th>
<th>dA/dt</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0.0555</td>
<td>0.013</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>5</td>
<td>0.0638</td>
<td>0.008404</td>
<td>0.0007104</td>
<td>0.0014208</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20</td>
<td>10</td>
<td>0.0686</td>
<td>0.014546</td>
<td>0.0006142</td>
<td>0.0012284</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40</td>
<td>20</td>
<td>0.066</td>
<td>0.032735</td>
<td>0.00090945</td>
<td>0.0018189</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80</td>
<td>40</td>
<td>0.0843</td>
<td>0.057073</td>
<td>0.00060845</td>
<td>0.0012169</td>
</tr>
<tr>
<td></td>
<td></td>
<td>120</td>
<td>60</td>
<td>0.1021</td>
<td>0.086961</td>
<td>0.0007472</td>
<td>0.0014944</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Average</td>
<td>0.00071063</td>
<td>0.00142125</td>
</tr>
<tr>
<td>Cutting Speed (m/s)</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------------------</td>
<td>-----</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth of Cut (μm)</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cutting Distance, s (m)</td>
<td>Time, t (s)</td>
<td>Edge Radius</td>
<td>Worn Area, A (μm²)</td>
<td>dA/ds</td>
<td>dA/dt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0.0555</td>
<td>0.0013</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>5</td>
<td>0.0981</td>
<td>0.022921</td>
<td>0.00108105</td>
<td>0.0043242</td>
<td></td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>20</td>
<td>0.1029</td>
<td>0.119608</td>
<td>0.00161145</td>
<td>0.0064458</td>
<td></td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>30</td>
<td>0.136</td>
<td>0.178986</td>
<td>0.00148445</td>
<td>0.0059378</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.00139232</td>
<td>0.00556927</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cutting Speed (m/s)</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth of Cut (μm)</td>
<td>2</td>
</tr>
<tr>
<td>Cutting Distance, s (m)</td>
<td>Time, t (s)</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>3.33</td>
</tr>
<tr>
<td>80</td>
<td>13.33</td>
</tr>
<tr>
<td>120</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cutting Speed (m/s)</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth of Cut (μm)</td>
<td>2</td>
</tr>
<tr>
<td>Cutting Distance, s (m)</td>
<td>Time, t (s)</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX K. WEAR MEASUREMENTS FOR 6061 ALUMINUM

Table 0-14. Wear measurements and Archard coefficient parameters for 2 μm DoC at 1 m/s for Al6061.

<table>
<thead>
<tr>
<th>Cutting Distance (m)</th>
<th>Edge Radius (um)</th>
<th>Unworn Area (μm²)</th>
<th>Workpiece Thickness (mm)</th>
<th>Unworn Volume (μm³)</th>
<th>Average Flank Force (N)</th>
<th>(Flank Force) x (Distance)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.050</td>
<td>0.001</td>
<td>0.813</td>
<td>0.813</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3000</td>
<td>0.1039</td>
<td>0.0558</td>
<td>0.813</td>
<td>45.36</td>
<td>1.65</td>
<td>4950</td>
</tr>
<tr>
<td>5000</td>
<td>0.1527</td>
<td>0.1278</td>
<td>0.813</td>
<td>103.86</td>
<td>1.75</td>
<td>8750</td>
</tr>
<tr>
<td>7500</td>
<td>0.1944</td>
<td>0.2431</td>
<td>0.813</td>
<td>197.60</td>
<td>2.25</td>
<td>16875</td>
</tr>
</tbody>
</table>

Table 0-15. Wear measurements and Archard coefficient parameters for 5 μm DoC at 1 m/s for Al6061.

<table>
<thead>
<tr>
<th>Cutting Distance (m)</th>
<th>Edge Radius (um)</th>
<th>Unworn Area (μm²)</th>
<th>Workpiece Thickness (mm)</th>
<th>Unworn Volume (μm³)</th>
<th>Average Flank Force (N)</th>
<th>(Flank Force) x (Distance)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.050</td>
<td>0.001</td>
<td>0.813</td>
<td>0.813</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2500</td>
<td>0.0929</td>
<td>0.0374</td>
<td>0.813</td>
<td>30.37</td>
<td>5.39</td>
<td>13475</td>
</tr>
<tr>
<td>5000</td>
<td>0.1604</td>
<td>0.1443</td>
<td>0.813</td>
<td>117.34</td>
<td>6.08</td>
<td>30400</td>
</tr>
</tbody>
</table>

APPENDIX L. FORCE MEASUREMENTS FOR 1215 STEEL

Table 0-16. 1215 steel, 2 μm, 0.5 m/s.

<table>
<thead>
<tr>
<th>End Cutting Dist (m)</th>
<th>Cutting Force (N)</th>
<th>Std Dev</th>
<th>Thrust Force (N)</th>
<th>Std Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>7.214</td>
<td>0.488</td>
<td>3.634</td>
<td>0.328</td>
</tr>
<tr>
<td>10</td>
<td>6.866</td>
<td>0.543</td>
<td>3.210</td>
<td>0.369</td>
</tr>
<tr>
<td>20</td>
<td>5.269</td>
<td>0.257</td>
<td>3.155</td>
<td>0.361</td>
</tr>
<tr>
<td>40</td>
<td>7.473</td>
<td>0.576</td>
<td>3.936</td>
<td>0.382</td>
</tr>
<tr>
<td>60</td>
<td>7.827</td>
<td>0.632</td>
<td>3.987</td>
<td>0.403</td>
</tr>
</tbody>
</table>
Table 0-17. 1215 steel, 2 μm, 1 m/s.

<table>
<thead>
<tr>
<th>End Cutting Dist (m)</th>
<th>Cutting Force (N)</th>
<th>Std Dev</th>
<th>Thrust Force (N)</th>
<th>Std Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>6.804</td>
<td>0.395</td>
<td>3.292</td>
<td>0.336</td>
</tr>
<tr>
<td>20</td>
<td>6.899</td>
<td>0.412</td>
<td>3.176</td>
<td>0.357</td>
</tr>
<tr>
<td>40</td>
<td>4.745</td>
<td>0.171</td>
<td>3.188</td>
<td>0.381</td>
</tr>
<tr>
<td>80</td>
<td>7.616</td>
<td>0.487</td>
<td>3.818</td>
<td>0.399</td>
</tr>
<tr>
<td>120</td>
<td>8.049</td>
<td>0.524</td>
<td>4.046</td>
<td>0.429</td>
</tr>
</tbody>
</table>

Table 0-18. 1215 steel, 2 μm, 2 m/s.

<table>
<thead>
<tr>
<th>End Cutting Dist (m)</th>
<th>Cutting Force (N)</th>
<th>Std Dev</th>
<th>Thrust Force (N)</th>
<th>Std Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>7.113</td>
<td>0.357</td>
<td>3.729</td>
<td>0.353</td>
</tr>
<tr>
<td>20</td>
<td>7.085</td>
<td>0.346</td>
<td>3.581</td>
<td>0.321</td>
</tr>
<tr>
<td>40</td>
<td>4.426</td>
<td>0.206</td>
<td>3.442</td>
<td>0.355</td>
</tr>
<tr>
<td>80</td>
<td>7.732</td>
<td>0.422</td>
<td>4.133</td>
<td>0.387</td>
</tr>
<tr>
<td>120</td>
<td>8.294</td>
<td>0.500</td>
<td>4.573</td>
<td>0.450</td>
</tr>
</tbody>
</table>

Table 0-19. 1215 steel, 2 μm, 1 m/s.

<table>
<thead>
<tr>
<th>End Cutting Dist (m)</th>
<th>Cutting Force (N)</th>
<th>Std Dev</th>
<th>Thrust Force (N)</th>
<th>Std Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>7.487</td>
<td>0.421</td>
<td>3.976</td>
<td>0.373</td>
</tr>
<tr>
<td>80</td>
<td>7.724</td>
<td>0.577</td>
<td>4.181</td>
<td>0.448</td>
</tr>
<tr>
<td>120</td>
<td>8.539</td>
<td>0.674</td>
<td>4.374</td>
<td>0.501</td>
</tr>
</tbody>
</table>

Table 0-20. 1215 steel, 2 μm, 4 m/s.

<table>
<thead>
<tr>
<th>End Cutting Dist (m)</th>
<th>Cutting Force (N)</th>
<th>Std Dev</th>
<th>Thrust Force (N)</th>
<th>Std Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>7.618</td>
<td>0.376</td>
<td>4.497</td>
<td>0.350</td>
</tr>
<tr>
<td>80</td>
<td>7.756</td>
<td>0.421</td>
<td>4.485</td>
<td>0.384</td>
</tr>
<tr>
<td>120</td>
<td>8.606</td>
<td>0.509</td>
<td>5.184</td>
<td>0.443</td>
</tr>
</tbody>
</table>
Table 0-21. 1215 steel, 2 μm, 6 m/s.

<table>
<thead>
<tr>
<th>End Cutting Dist (m)</th>
<th>Cutting Force (N)</th>
<th>Std Dev</th>
<th>Thrust Force (N)</th>
<th>Std Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>7.752</td>
<td>0.383</td>
<td>4.757</td>
<td>0.364</td>
</tr>
<tr>
<td>80</td>
<td>8.454</td>
<td>0.450</td>
<td>5.380</td>
<td>0.452</td>
</tr>
<tr>
<td>120</td>
<td>8.832</td>
<td>0.495</td>
<td>5.754</td>
<td>0.493</td>
</tr>
</tbody>
</table>

APPENDIX M. ADVANTEDGE SIMULATIONS FOR STEEL

Table 0-22. Tool dimensions and mesh for steel models.

<table>
<thead>
<tr>
<th>Cutting radius</th>
<th>0.0005 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rake angle/length</td>
<td>0°/0.025 mm</td>
</tr>
<tr>
<td>Relief angle/length</td>
<td>6°/0.025 mm</td>
</tr>
<tr>
<td>Minimum tool element size</td>
<td>0.0002 mm</td>
</tr>
<tr>
<td>Maximum tool element size</td>
<td>0.025 mm</td>
</tr>
<tr>
<td>Mesh grading</td>
<td>0.8</td>
</tr>
<tr>
<td>Tool material</td>
<td>Diamond-Single Crystal</td>
</tr>
</tbody>
</table>
Table 0-23. AdvantEdge process options for steel models.

<table>
<thead>
<tr>
<th>Width of cut</th>
<th>1 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed</td>
<td>0.002 mm</td>
</tr>
<tr>
<td>Cutting speed</td>
<td>0.5, 1, 2, 4, 6 m/s</td>
</tr>
<tr>
<td>Length of cut</td>
<td>0.022 mm</td>
</tr>
<tr>
<td>Friction coefficient</td>
<td>0.4</td>
</tr>
<tr>
<td>Workpiece length</td>
<td>0.05 mm</td>
</tr>
<tr>
<td>Workpiece height</td>
<td>0.015 mm</td>
</tr>
<tr>
<td>Workpiece material</td>
<td>1118 Steel</td>
</tr>
<tr>
<td>Simulation mode</td>
<td>Standard</td>
</tr>
<tr>
<td>Initial Temperature</td>
<td>20°C</td>
</tr>
<tr>
<td>Steady-state analysis</td>
<td>Yes</td>
</tr>
<tr>
<td>Average length of cut ratio</td>
<td>10%</td>
</tr>
</tbody>
</table>

Table 0-24. AdvantEdge mesh parameters for steel models.

<table>
<thead>
<tr>
<th>Max number of nodes</th>
<th>10000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fraction of radius/feed</td>
<td>0.1/0.1</td>
</tr>
<tr>
<td>Mesh refine/coarse</td>
<td>1/8</td>
</tr>
<tr>
<td>Maximum/minimum element size</td>
<td>0.1/0.001</td>
</tr>
<tr>
<td>Approximate computation time</td>
<td>20 hours</td>
</tr>
</tbody>
</table>

Table 0-25. Results for steel models.

<table>
<thead>
<tr>
<th>Cutting Speed (m/s)</th>
<th>Cut Force (N)</th>
<th>Thrust Force (N)</th>
<th>Peak Temperature (°C)</th>
<th>Boundary Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>6.73</td>
<td>3.28</td>
<td>36.21</td>
<td>34</td>
</tr>
<tr>
<td>1</td>
<td>6.74</td>
<td>3.28</td>
<td>49.45</td>
<td>46</td>
</tr>
<tr>
<td>2</td>
<td>6.93</td>
<td>3.31</td>
<td>72.18</td>
<td>66</td>
</tr>
<tr>
<td>4</td>
<td>7.37</td>
<td>3.51</td>
<td>125.63</td>
<td>116</td>
</tr>
<tr>
<td>6</td>
<td>7.66</td>
<td>3.57</td>
<td>166.57</td>
<td>153</td>
</tr>
</tbody>
</table>
APPENDIX N. MICRO-MODE ADVANTEdge SIMULATIONS FOR STEEL

Table 0-26. Tool dimensions and mesh for micro-mode model.

<table>
<thead>
<tr>
<th>Type</th>
<th>Custom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting radius</td>
<td>0.00005 mm</td>
</tr>
<tr>
<td>Rake angle/length</td>
<td>0°/0.025 mm</td>
</tr>
<tr>
<td>Relief angle/length</td>
<td>6°/0.025 mm</td>
</tr>
<tr>
<td>Minimum tool element size</td>
<td>0.00002 mm</td>
</tr>
<tr>
<td>Maximum tool element size</td>
<td>0.05 mm</td>
</tr>
<tr>
<td>Mesh grading</td>
<td>0.8</td>
</tr>
<tr>
<td>Tool material</td>
<td>Diamond-Single Crystal</td>
</tr>
<tr>
<td>Tool BCs</td>
<td>Isothermal, 36°</td>
</tr>
</tbody>
</table>

Table 0-27. AdvantEdge process options for micro-mode model.

| Width of cut                  | 1 mm                          |
| Feed                          | 0.002 mm                      |
| Cutting speed                 | 0.5 m/s                       |
| Length of cut                 | 0.022 mm                      |
| Friction coefficient          | 0.35                          |
| Workpiece length              | 0.04 mm                       |
| Workpiece height              | 0.012 mm                      |
| Workpiece material            | 1118 Steel                    |
| Simulation mode               | Mico-machining                |
| Initial Temperature           | 20°C                          |
| Steady-state analysis         | No                            |
| Average length of cut ratio   | 10%                           |
Table 0-28. AdvantEdge mesh parameters for micro-mode model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max number of nodes</td>
<td>24000</td>
</tr>
<tr>
<td>Fraction of radius/feed</td>
<td>0.8/0.4</td>
</tr>
<tr>
<td>Mesh refine/coarse</td>
<td>1/8</td>
</tr>
<tr>
<td>Maximum/minimum element size</td>
<td>0.07/0.00002</td>
</tr>
<tr>
<td>Approximate computation time</td>
<td>1-2 weeks</td>
</tr>
</tbody>
</table>

**APPENDIX O. LOAD CELL AMPLIFIER SETTINGS**

<table>
<thead>
<tr>
<th>Settings</th>
<th>Thurst Force ($F_x$)</th>
<th>Cutting Force ($F_y$)</th>
<th>Side Force ($F_z$)</th>
<th>Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity Settings</td>
<td>6.76</td>
<td>6.76</td>
<td></td>
<td>5.35</td>
</tr>
<tr>
<td>Capacitor Decay</td>
<td>Long</td>
<td>Long</td>
<td></td>
<td>Long</td>
</tr>
<tr>
<td>Scale (Mech/V)</td>
<td>50</td>
<td>50</td>
<td></td>
<td>50</td>
</tr>
<tr>
<td>Scaling Factor (N/V)</td>
<td>4.2287</td>
<td>4.3305</td>
<td></td>
<td>7.6487</td>
</tr>
</tbody>
</table>