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Numerical Study of Welding with Trailing Heat Sink Considering Phase Transformation Effects

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Abstract: Welding process with trailing heat sink for 2 mm mild steel plates has been analyzed to estimate distortion and residual stresses using a finite element modeling software Sysweld. The material properties used for the analysis are both temperature dependent and phase dependent. A transient thermal analysis is carried out using Goldak double ellipsoidal heat source model and heat sink as Gaussian model with negative heat flux. The finite element analysis (FEA) is conducted by considering the material properties of all phases of steel as well as without phase transformation i.e. by considering properties of only ferrite phase. Temperature distribution, distortion and residual stresses are calculated and compared for four cases: without phase without cooling, without phase with cooling, with phase without cooling and with phase with cooling. It is found that FEA without phase transformation effects overestimates the residual stresses in the fusion zone (FZ) and heat affected zone (HAZ). It is also found that a trailing heat sink reduces transverse compressive residual stresses thus minimizing the possibilities of buckling.

Introduction

Welding is an important metal joining process widely used in the fabrication of structures. The large temperature gradients produced due to high energy arc results into distortion and residual stresses in the structure. Finite element analysis aids in calculation of distortion and residual stresses which helps in deciding various design and fabrication parameters of welding process. Many researchers have worked and still working in this field for the past four decades. Earlier works involved simplified models, but with reduction of computation cost, many process complexities are being incorporated to make more realistic models. Also various process scenarios, sequence and technique are tried out which would reduce the distortion and residual stresses. One such technique studied in this work is trailing heat sink. For a complex process such as welding, temperature dependent material properties are used as the temperature of material during welding varies from room temperature to melting temperature. When the material under study is steel, it also undergoes phase changes where properties may be different from the parent phase. Therefore in this study the welding process is numerically simulated with and without trailing heat sink and with and without phase transformations. The numerical results are validated with published experimental values.

Soul and Yanhua [1] conducted numerical studies to investigate the temperature distribution, distortion and residual stresses in conventional arc welding and after enhancement with a trailing heat sink. The studies showed that trailing heat sink reduces residual stresses and minimizes distortion in thin plates. Li et al. [2] studied temperature field in TIG welding both numerically and experimentally for titanium alloy using conventional welding and modified process in which trailing heat sink is introduced to control residual stresses and distortion. van der Aa et al. [3] found that active cooling in the form of trailing heat sink reduces the negative transverse stresses below critical buckling stress and hence eliminates the buckling distortion. Zhang et al. [4] compared the calculated residual stresses with and without phase transformation effects and showed that values calculated by considering phase transformation matched better with experimentally measured stresses. Warren et

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al. [5] showed that inclusion of phase transformation significantly affects the predicted residual stresses in ferritic materials in the area close to weld zone and not so pronounced in the area adjacent to HAZ . Sudheesh and Siva Prasad [6] studied effectiveness of liquid nitrogen jet as trailing heat sink on different types of steels. They also used inverse heat transfer technique to estimate the cooling parameters of the heat sink. Their experimental values are used in this work to validate the FEA results. In the present work, both phase transformation effects and trailing heat sink have been numerically simulated and calculated values are compared with conventional welding.

Finite Element Model

The distortion and residual stresses in the welded joint are calculated by uncoupled thermo -metallurgical and elasto-plastic finite element analysis. A three dimensional finite element model for two steel plates of dimension 300 x 75 x 2 mm is modeled and meshed using Sysweld software. The geometry is meshed such that it has fine mesh in the fusion zone and HAZ and coarse mesh away from HAZ as shown in Fig. 1. Minimum of four elements are created in the estimated molten pool size of 4 mm i.e. with element edge length of 1 mm along welding direction and 0.5 mm along the thickness. Area element are created on the surface for the convective heat transfer between plate and surrounding. The temperature and phase dependent material properties for the material under consideration (mild steel) is assigned from the material database available with the Sysweld. The analysis where phase transformation effects are neglected, the properties of only ferritic phase are used. The moving heat source is modeled using Goldak et al. [7] double ellipsoidal model whose parameters are calibrated after studying the size and shape of molten pool. The cooling flux is modeled using Gaussian distribution is applied to the thermal model at a fixed distance behind the weld arc. The cooling flux is assumed using trial and error so as to match with the experimental temperature profile.
The governing differential equation for heat conduction is given in Eqn.(1).

$$\frac{\partial}{\partial(x)}\left[k_x\frac{\partial T}{\partial x}\right]+\frac{\partial}{\partial(y)}\left[k_y\frac{\partial T}{\partial y}\right]+\frac{\partial}{\partial(z)}\left[k_z\frac{\partial T}{\partial z}\right]+q_{sup}=\rho c\frac{\partial T}{\partial t} \quad (1)$$

In addition to heat source and trailing heat sink which are moving boundary conditions, the initial nodal temperature is taken as ambient temperature and convective heat transfer is applied over the entire outer boundary of the model.

Phase Transformation: The solid state phase transformation effects are considered by including the phase dependent material properties as well as phase transformation kinetic models. The diffusion based phase transformations such as austenite to bainite are modeled using Leblond model (Eqn. 2). The diffusion less transformation such as austenite to martensite is modeled using Koinstinen Marburger (KM) model (Eqn. 3). The material is assumed to have four phases : Ferrite (initial phase), bainite, martensite and austenite. The transformation of phases take place as follows: Heating: Ferrite to austenite Cooling: Austenite to ferrite or bainite or martensite depending upon the cooling rate.

$$\frac{dP(T)}{dt}=f(\dot{T})\frac{P_{eq}(T)-P(T)}{\tau(T)} \quad (2)$$

$$P(T)=1-\exp(-b(M_s-T) \quad (3)$$

The phase dependent properties are mixed based on the computed phase proportion. To determine the parameters of the law of Leblond for the phase transformations, the data must be extracted from the continuous cooling transformation (CCT) diagram. The computed CCT diagram is fitted using t_{8-5} cooling rate i.e. time required to cool from 800 ^{o}C to 500 ^{o}C temperature for each cooling curve. The end temperature of the ferrite/pearlite transformation should be the start temperature of the bainite transformation and so on. A suitable start and end temperatures for each phase transformation is

assumed based on the CCT diagram. Phase proportions are controlled by predefined kinetics and the differential equation is integrated over time during the computation.
When the base metal is heated above 730 ^{o}C the body centered cubic (BCC) structure of ferrite transforms to face centered cubic (FCC) structure of austenite and the volume decreases, whereas during cooling FCC structure of austenite transforms to BCC structure of bainite/ferrite or BCT structure of martensite and hence volume increases.

Mechanical Analysis: It uses a transient nodal temperature values from thermal analysis as input. Material properties considered for structural analysis are Young's modulus, Poisson's ratio, thermal strain, yield stress and strain hardening values. The elasto-plastic analysis is performed assuming strain hardening behavior as isotropic hardening and considering the large displacement theory. The mechanical constraints imposed on the model are minimum, just to avoid rigid body motion and allow free deformation during welding. The influence of thermal history on the mechanical results is computed by simultaneously considering variations of mechanical properties with temperature and thermal expansion or contraction due to phase transformation. There is significant influence of metallurgical structure and phase proportions on the mechanical properties. Especially, yield strength which is calculated as an average of the yield strength of the individual phases, with a law of linear weighting in the case of fully ferritic mixture [8], and a law of nonlinear weighting as a function of the proportion of phases is used for austeno-ferritic mixture.
Two sets of thermal strains for ferritic and austenitic phase are estimated using dilatometric tests. In addition to different thermal strains, transformation plasticity which relates the difference of volume between the various phases is included. It is the occurrence of plastic flow of weaker phase in the presence of stronger phase even when external stress is absent. Hence the total strain would be sum of elastic, plastic, thermal and transformation plasticity strains.

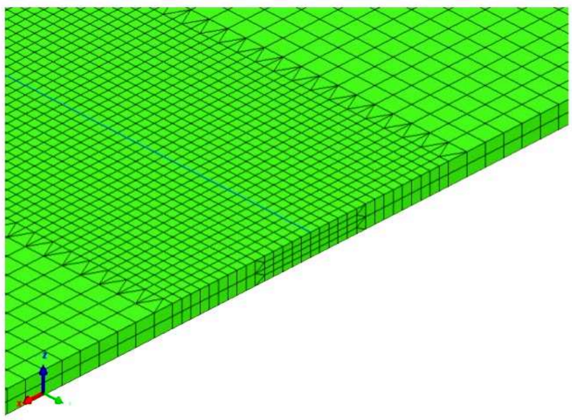

Figure 1: Meshed Model

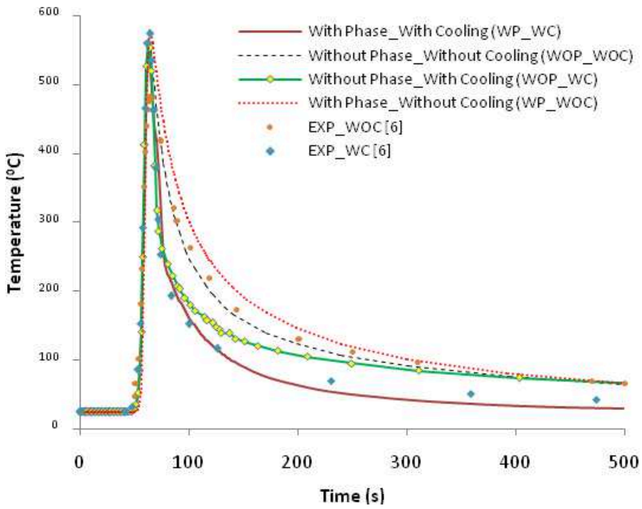

Figure 2: Temperature Distribution Over Time

Results and discussion

Figure 2 shows the temperature distribution at a point 5 mm away from weldline plotted with respect to the simulation time. The graph is plotted for four simulation cases with phase (WP) and without phase transformation (WOP) and with cooling (WC) and without trailing heat sink (WOC). The analysis without phase transformation is carried out by considering material properties of only ferritic phase. Two sets of experimental values with and without cooling from the literature [6] are also plotted for comparison. Since metallurgical changes have little or no influence on the thermal profiles, very small variation between with and without phase transformation cases can be observed. Figure 3 shows the maximum bainite and martensite phase proportions in the FZ and HAZ at the end of simulation time. The increased martensite proportion can be observed for the with cooling case.

Figure 4 shows the out of plane distortion (in z-direction) plotted along longitudinal direction, for all four simulation cases and two experimental cases. The graphs clearly show that the simulation results with phase transformation considerations are closer to the experimental values. The distortion with cooling, show reduction in 0.48 mm i.e. 4.4% for without phase transformation and 2.53 mm i.e. 22.1% for with phase transformation. This indicates that the trailing heat sink has predominant effect on the material which undergoes phase transformation. The mismatch between experimental and FEA results may be attributed to the lack of precise phase dependent material properties. Figure 5 shows longitudinal residual stresses measured at mid-section in the transverse direction. The FEA values with phase transformation in the FZ and HAZ are lesser compared to the without phase transformation. This is due to the development of martensite in this region. The residual stresses are little relaxed due to volumetric increase of martensitic transformation and hence its calculated values are less when compared to the FEA values without phase transformation. Due to the trailing heat sink the stress levels have decreased in the farther region but there is little increase in the nearby region. The transverse residual stresses for all four cases are plotted as shown in Fig. 6. In the FEA results without phase transformation there is little or no difference between with and without cooling cases. But when phase transformation effects are considered the maximum compressive stresses have decreased from 187.59 MPa to 155.22 MPa. This decrease is significant as it reduces the chances of buckling in the welded plates.

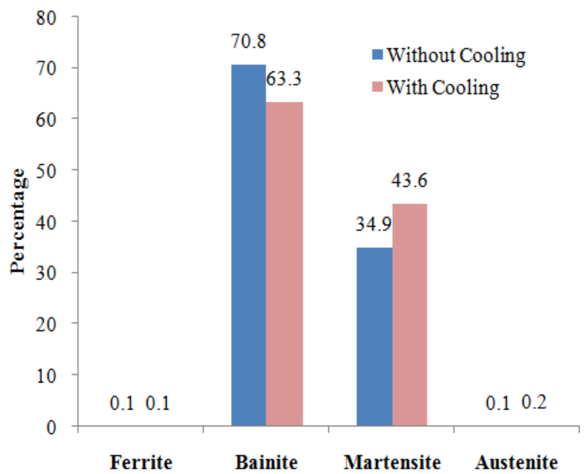

Figure 3: Phase Proportion

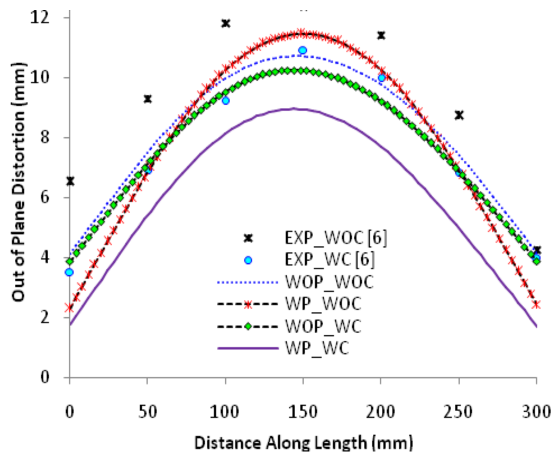

Figure 4: Out of Plane Distortion (Longitudinal Direction)

Conclusions

A 3D FEA of single pass bead on plate is carried out for four different case: with and without phase transformation and with and without trailing heat sink. Based on this study the following conclusions are drawn

a) There is a decrease in out of plane distortion in longitudinal due to trailing heat sink.
b) The compressive residual stress in the transverse direction decreased when welding is done with trailing heat sink
c) The tensile residual stresses in the FZ and HAZ decrease when effects of phase transformations are considered and the calculated results are closer to the experimental values.

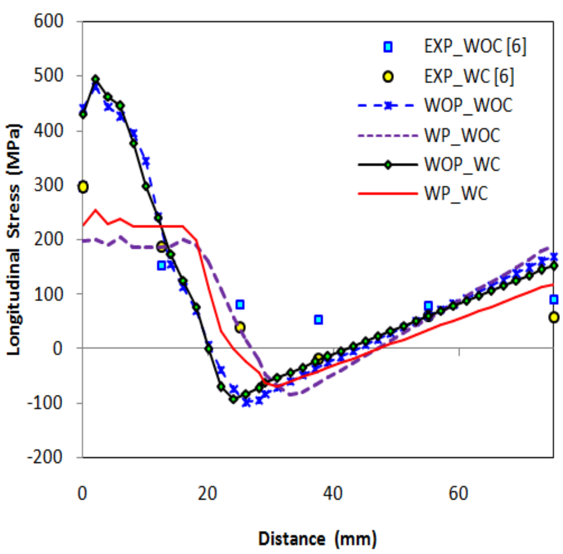

Figure 5: Longitudinal Residual Stresses

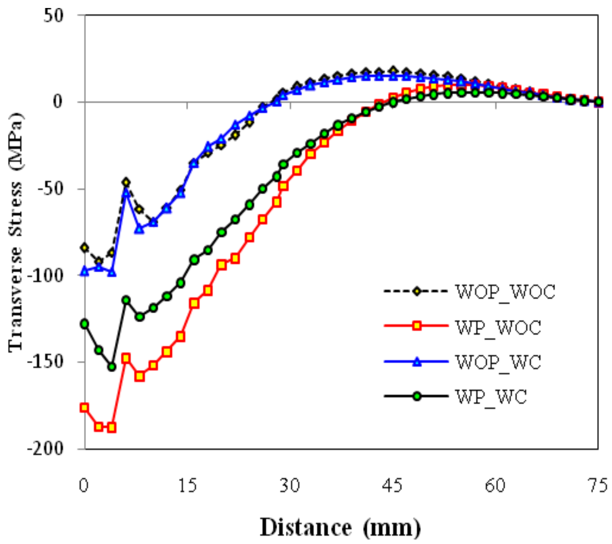

Figure 6: Transverse Residual Stresses

NOMENCLATURE.

k - thermal conductivity

c - specific heat

P_{ep}- proportion at phase equilibrium

Ms - martensite start temperature

ρ - density

$\dot{T}$- heating or cooling rate

τ - delay time as a function of the temp.

b - law parameter

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