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Welding Residual Stress Analysis of Dissimilar Metal Welds using Proper Generalized Decomposition

Sung-Sik Kang[1],*, Jin-Gyum Kim[1], Changsik Oh[1], Jangho Ahn[2], and Kyeongwook Min[2]

ABSTRACT

Welding residual stress (WRS) in dissimilar metal welds is a critical factor in crack initiation and structural integrity, especially in nuclear power plant components. This study applies the Proper Generalized Decomposition (PGD) method, a model order reduction (MOR) technique, to efficiently analyze WRS while maintaining the accuracy of full finite element analysis (FEA). Using a two-dimensional FEA model of a pressurizer surge nozzle, 112 simulations were conducted based on variations in five welding parameters: input energy, welding speed, inter-pass temperature, yield strength, and strain hardening behavior. PGD post-processing was performed via the ADMORE platform, enabling real-time visualization and sensitivity analysis across the parameter space. The results showed strong agreement between PGD and FEA outputs. Sensitivity analysis identified the strain hardening ratio and inter-pass temperature as dominant factors influencing WRS. The study confirms the effectiveness of PGD for accurate, rapid, and interpretable residual stress analysis, with strong potential for use in design evaluation and regulatory assessment of welded components.

INTRODUCTION

Welding residual stress (WRS) in dissimilar metal welds of components and piping is a key contributor to crack initiation, particularly in safety-critical systems such as nuclear power plants. An accurate assessment of WRS is essential, as it plays a significant role in the structural integrity of welded joints and directly affects the susceptibility to stress corrosion cracking (SCC). However, the experimental evaluation of WRS remains challenging due to inconsistencies in measurement techniques and significant variability in the resulting data.

As a result, computational approaches—particularly finite element analysis (FEA)—have been increasingly adopted as practical and reliable alternatives for WRS prediction. To further improve computational efficiency and enable rapid parametric studies, this study employs the Proper Generalized Decomposition (PGD) method (2011), an advanced model order reduction (MOR) technique capable of efficiently solving high-dimensional problems. Unlike conventional FEA, which requires repeated full-scale simulations for each parameter variation, PGD constructs a generalized solution space through variable separation, allowing for real-time evaluation of WRS under varying input conditions. This approach significantly reduces computational cost while preserving accuracy, making it highly suitable for sensitivity analysis and early-stage design assessments.

In this study, thermo-mechanical simulations were conducted using SYSWELD (ESI Group), and PGD-based post-processing was performed on the results using the ADMORE platform. The proposed

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[1] Korea Institute of Nuclear Safety, Daejeon, Republic of Korea
[2] ESI group, Seoul, Republic of Korea
* Corresponding author: sskang@kins.re.kr

framework enables efficient, scalable analysis of residual stress under a wide range of parametric conditions, providing valuable insights into the influence of welding parameters on WRS development.

Importantly, this approach offers practical advantages not only for designers and analysts but also for regulatory and technical authorities who are responsible for reviewing and validating industry-provided simulation results. The ability to generate WRS evaluations efficiently and to compare alternative parameter sets in a structured, interpretable manner enhances transparency and reliability in the verification process, thereby supporting regulatory confidence and decision-making.

METHODS

Model order reduction (MOR) techniques aim to reduce the computational complexity of high-fidelity numerical simulations while maintaining sufficient accuracy. Among these, the Proper Generalized Decomposition (PGD) method stands out as a powerful a priori MOR technique that utilizes a variable separation strategy. This approach decomposes high-dimensional problems into a series of low-dimensional functions, each dependent on a single variable, thereby enabling efficient computation and scalability.

$$U(\boldsymbol{x}, t; M_1, \dots, M_m, G_1, \dots, G_g, L_1, \dots, L_l) \approx \sum_{i=1}^{N} \boldsymbol{X}_i(\boldsymbol{x}) \cdot \boldsymbol{T}_i(\boldsymbol{t}) \cdot \boldsymbol{M}_i(\boldsymbol{m}) \cdot \boldsymbol{G}_i(\boldsymbol{g}) \cdot \boldsymbol{L}_i(\boldsymbol{l}) \quad (1)$$

The benchmark model employed in this study is based on the dissimilar metal weld (DMW) configuration of the pressurizer surge nozzle, as described in the U.S. Nuclear Regulatory Commission (NRC) guideline for welding residual stress analysis (2021). The geometry and mesh design of the finite element (FE) model are shown in Fig. 1, representing the actual welded joint with appropriate simplifications for numerical simulation.

Material types assigned to each section of the model, including the stainless steel pipe, nickel-based weld metal, and carbon steel nozzle, are listed in Table 1. These materials were selected to reflect the typical DMW configuration in nuclear power plant components.

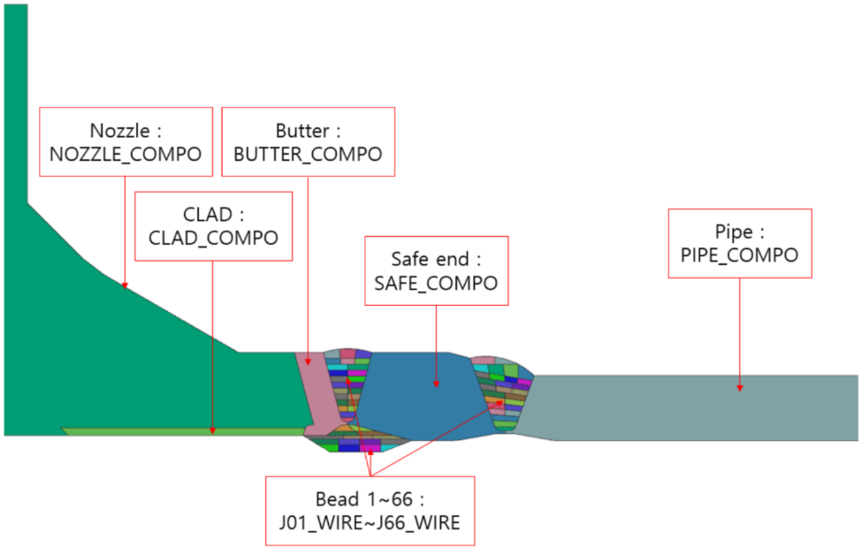


Figure 1. Two-dimensional finite element modeling of the target component

Table 1: Material specifications for each part of modeling

Part	Material Type
Clad	TP316L
Safe end	TP316L
Pipe	TP316L
Nozzle	SA182
Buttering	Inconel Alloy 82
Bead 1 ~24	Inconel Alloy 82
Bead 25 ~ 39	Inconel Alloy 82
Bead 40 ~66	TP316L

Five key parameters were selected for the sensitivity analysis based on design drawings and the welding procedure specification (WPS): input energy (current × voltage), welding speed, inter-pass temperature, yield strength of the stainless steel base material, and the strain hardening model. The applied range for each parameter is summarized in Table 2, representing realistic variations typically observed in industrial welding applications.

In particular, the variation in yield strength was introduced to evaluate the sensitivity of welding residual stress (WRS) to material property deviations. Based on the nominal value from the WPS, yield strength was varied from 70% to 130% to reflect possible deviations due to manufacturing tolerances, material heat treatment, or aging effects.

The strain hardening behavior was also included as a critical parameter to examine its influence on residual stress development. Three types of hardening models were considered: kinematic, isotropic, and a mixed model. In SYSWELD, this is controlled via an internal parameter where a value of 0 corresponds to a fully kinematic hardening model, and a value of 1 represents a fully isotropic model. Intermediate values between 0 and 1 define a mixed hardening model, allowing for flexible calibration based on experimental data or engineering estimates. This enables the investigation of how different assumptions regarding the material's plastic response affect the predicted residual stress field.

Thermal–mechanical finite element simulations incorporating these parameter variations were performed using SYSWELD. The resulting residual stress data were then processed with the Proper Generalized Decomposition (PGD) method via the ADMORE platform to construct a reduced-order parametric solution. This allowed for efficient exploration of the multidimensional input space and provided insights into the individual and combined effects of welding parameters on WRS.

Table 2: Defined value ranges for the five key welding parameters

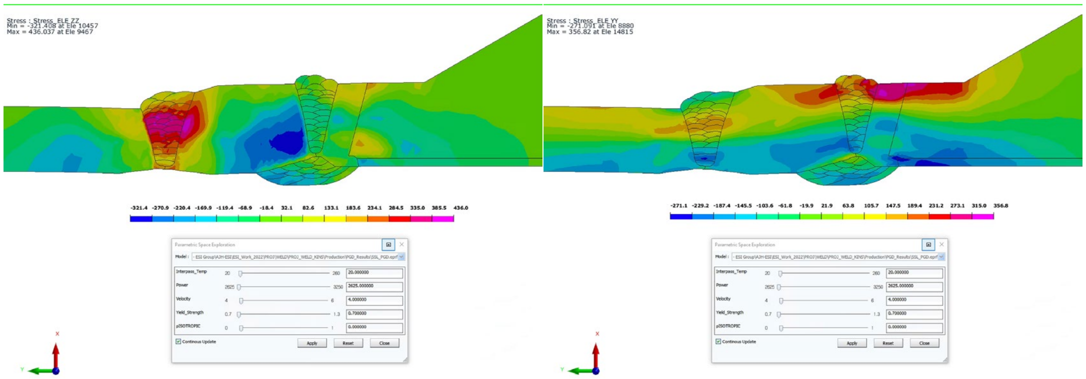
Parameter	Range of input value
Input energy	2625 W ~ 3250 W
Welding speed	4 ipm ~ 6 ipm
Inter-pass temperature	20°C ~ 260°C
Yield strength of stainless steel	70% ~ 130%
Ratio of stain hardening model	0 (fully kinematic) ~ 1 (fully isotropic)

RESULTS AND CONCLUSIONS

The comparison between results obtained using the Proper Generalized Decomposition (PGD) method and those from full finite element analysis (FEA) demonstrated a high level of agreement, confirming the validity, accuracy, and robustness of the PGD-based modeling framework. This reduced-order modeling approach effectively captured the essential characteristics of welding residual stress (WRS) distributions while significantly reducing computational cost.

In this study, Sparse Subspace Learning (SSL)-based PGD (2019) was adopted, and 112 FEA simulations were generated using a design of experiments (DOE) framework to construct the PGD solution space. The PGD interface allows for real-time manipulation of key parameters through interactive scroll bars, enabling users to instantly observe corresponding changes in residual stress profiles. This interactive capability facilitates rapid parametric sensitivity analysis, supporting both early-stage design evaluations and regulatory reviews.

Overall, the PGD method not only reproduced the FEA results with high fidelity but also enabled fast and accurate identification of key parameter effects across the design space. The model accurately captured transitional behavior near mid-range parameter values, offering enhanced interpretability. These findings demonstrate the high potential of PGD for practical use in process optimization, structural integrity evaluations, and regulatory validation for dissimilar metal welds.



Model : - ESI Group\AJH-ESI\ESI_Work_2022\PROJ\WELD\PROJ_WELD_KINS\Production\PGD_Results\SSL_PGD.eprf

Interpass_Temp	20	260	20.000000
Power	2625	3250	2625.000000
Velocity	4	6	4.000000
Yield_Strength	0.7	1.3	0.700000
pISOTROPIC	0	1	0.000000

☑ Continous Update

Figure 2. Axial and hoop stress distributions obtained from PGD analysis with five varying parameters (hoop stress: left, axial stress: right)

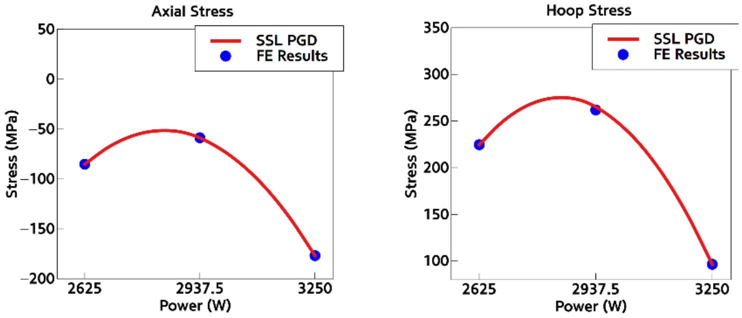
To investigate the influence of welding parameters on WRS, both FEA and PGD simulations were conducted for five parameters: input energy, welding speed, inter-pass temperature, yield strength, and strain hardening behavior. Figure 3 presents the comparative residual stress distributions from both methods, demonstrating consistently close agreement across all parameters.

In the case of input energy, residual stress increased with power level; however, the highest stress was unexpectedly observed at the mid-level value (2937.5 W). This result suggests potential nonlinearities or interactions, though further investigation is required. For now, the focus of this study remains on the consistency between PGD and FEA results.

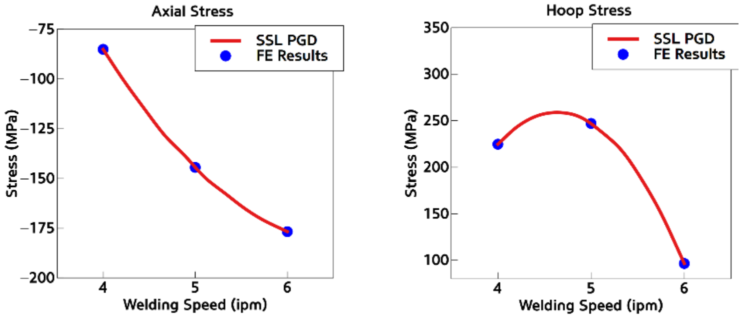
As welding speed increased, residual stress generally decreased due to reduced heat input. However, in hoop stress, the highest stress appeared at the mid-range value of 5 ipm. Again, PGD closely matched FEA predictions, confirming its robustness even in non-monotonic conditions.

Regarding inter-pass temperature, both axial and hoop stress predictions from PGD and FEA aligned closely across the entire range. Similarly, for yield strength, the results remained consistent between the two methods. One minor discrepancy was observed in hoop stress at the upper end of the range (130%), where PGD slightly diverged from the FEA prediction, potentially due to nonlinear mechanical behavior at high strength levels.

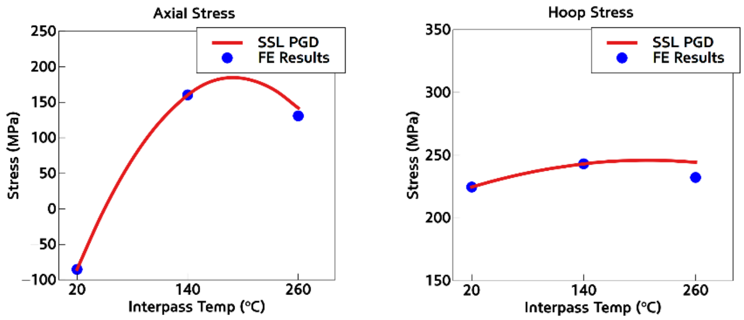
For strain hardening behavior, residual stress distributions varied according to the selected hardening model. In axial stress, the fully isotropic model produced the highest residual stress, whereas for hoop stress, the fully kinematic model yielded the largest value. Slight differences between PGD and FEA predictions were noted, particularly under mixed-model conditions, indicating that stress predictions are sensitive to plastic deformation history modeling.



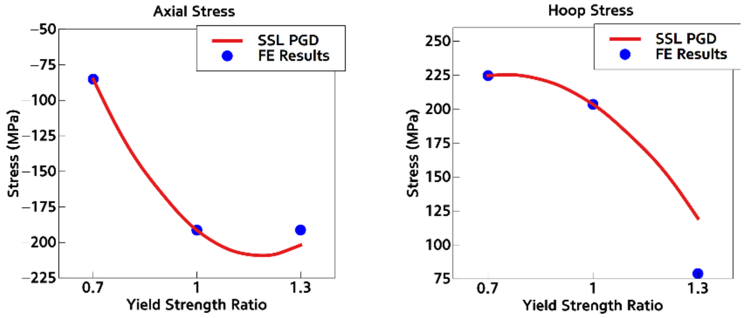
(a) Change in residual stress as a function of input energy



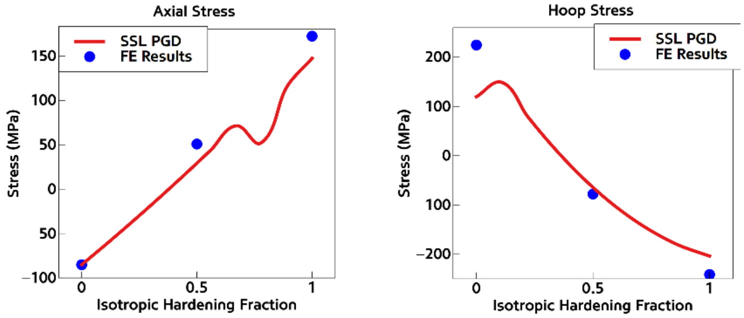
(b) Change in residual stress as a function of welding speed



(c) Change in residual stress as a function of inter-pass temperature



(d) Change in residual stress as a function of yield strength of stainless steel



(e) Change in residual stress as a function of ratio of strain hardening

Figure 3. Comparison of residual stress predictions using PGD and finite element (FE) methods under the influence of five varying parameters

A comprehensive sensitivity analysis based on PGD (shown in Figure 4) revealed the following insights:

- For axial stress, inter-pass temperature and strain hardening ratio had the most significant influence.
- For hoop stress, the strain hardening ratio was identified as the dominant factor.

Among all five parameters, the strain hardening model emerged as the most influential in capturing WRS variability—highlighting its importance in modeling applications where plastic strain history plays a significant role.

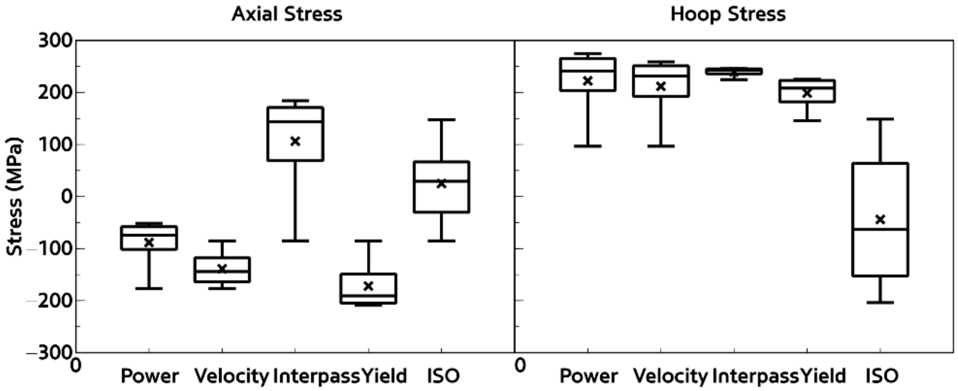


Figure 4. Results of residual stress sensitivity analysis considering variations in five input parameters

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