Transactions, **SMiRT-24**
BEXCO, Busan, Korea - August 20-25, 2017
Division 2

Effect of Welding Parameters on Fracture Behavior of Al-Mg Alloy Weld Joints

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Abstract

Aluminium alloys now a days are widely used due to their low weight, better neutronics, corrosion resistance, moderate high strength etc in nuclear facilities. They are usually more difficult to weld due to their narrow plastic range, low bulk resistance and good thermal conductivity. Weld joint locations are generally critical in comparison to base metal because of distortions, gas porosities and metallurgical precipitations in weld metal and heat affected zone (HAZ). Material and metallurgical properties of the weld and HAZ also depend on the heat input and cooling rate during and after welding. Cooling rate also depends on the interpass temperatures. It has been observed that it is difficult to weld aluminum alloys at lower interpass temperature and higher interpass temperature may change the material properties.

In this study aluminium-magnesium alloy (Al-5154) plate of 40 mm thickness has been used for welding with consumable ER-5356. Double V-groove has been used to minimize the distortion. Welding has been carried out using gas tungsten arc welding (GTAW). Interpass temperatures considered for the study ranges from 200 to 320 deg C. Weld has been subjected to 100 % radiographic examination and qualified as per the ASME acceptance criteria. Tensile and fracture toughness tests has been carried out as per the procedure given in ASTM standard. Evaluation of fracture toughness of weld requires plastic eta factor for given specimen. Compact Tension (CT) specimens have been used for carrying out fracture toughness. Plastic eta factor is not available in the ASTM standard for welds. Therefore plastic eta factor has been evaluated by carrying out finite element analysis of the CT specimen. Results of the tensile and fracture toughness tests of welds for different interpass temperatures will be discussed.

Introduction

Now a days Aluminium alloys are widely used due to their many advantages like low weight, better neutronics (from nuclear industrial point of view), corrosion resistance, moderate high strength etc. Aluminium is extensively used in water-cooled research reactors because of its low cross section for the capture of thermal neutrons, excellent corrosion resistance and thermal conductivity. 5xxx are one of the most commonly used aluminium alloys. These are solid solution or precipitation hardened alloys that provide satisfactory mechanical properties for the intended service in the reactor facility. In these alloys of the 5xxx series, the increase in strength over pure aluminium is due to magnesium in solid solution. This alloy has good properties as regards to formability and resistance to corrosion in water. Aluminium alloys are suitable for use in radiation environments as their properties are well understood and show predictable behaviour under such conditions.

With very few exceptions it is not possible to make an engineered structure from a single monolithic piece of material. Elements of a structure must therefore be joined together in order for it to fulfil a useful function. Welding is a one such joining technique that forms metallurgical bond between parts by the application of heat or pressure or both.

Aluminium alloys can be readily welded in comparison to other neutron economical materials like zirconium by employing welding processes with gas protection (TIG welding) using AC power supply. Welding is carried out in an atmosphere of argon or helium. In addition, the shielding gas has been used to regulate the cross section of the seam and the deposition speed. The welding process and procedure selection will ensure appropriate performance of these welds. If the magnesium content in the 5xxx series alloys is higher the welding quality will be better.Al-5154 is used for this project.

Although welding is the most adaptable and efficient of all the joining process but it is not a perfect one i.e. it comes with its own set of disadvantages such as defects like internal air pocket that may lead to crack extension on the application of load.This crack extension will lead to catastrophic fracture of the component.

The project aims to understand the effect of welding parameters on fracture behaviour of Al-Mg alloy weld joints. In order to address the above it is proposed to carry out experimental and analytical investigations. Aluminium plates were welded by GTAW with varying preheat and interpass temperature. Eta factor for compact tension specimens with weld at the centre were determined analytically. Then initiation fracture toughness and fracture resistance curve were experimental evaluated. Quantification of effect of welding parameters on fracture behaviour of the weld joint was done afterwards.

Material

Aluminium alloys can be conveniently divided into two major categories, casting compositions and wrought compositions: differentiation for each category is based on the primary mechanism of property development (i.e. heat-treatable and non-heat treatable alloys).The used Al-Mg alloy is a non-heat-treatable or work hardened alloy. These Al515 alloys are used in cases where still higher strengths are required; this strength is achieved from large quantities of magnesium in solid solution. More importantly, magnesium promotes work hardening by lowering the stacking fault energy, thus reducing the tendency for dynamic recovery.

In general, the filler alloy selected should be similar in composition to the base metal alloy [3]. Hence, 5xxx filler alloys are used to join 5xxx-series base metal alloys. Al 5356 is used as filler alloy.

Table 1: Material Composition of Aluminium Alloy and Filler wire

Composition (wt %)	**Mg**	**Mn**	**Cr**	**Ti**	**Si**	**Al**	**Cu**
Content of parent material Al-5154 O	3.1-3.9	<=0.1	<=0.1	<=0.2	<=0.25	94.3-96.8	<=0.1
Content of Filler material ER-5356	5	0.35	0.10	0.15	-	Base	-

Fracture Mechanics

ASTM E 1820 limits the fracture toughness calculation for homogeneous material. This project tries to evaluate the J-integral for inhomogeneous material i.e base. According to Kim Y J et. al (2003) a higher mismatch decreases the plastic η factor for overmatching, whereas it increases the plastic η factor for under-matching. This effect is more pronounced for overmatching than for under-matching. More interestingly the effect of $\frac{(W-a)}{H}$. is prominent. The mismatch effect on the plastic η factor diminishes, regardless of the strength mismatch, for the following two cases: for thicker welds ($\frac{(W-a)}{H}$. <~1) and for narrower welds ($\frac{(W-a)}{H}$. >~10). In-between, the plastic η factor not only depends on both strength mismatch and $\frac{(W-a)}{H}$. but can also depend on strain hardening.

The project involves calculation η_p^{CMOD} to calculate the J integral values. η_p^{VLL} could have been used to for he same purpose but according to Kim Yun Jae et. al (2001) the use of the experimental load CMOD records offers several advantages over the use of the load-LLD records, for measuring the J integral in toughness testing (or C-integral in creep crack growth testing) for homogeneous specimens. Some advantages include for instance its robustness and accuracy, particularly for shallow cracked specimens.

Experiment

Since J groove geometries are more economical (than V and bevel grooves) in terms of volume of weld metal to be deposited, offer less distortion, less residual stress and higher welding speed.Root face of 4 mm has been chosen to provide adequate support for the initial weld which serves as backing for the weld from the opposite side. The root gap has been taken to be 4.8 mm based on the availability of the filler wire. Filler wire diameter of 3.2mm has been used hence root gap is 1.5 times of diameter of filler wire. The schematic sketch for the groove is shown in Figure 1.

These base plates of Al-5154 of 40mm thickness were welded using GTAW process. Welding was done in 1G position using ER5356 filler wire of 3.2mm diameter. Non-consumable 2% Thoriated Tungsten electrode was used as welding electrode.

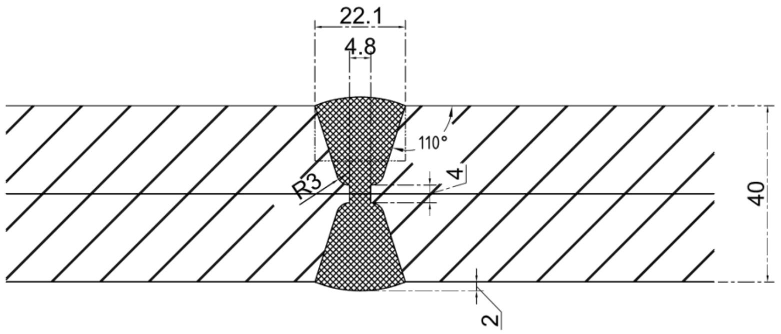


Figure 1: Weld Groove

Preheat and interpass temperature were taken to be same. The weld was carried out at three different preheat and interpass temperature i.e. 200^{0}C, 260^{0}C and 320^{0}C. It was ensured that the preheat or interpass temperature do not vary by more than 10^{0}C on either side. The welds were fully radiographed and it was seen that they qualify as per ASME section IX.

The sub standard tensile specimens as shown in fig. _ were prepared from the weld centre line and base.

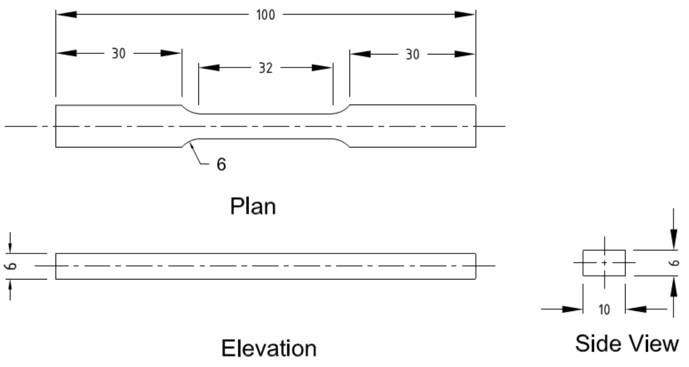


Figure 2: Sub-standard Tensile Specimen

The tensile tests were carried out for these specimens to evaluate their true stress strain curve. This tensile property was used to determine the eta values by FE analysis.

Also, compact tension (CT) specimens have been selected for the toughness measurement of the weld. The CT specimen has the advantage over other specimen types due to their compact design and hence it requires the least amount of test material to evaluate fracture toughness of the weld. A Compact Tension specimen has been designed dimensionally as per ASTM E-1820 standards.

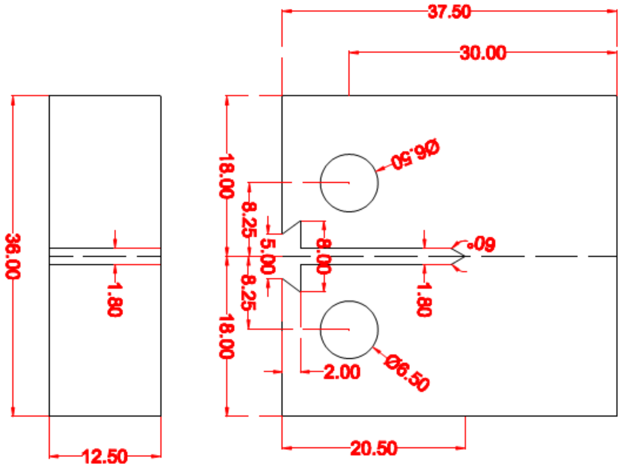


Figure 3: Compact Tensile Specimen

The CT specimens have been cut in T-L orientation i.e. loading is in transverse direction and notch is in longitudinal direction of the weld.

Since it is impractical to obtain a reproducibly sharp, narrow machined notch that will simulate a natural crack well enough to provide a satisfactory fracture toughness test result, a narrow notch from which extends a comparatively short fatigue crack, called the precrack, was generated by fatigue loading as per ASTM E 1820 standard. Side grooves were generated as the compliance method of crack size prediction is used. As it ensures a straight crack front. So the CT specimens were side grooved as per the codal requirement i.e. 10% of the thickness was trimmed on both sides of the specimens on the notch plane.

Numerical Modelling

For accurate estimation of plastic η factor, it was necessary to carry out detailed FE analysis for fracture specimens fabricated from weld joints & base with postulated crack. Since the weld height changes continuously along the specimen thickness hence 2 D half CT models (specimens which are symmetrical about the crack plane) with mean weld height was developed to carry out the analysis.

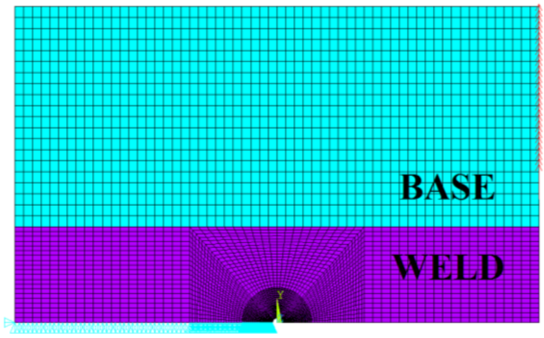


Figure 4: FE Model of CT Specimen

Isotropic strain hardened plastic material model was used for the analyses. The true strain stress curve generated from the tensile tests conducted earlier were used for this purpose. The elastic material properties in all the cases (i.e. base, welds and HAZ) were taken as same. The Elastic Modulus for Al-5154 is 70GPA and the Poissons' ratio is 0.3. The true stress strain curve of welds and HAZ were as shown in Figure 5

Table 2: Elastic properties of Base and Welds

Specimens	**Base**	**Weld 200**	**Weld 260**	**Weld 320**
Elastic Modulus (MPa)	70000	70000	70000	70000
Poissons' Ratio (ν)	0.3	0.3	0.3	0.3
Yield sress (MPa)	109	114	108	116
Ultimate stress (MPa)	231	254	285	278

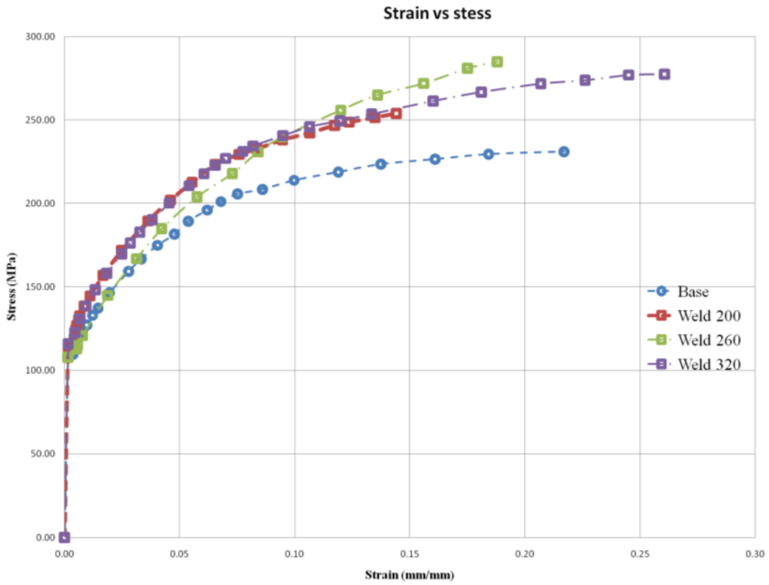


Figure 5: Experimental True Stress Strain Curve

J integral is evaluated using 'path independent line integral method'. The J-integral expression for a two-dimensional crack, in the x-z plane with the crack front parallel to the z axis, is the line integral,

$$J = \int_{\tau} Wdy - T\frac{\partial u}{\partial x}ds \tag{1}$$

where:
W = loading work per unit volume or, for elastic bodies, strain energy density,
τ = path of the integral, that encloses (i.e. contains) the crack tip,
ds = increment of the contour path,
T = outward traction vector on ds,
U = displacement vector at ds,
x, y, z = rectangular coordinates, and
$T\frac{\partial u}{\partial x}ds$ = rate of work input from the stress field into the area enclosed by τ.

After computing the J integral values at different a/W ratio along the pre-developed path for all the specimens plastic eta factor was to be evaluated. Plastic part of J integral was calculated by deducting the elastic part of J (which is directly proportional to square of applied load) from the evaluated J. In order to compute the plastic eta factors for different a/W ratio, plastic area (i.e. area under load vs plastic CMOD curve) was calculated and eta factor was evaluated using Equation (2)

$$\eta_{pl} = \frac{J_{pl} B_N b_0}{A_{pl}} \tag{2}$$

Results & Discussions

The FE analysis of the CT specimens using the tensile properties as generated from the tensile tests are described here. The eta plastic values has been calculated and plotted against the crack length to specimen width ratio. These are shown in Figure 6. As pointed out before by Table 2 that tensile strength of the welds are greater than that of base, it is a clear case of overmatching (M>1), the results fall in line with the conclusion pointed out in Y J Kim et. al (2003). Though the effect of temperature is not clearly marked out by the result.

From the evaluated eta values the fracture resistance curve was generated using ASTM E 1820 i.e. applicable for homogeneous material. These were compared with the fracture resistance curve generated using eta factors obtained from FE analysis. As shown in Figure 7 the fracture resistance curve does not match with the actual evaluated JR curve. Also the eta factor in both the conditions is similar to fracture resistance curve. These results show that ASTM E 1820 can be used only for homogeneous material only and not for inhomogeneous materials as in case of welds.

As seen in Figure 7 initial crack propagation tends to be negative. This cannot be analyzed according to the existing standards. According to ASTM E 1820, one is asked to fit only the data which fall within the exclusion interval. In extreme cases it is possible that some negative crack extension values might be included in the acceptable data points, but ASTM E 1820 method cannot accept negative values for crack extension. This problem is treated by eliminating the negative data points by shifting the resistance curve to a new zero, such as the most negative point. The procedure of the offset technique is as follows. The first step is to plot J vs Δa data and draw a blunting line. In next step is to shift all J versus Δa data along the Δa direction by an amount of distance from the most negative Δa point (Ain Figure 5) to the blunting line. The corrected data points are used for the purpose of curve fitting. Now according to ASTM E 1820 section A9 the exclusion lines, construction lines and limit line were developed. The acceptable data lie within the area between exclusion lines and J limit line. A power law regression line is fitted to the acceptable data and J_Q is determined as shown in Figure 8. According to the code, intersection point of regression line to 0.2mm offset line determines the provisional fracture toughness value which is size dependent.

As shown in Table 3 the provisional J_{IC} values for weld is less than that of base. According to ASTM E 1820 section A9.10 the evaluated J_Q can be qualified as J_{IC} if

a) Thickness, $B > 10J_Q/\sigma_Y$

b) Initial Ligament, $b_0 > 10J_Q/\sigma_Y$

The Table 3 checks if the J_Q values are fit to be J_{IC} (the toughness of a material near the onset of crack extension from a preexisting fatigue crack) . The J_{IC} value marks the beginning stage of material crack growth resistance development, which are size independent values of toughness.

Table 3: J_Q to J_{IC} Qualification

Specimen	**J_Q**	**B**	**b_0**	**$10J_Q/\sigma_Y$**	**Remarks**
Base	128.34	12.5	15	11.77	$B > 10J_Q/\sigma_Y$, $b_0 > 10J_Q/\sigma_Y$, $J_Q=J_{IC}$
Weld 200	59.25	12.5	15	5.19	$B > 10J_Q/\sigma_Y$, $b_0 > 10J_Q/\sigma_Y$, $J_Q=J_{IC}$
Weld 260	52.76	12.5	15	4.88	$B > 10J_Q/\sigma_Y$, $b_0 > 10J_Q/\sigma_Y$, $J_Q=J_{IC}$
Weld 320	52.57	12.5	15	4.53	$B > 10J_Q/\sigma_Y$, $b_0 > 10J_Q/\sigma_Y$, $J_Q=J_{IC}$

As according to Table 3 the J_Q values qualify to be J_{IC} values hence it can be stated that fracture toughness of the non-heat treatable aluminium alloy i.e. Al 5154 is less than that of base irrespective of the specimen size.

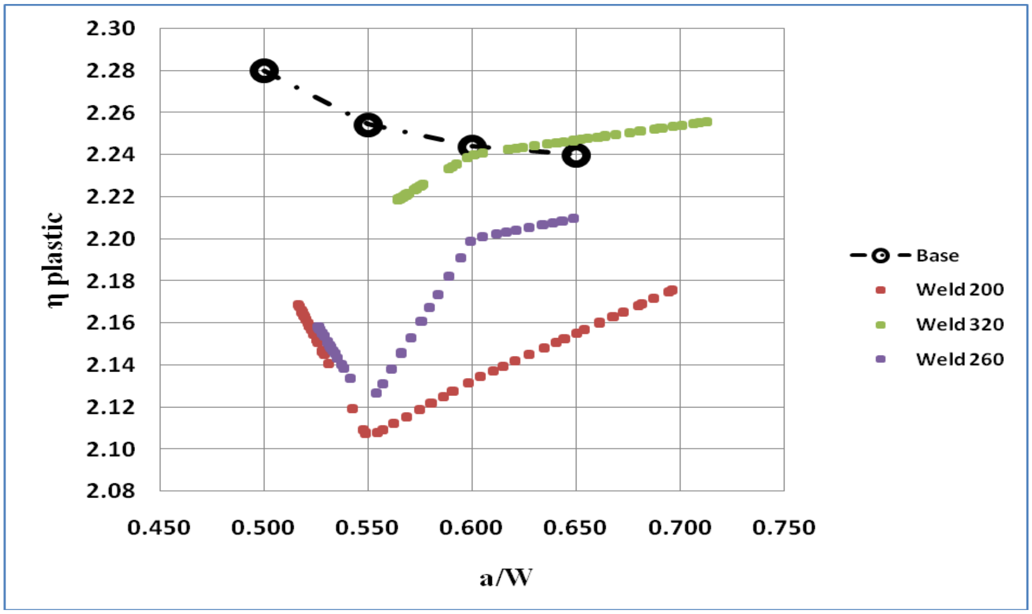
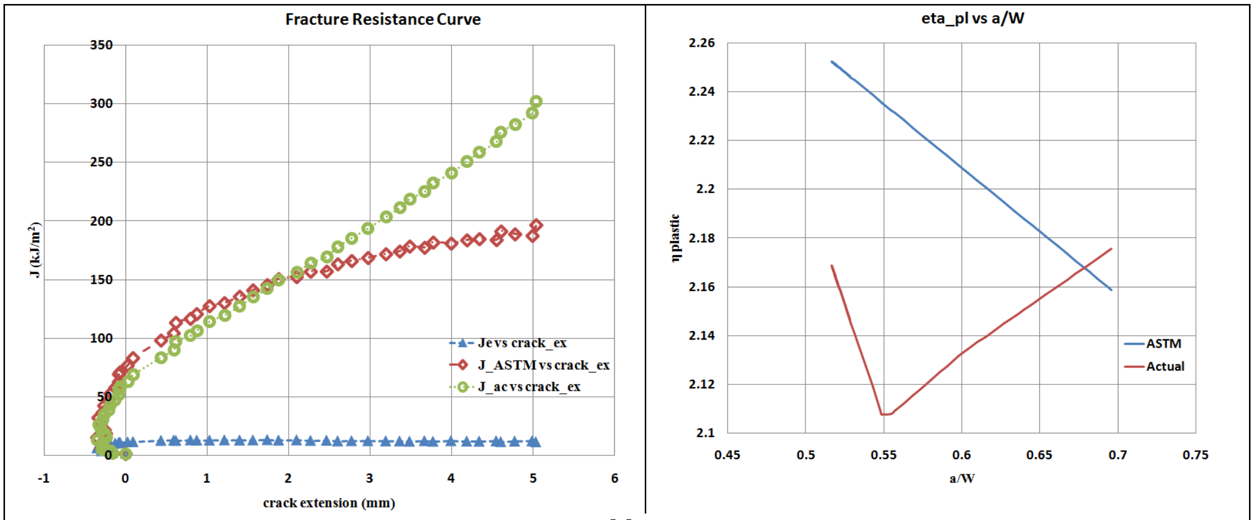


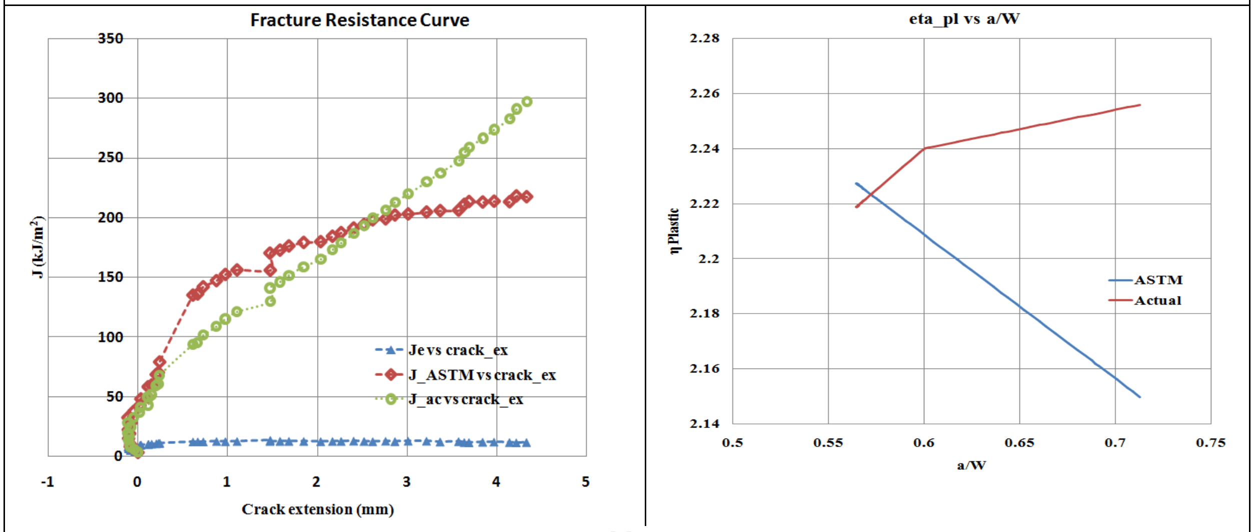
Figure 6: Plastic Eta vs a/W Curve

Conclusion

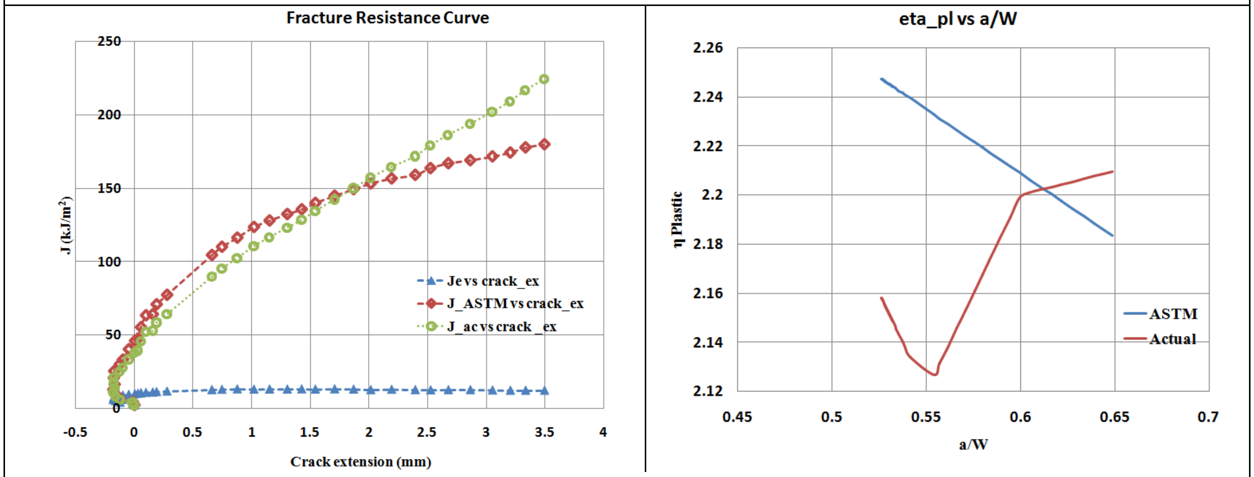
1) There is not much change in plastic eta factor, fracture toughness of welds with change in preheat and interpass temperature.
2) Fracture toughness values decreases for weld with increase in preheat and interpass temperature for Al 5154 alloy.



Weld 200

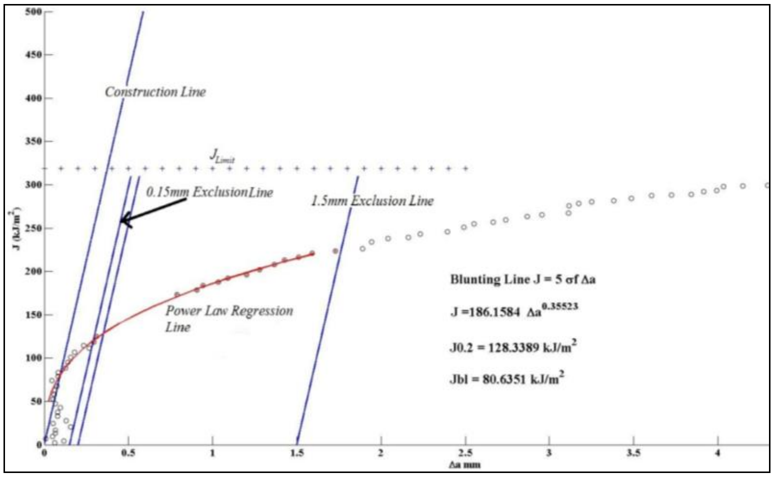


Weld 260

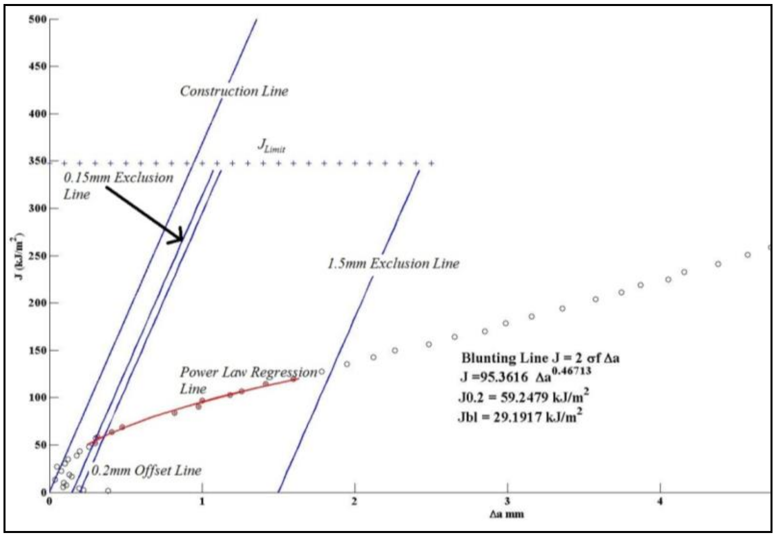


Weld 320

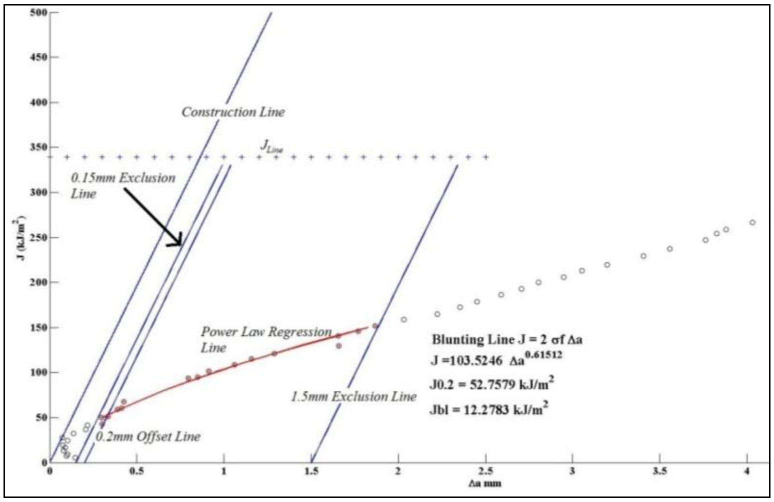
Figure 7: Comparison of ASTM & Actual Curves



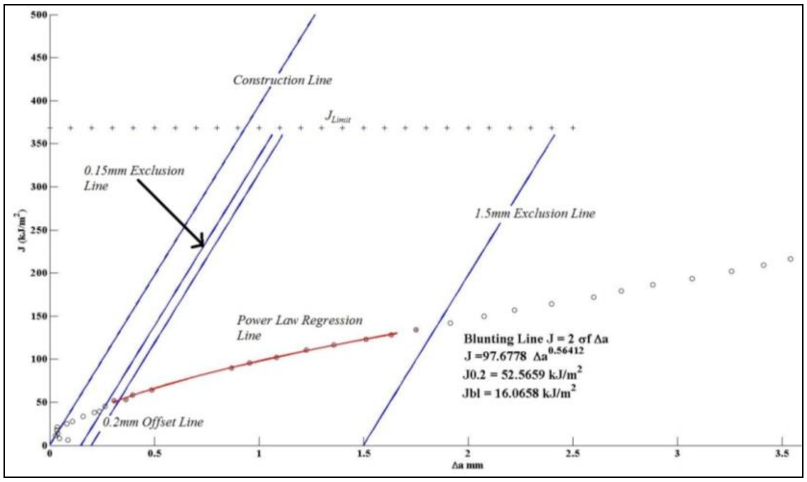
Base
J_Q=128.34 kJ/m^2



Weld 200
J_Q=59.25 kJ/m^2



Weld 260
J_Q=52.76 kJ/m^2



Weld 320
J_Q=52.57 kJ/m^2

Figure 8: J_Q Evaluation according to ASTM E 1820

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