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Effects of Heat Input and Bead Generation Methods on Finite Element Analysis of Multi-Pass Welding Process

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1. Introduction

Welding residual stresses are determined by various factors such as heat input, initial temperature of molten bead, heating time, cooling time, cooling conditions, and boundary conditions(1). In this study, a sensitivity analysis was performed to find the major factors and reasonable assumptions for simulation.

Two-dimensional axisymmetric simulation was conducted by using commercial finite element analysis program ABAQUS(2), for multi-pass Alloy 82 welds in a 304 Stainless Steel and SA-105 Carbon Steel (EPRI MRP-316 report(3), phase 1, C-3).

2. Finite Element Analysis Model and Process

2.1. Modeling and properties

A cylindrical model(phase 1, C-3) introduced in EPRI MRP-316 and NUREG-2162 report(4) was chosen for a finite element thermal-structure analysis. Fig. 1 shows the feature of whole model. Properties of materials were taken from MRP-317 report appendix A(5). Two dimensional planar element(DC2D4) used in thermal analysis and axisymmetric element(CAX4R) was used in structural analysis.

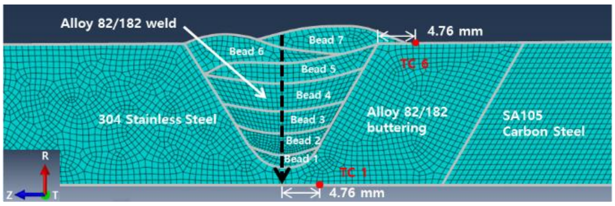


Fig. 1. Axisymmetric FE model of the cylinder

2.2. Thermal analysis

By using "model change" option in ABAQUS, all of welds were stacked sequentially on pre-deposited welds in thermal analysis.

The major factors determining cooling rates of welds are material's thermal conductivity, convective heat transfer coefficient and radiant heat transfer coefficient.

Following equation 1(6) shows the bilinear relationship of convective heat transfer coefficient and surface temperature. This equation represents combined boundary conditions(h, convective heat transfer coefficient) of weld and air for natural convection and radiation.

$$h\,(W/m^2\cdot ℃) = \begin{cases} 0.0688\,T & for\;\; 0 \le T \le 500\ ℃ \\ 0.231\,T - 82.1 & for\;\; 0 \le T \le 500\ ℃ \end{cases} \qquad (1)$$

2.2.1. Flux method

There are two heat input method applying heat to welds. The first one is flux method(6,7,8) which is simulated by applying power density(q, J/s/mm^3) into the weld according to the following equation (2)(3). Power density decreases exponentially to the time (about 30 sec).

$$q = \begin{cases} Ke^{-\frac{st^2}{a^2}} \quad \left(K = \sqrt{\frac{3}{\Pi}}\cdot\frac{EVA}{A_w}, a = \frac{L}{S}\right) \end{cases} \qquad (2)$$

where, q = power density(J/s/mm^3), t = time from start of weld(sec), L = characteristic length(mm), S = torch travel speed(mm/s), E = scaling coefficient, V · A = welding power (J/s), A_w = weld volume(mm^3).

Table 1 shows welding variables for flux method. Amount of power density were calculated by considering these variables which were taken from the MRP-317 report(5) or assumed. Especially, scaling coefficients were determined by considering practically measured temperature history in specific thermocouples during the welding process.

Table 1: Welding variables for flux method

Bead number	Aw (mm^3)	E	V·A (J/s)(3)	L(mm)	S(mm/s)
1	127.25	1.725	1649	50.8	25.4
2	297.43	1.4	1739		
3	494.28	1.38	2256		
4	605.03	1.05	3135		
5	530.86	1.27			
6	484.12	1.21			
7	439.17	0.92			

2.2.2. Temperature method

Second one is temperature method(8) which sets up the melting point (about 1345 ℃) and holds the temperature (about 1800 ℃) until the transient energy spread to the surroundings is equal to the required weld heat input.

In Table 2, heating times were also determined by considering practically measured temperature history.

Table 2: Welding variables for temperature method

Bead number	Initial temperature(℃)	Heating time(sec)
1	1800	4.2
2		1.3
3		1.6
4		2.1
5		2.8
6		4.1
7		3.0

2.2.3. Thermal analysis conditions

Table 3 shows the conditions of welding process simulation for thermal analysis. Excluding initial temperature of base metals and welds and heating time, other conditions are the same.

Table 3: The conditions of welding process simulation for thermal analysis

Heat input method	Flux method	Temperature method
Initial temperature of base metals	21 ℃	21 ℃
Initial temperature of welds	21 ℃	1800 ℃
Heating time	50 sec	1.3 ~ 4.2 sec
Cooling time	10^4 sec	
Pass sequence	See Fig. 1 (Element birth technique was used)	
Thermal boundary condition	See equation 1	
Element type	DC2D4	

2.3. Stress analysis

By performing a sequentially coupled temperature-stress analysis(8), the temperature history from the thermal analysis is read for each time step increment.

2.3.1. Element birth technique.

There are two methods to generate welds. First, the element birth technique(6,9) is to deposit weld elements sequentially by using “model change” option of ABAQUS in mechanical analysis. This method is typical to simulate welding process. However, weld elements could be overlapped by thermal expansion and shrink. Boundaries of previous weld elements and next weld elements could be distorted.

2.3.2. Quiet element technique.

Second, quiet element technique(6,9,10) is to deactivate all of the initial weld elements at temperature higher than melting point and activate weld elements sequentially by applying realistic temperature. Since elements have a low stiffness, a very low yield stress and thermal strain free at high temperature, effects of deactivated element behavior are minimized. Although quiet element technique could avoid weld elements overlapping problem, unnecessary computational resource waste happens.

2.3.3. Stress analysis conditions

Table 4 shows the conditions of welding process simulation for mechanical analysis. Most of conditions are the same to compare effects of weld bead generation method. Minimized constraint was assigned, geometry non-linearity wasn’t considered and annealing effect was considered at materials melting point.

Table 4: The conditions of welding process simulation for stress analysis

Weld bead generation method	Element birth technique	Quiet element technique
Element type	CAX4R	
Constraint conditions	One of the sides was fixed (vertical cross section to Z-axis direction)	
Material hardening behavior	Isotropic hardening material	
Geometry non-linearity	Nlgeom option OFF	
Annealing effect	Plastic strain is erased at the melting point($T_{m,\ alloy\ 82}$ = 1345 ℃, $T_{m,\ 304\ S.S,\ 105C.S}$ = 1500 ℃)	

3. Results

Estimated residual stresses have been extracted from top of the weld to bottom (along the black line, see Fig. 1) and plotted on following graphs. The result of EPRI MRP-316 estimated with similar boundary conditions was also plotted as reference. Although analysis conditions were a little different, tendency of weld residual stress was similar.

3.1. Comparison of heat input methods and weld bead generation methods

Fig. 2 shows the comparison of the HAZ(heat affected zone) at maximum temperature after weld bead 1 and 6 were deposited respectively(flux method and temperature method was used). There are non-negligible differences in HAZ depending on heat input method.

Temperature method has broader HAZ than flux method. Therefore, giving the proper heat energy into the individual bead is needed to perform the more practical thermal analysis. Comparing FEA Model A, C and B, D respectively in Fig. 3, effects of heat input method on weld residual stress could be found.

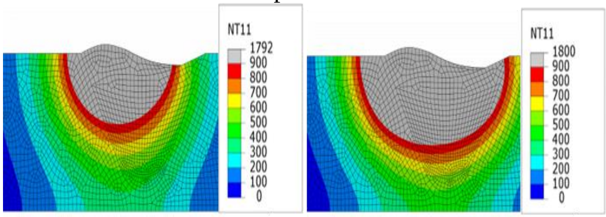
Although welding residual stresses are different in center of welds, welding residual stress distributions have similar trends roughly.

Comparing FEA Model A, B and C, D respectively in Fig. 3, effects of weld bead generation method on weld residual stress could be found. The vertical dashed-line represents initial depth of total welds (about 12.77 mm).

Depth of total welds were increased in all of FEA models by thermal expansion, shrink and bending of welds and base metals during the welding process. When element birth technique was used, depths of total weld are deeper than quiet element technique was used.

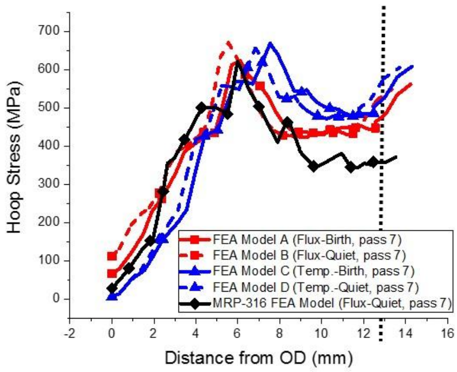
Fig. 4 shows residual stress contour of FEA models. There are differences of welding residual stress distribution in weld zone depending on heat input methods. However, welding residual stress of weld zone depends on beat generation methods.

It seems that gaps and overlaps were happened on distorted boundaries in case of the element birth technique. These gaps and overlaps caused undesirable increases of total weld depths.

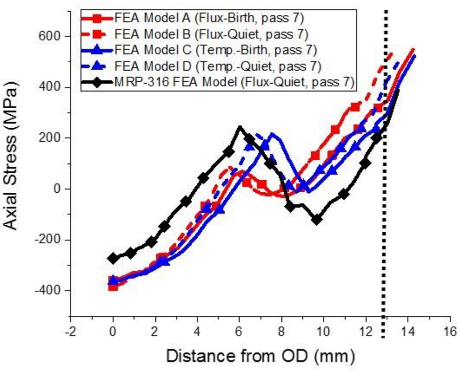


(a) (b)

Fig. 2. Comparison of the HAZ when flux method and temperature method was used respectively. (a) flux method (b) temperature method

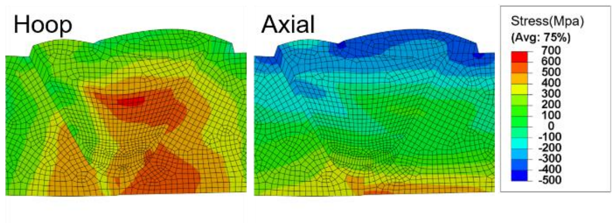


(a)

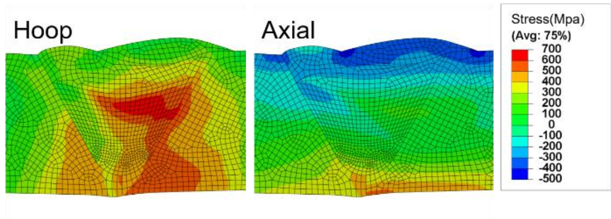


(b)

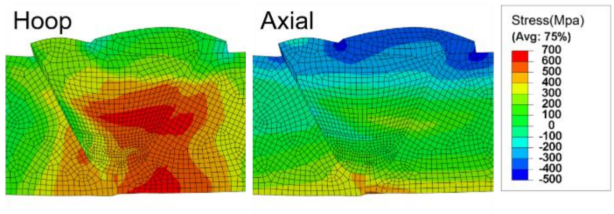
Fig. 3. Residual stress distribution along the weld thickness. (a) hoop and (b) axial stress



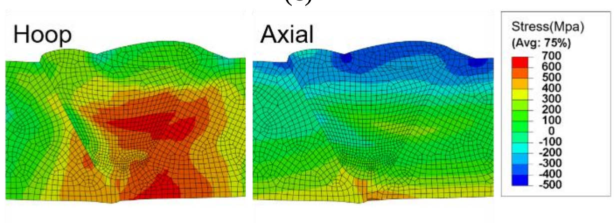
(a)



(b)



(c)



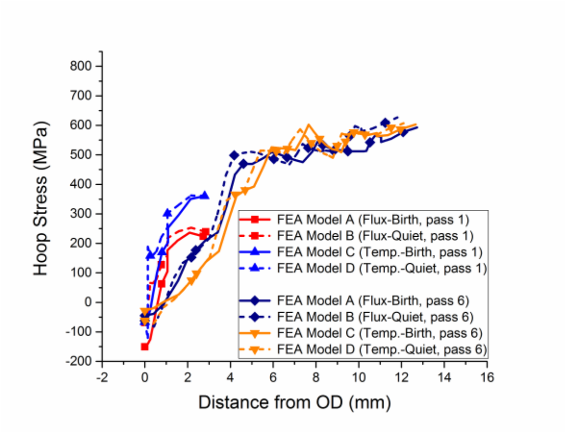
(d)

Fig. 4. Residual stress contour (left: hoop, right: axial). (a) FEA Model A(Flux-Birth) (b) FEA Model A(Flux-Quiet) (c) FEA Model A(Temperature-Birth)) (d) FEA Model A(Temperature-Quiet)

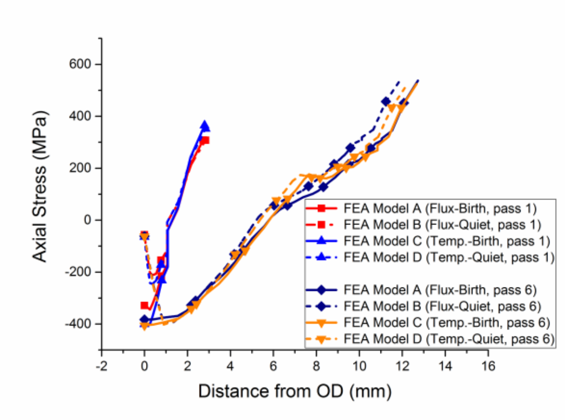
3.2. Verification of quiet element technique

Fig. 5 shows residual stress distributions as soon as pass 1 and pass 6 were deposited respectively.

In FEA Model B and D, axial stresses were high on the top of weld bead(0 ~ 1 mm). It seems that existence of inactive bead elements caused inaccurate weld residual stresses in boundaries of previous weld elements and next weld elements in case of quiet element technique. However, except for final weld bead, undesirable residual stresses were eliminated due to the annealing effect during the next weld beads were deposited. Fig. 3 shows that the final residual stress distributions are similar after final weld bead was deposited.



(a)



(b)

Fig. 5. Residual stress distribution along the weld thickness according to heating method and weld bead generation technique when pass 1 and pass 6 are deposited respectively. (a) hoop and (b) axial residual stress

4. Conclusions

The major object is to evaluate effects of the heat input methods and weld bead generation methods on the welding residual stress distribution. Totally four kinds of methods were compared. From the previous results, we could make the following conclusions.

1. Although there are non-negligible differences in HAZ depending on heat input method, welding residual stress distributions have roughly similar trends. However, it is needed to perform the more exact analysis to apply heat energy more carefully into the individual bead.

2. Residual stress distribution were similar for the two weld bead generation technique. However, overlapping was happened when element birth technique was applied. Effects of overlapping could not ignore as deformation increases. However, overlapping problem was avoided when quiet element technique was used.

3. Since existence of inactive bead elements, inaccurate weld residual stresses could be occurred in boundaries of previous and next weld elements in case of quiet element technique. However, these effects disappeared in most of weld beads except for final weld bead due to the annealing effect caused by next beads.

4. Therefore, comparing results of each bead generation technique could compensate the overlapping problem for estimating welding residuals stress more practically.

Acknowledgements

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