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Studies on multipass welding with trailing heat sink considering phase transformation

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ABSTRACT

A two pass butt welding of 6 mm mild steel plates was simulated using 3D finite element model using temperature and phase dependent material properties. Material phase transformations were simulated using suitable phase transformation kinetic models. Mechanical analysis is carried out using nodal temperature and phase proportions as input. Experiments were carried out using liquid nitrogen (LN2) as trailing heat sink. Trailing heat sink helped to reduce the residual stress in the fusion zone (FZ) and heat affected zone (HAZ) although distortions were found be increasing. A parametric study was conducted to study the effect of distance between weld arc and trailing heat sink. The heat sink closer to weld arc reduced both distortions and residual stresses.

1. Introduction

Fusion welding is an effective metal joining process extensively used in fabrication of structures. The nonuniform and localized heating results into weld distortions and residual stresses. Finite element modelling (FEM) is an effective tool which can be used to predict the distortion and residual stresses in the welded joints.

Li et al. (2004) investigated TIG welding both numerically and experimentally for titanium alloy using conventional welding and modified process in which trailing heat sink was introduced to control residual stresses and distortion. van der Aa et al. (2006b) used a five bar conceptual model to explain development of longitudinal plastic strain and stress during conventional welding and compared it with welding with trailing heat sink. The model demonstrated that modified temperature profile results into changes in thermal strains in the bars causing increased stress in one bar which was balanced by decrease in stress in other bars.

Yanagida and Koide (2008) carried out multipass welding with trailing water shower and different interpass time. They found that by applying water shower with suitable interpass time the tensile residual stresses were converted to compressive residual stress which is good to prevent stress corrosion cracking. Sudheesh and Siva Prasad (2011) studied the effect of liquid nitrogen trailing heat sink on distortion and residual stresses in single pass arc welding. The introduction of liquid nitrogen reduced residual stress and distortion by redistributing thermal strains and distortion.

Soul and Yanhua (2005) demonstrated through numerical studies that welding with trailing sink reduced residual stresses and minimized distortion in thin plates. van der Aa et al. (2006a) found that active cooling in the form of trailing heat sink reduces the negative transverse stresses below critical buckling stress and hence eliminated the buckling distortion.

Heinze et al. (2012) conducted numerical and experimental investigation on the effect of transverse shrinkage in multipass welding. Transverse shrinkage was imposed in order to include actual structural effects. Deng and Murakawa (2008) developed computational procedure to calculate temperature field, microstructure and residual stresses in multipass butt welded joint of 2.25Cr-1Mo steel pipes, considering the influence of solid state phase transformation. It was suggested that phase dependent material properties must be incorporated in the analysis to obtain accurate results.

Borjesson and Lindgren (2001) simulated multipass welding using temperature and phase dependent material properties where properties of individual phases were subjected to mixture rule to calculate the macro material property. Residual stresses measured using hole drilling technique showed good agreement with

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Nomenclature

y	welding direction
ς	lag factor to decide starting point of the heat source
k	thermal conductivity
I	input current
$\dot{T}$	heating or cooling rate
P_{eq}	phase proportion at equilibrium
Ms	martensite start temperature
Pi	proportion of phase i
ε_i^{th}	thermal strain of phase i
ε^e	elastic strain
ε^{pc}	plastic strain and
v	welding speed
t	time
η	arc efficiency
V	input voltage
P	proportion of phase
T	temperature
τ	delay time as a function of the temperature
b	law parameter (0.018 assumed, Sysweld, 2005)
λ	proportion of ferrite mixture
ε	total strain
ε^{th}	thermal and metallurgical strain
ε^{tp}	transformation plasticity

calculated residual stresses in transverse direction but not in longitudinal direction.

Lee and Chang (2009) conducted finite element analysis of high carbon steel multipass butt weld considering solid state phase transformation. It was concluded that volumetric increase during austenite to martensite phase transformation reduced longitudinal tensile residual stresses in the weld region and heat affected zone. Becker et al. (2005) attempted to predict phase transformation, phase dependent material properties and residual stresses using experimentally determined continuously cooling transformation (CCT) diagrams.

Wang and Felicelli (2007) developed a three dimensional finite element model to predict the temperature distribution and phase transformation in laser deposition process. They calculated molten pool size and volume fraction of solid phases formed at different speeds. Deng (2009) noted that in medium carbon steel, the solid state phase transformation has significant effect on residual stresses and distortion values due to large dilatation and low transformation temperature, whereas for low carbon steel, phase transformation has no significant effect on calculated values because of small dilatation and relatively high temperature range.

Ferro et al. (2006) investigated the effect of phase transformation considering both volume change and transformation plasticity on residual stress calculation using 2D and 3D numerical models. Han et al. (2011) developed constitutive models for elasto-plastic deformation which included transformation plasticity and Leblonde's phase evolution equation (Leblond and Devaux, 1984). They demonstrated that the phase transformation and transformation plasticity had significant effect on residual stresses of a welded structure.

In the present study a multipass welding of mild steel plates was numerically simulated for conventional welding and welding with trailing heat sink using commercial finite element software Sysweld. The results were validated with experiments using liquid nitrogen (LN2) jet as trailing heat sink. Effect of phase transformations was studied by conducting numerical simulation with and without phase transformations. Preliminary trials on multipass welding with heat sink showed an increase in distortion. In this study, the role of distance between heat sink and heat source on the magnitude of distortion during multipass welds is demonstrated.

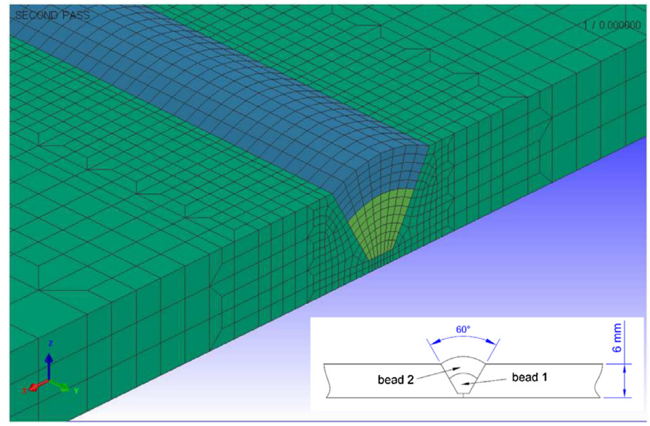

Fig. 1. Mesh of two pass butt joint.

2. Finite element analysis (FEA)

A 3D finite element mesh of two mild steel plates of size 300 mm × 75 mm × 6 mm is shown in Fig. 1. The V-groove of weld cross-section is shown in the inset of Fig. 1. The weld zone and expected heat zone is modelled with smaller brick elements of better aspect ratio. The region away from weld line are meshed coarsely and penta elements are used as transition elements between fine and coarse mesh. The meshed model consists of 119,400 solid elements to represent plate material, 24,904 2D elements on the surface of the plate to facilitate convection heat loss from plate material to the atmosphere. In addition, there are 600 1D elements to model weld path for two weld passes. Weld passes are modelled with a set of elements grouped separately and designated as *bead1* and *bead2*. A group of three nodes on the back of the plate are used to assign minimum clamping condition which would arrest the rigid body motions. The thermo-metallurgical analysis is conducted to calculate the transient temperature distribution and phase proportion which is followed by mechanical analysis to determine distortions and residual stresses in the welded plates.

2.1. Material modelling

Numerical simulation of welding process involves computation of transient temperature distribution and its effect on stress and strain and in turn on the material geometry. Temperature dependent thermal and structural properties of the material are required as temperatures are expected to vary from room temperature to above melting temperature. Analysis which includes phase transformations require material properties for various phases which the material may undergo. Material considered in this study is mild steel. As the material is heated, initial phase ferrite or bainite is transformed to austenite and during cooling austenite is transformed to bainite, martensite or ferrite depending upon the cooling rate. Accurate prediction of distortions and residual stresses during welding require material properties for all the phases as a function of temperature. A set of cooling rates extracted from the continuous cooling transformation (CCT) diagram are provided in the material database. Various thermal properties considered are specific heat, thermal conductivity and density and structural properties are Young's modulus, thermal strain, Poisson's ratio, yield strength and strain hardening data. The material properties used are also available in Heinze et al. (2012). The analysis without phase