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Numerical and experimental investigation of T-shape fillet welding of AISI 304 stainless steel plates

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ABSTRACT

Current study uses experimental data to develop an empirical relationship to model welding process in a fillet-weld joint of AISI 304 stainless steel plates. A new Double-Ellipsoidal Heat Source (DEHS) model, which is based on Goldak model, is developed to simulate fillet-welding process. Then, the extended model is implemented into a finite element code on which a 2D and also a 3D solutions are used to simulate the temperature field in the weldment. A series of experimental measurements and numerical analyses have been carried out and the effects of temperature dependent material properties and welding heat input on temperature field and deformation are investigated.

The results are compared with the experimental data, and the constants of the empirical relationship have been obtained using model updating method. For this purpose, an optimization computer code has been developed to modify the initial values in order to update the model to achieve agreement with measured data.

The results show that 2D model can only be used in thermal analysis; whereas, the developed 3D model can predict thermo-mechanical behavior with acceptable accuracy. The major advantage of this formulation is that the number of unknown coefficients has been reduced to only one coefficient and other coefficients have been related to the physical or geometrical parameters that are known for each weldment.

1. Introduction

Fillet welds are extensively used in ships, bridge structures, pressure vessels and piping. These welds are an extremely common method of connecting various elements of a welded construction, e.g. as in lap, T and cruciform joints [1]. The non-uniform expansion and contraction of the weld and surrounding base material, due to the heating and cooling cycle during the welding process, lead to thermal stresses in the weld and the adjacent areas. Also, because of the localized high temperature and severe temperature gradient in welding, different types of problems may occur during welding and after [2–4]. In many cases, such as hot tapping, it is necessary to carry out in service welding to provide T-shape branch connections. This process also may cause burn-through or hot cracking. The former phenomenon has always been a major concern in the industry [5]. Since the physical reasons behind all these problems lay on the welding process, it is very important to study and model this phenomenon as accurate as possible. Due the complexity of the welding process, it is crucial to use experimental data to develop a reliable model. Although carrying out experimental measurements in welding is very difficult and expensive. On the other hand, the prediction of temperature and stress fields during the welding process and cooling period is not an easy task due to the complexity involved. Hence, using numerical methods such as finite element based simulations gained a considerable popularity in predicting the adverse consequences of welding phenomenon in the last three decades [6–10].

As the simulation of the welding processes is highly computationally intensive and a large computer storage and CPU time are required, most of the recent research works reduce computational requirements by using simplifying assumptions in numerical simulations [11,12]. These assumptions severely reduce the computational demand at the cost of results accuracy. However, over simplified models usually lead to unrealistic results.

Many analytical and numerical models have been proposed for butt-weld joints, and a number of databases have been established [13–16]. Also, limited research works which describe fillet welds are available [17,18]. For example, a thermal and mechanical simulation was performed using a well-established two and three-dimensional code to study the formation of the residual stresses due to 3D effect of the welding process [19].

In general, any accurate model should consider temperature dependence of the physical and mechanical properties of the

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Table 1
Typical chemical composition of base metal and All-weld metal.

Wt.% of component	C	Cr	Mn	Ni	P	S	Si
Base metal	0.06	18.27	1.95	8.93	0.028	0.011	0.40
All-weld metal	0.03	19.8	0.8	10.2	–	0.021	0.8

Table 2
Welding conditions.

Case No.	Plate thickness (mm)	Current (A)	Voltage (V)	Speed (mm/s)	Length of leg (mm)
1	5	90	28	2.34	5
2	6	90	28	2.34	5
3	8	90	28	2.34	5

material, as well as the three-dimensional (3D) fields of the temperature and stresses around the heat source [11,20,21].

In order to validate the numerical solutions, it is necessary to compare the results with the experimental data. For example Oddy and McDill [5] have carried out an exploratory study using 3D thermal–mechanical Finite Element Analysis (FEA) of welding on pressurized vessels. The results of the FEA simulations were compared with those of the physical tests.

Current study also uses an empirical relationship to model welding process in a fillet-weld joint of stainless steel 304 plates in different conditions. A series of numerical analyses has been carried out, results are compared with the experimental data, and the constants of this empirical relationship have been obtained using model updating method. For this purpose, the Double-Ellipsoidal Heat Source (DEHS) model proposed by Goldak et al. [22] is modified by introducing a new set of coefficients to simulate fillet weld joint. Then, the extended model is implemented into the finite element code on which a 2D and also a 3D models are used to obtain the temperature field and deformation in the weldment.

2. Experimental procedure

Experiments were conducted to collect the welding information to provide data for updating the FE model. Experiments have been carried out on T shape fillet-weld joints of AISI 304 stainless steel plates with different thicknesses. Because of superior mechanical and corrosion properties of 304 austenitic stainless steel, it is used widely in industry [23]. Temperature and displacement histories of specific points on the specimens are measured continuously during the welding and cooling periods, using an online data acquisition system with computer interface.

2.1. Welding processing

The welding method selected for the experimental work is the Manual Metal Arc Welding (MMAW) process and “AWS 308L-17 rutile coated core wire electrodes” with 2.5 mm diameter are used. MMAW is usually used in “on-site” industrial applications, because the equipment is relatively simple, portable, and inexpensive. In order to remove moisture, the electrodes were baked in the oven for 45 min before welding. The chemical compositions of the base and all-weld metals are shown in Table 1.

This type of electrode is recommended for welding AISI 304 stainless steels by AWS A5.4/A5.4M [24]. The weld deposit contains a maximum of 0.04% carbon. The lower carbon content minimizes the formation of chromium carbides; consequently, reduces the intergranular corrosion up to +350 °C. This kind of electrode has a silica–titania type coating. Additional silicon in the coating acts as a wetting agent, having the effect of increasing puddle fluidity. This is particularly helpful with stainless steel, as it tends to have more of a sluggish weld bead than carbon steel. Manganese is considered to be a detrimental effect on the pitting resistance because of the formation of manganese sulfide. Cui and Lundin [25] have used three weld-deposit compositions to describe the corrosion initiating phase between austenite and ferrite in 316 austenitic stainless steel weld metals. They concluded that because of the primary austenite solidification mode, with the cores of the cellular dendrites depleted in chromium and nickel relative to the normal composition, austenite is the preferential phase for corrosion attack. Siewert [26] has showed that the toughness increases with nickel content and decreases with ferrite number (a measure of the ferrite phase content of austenitic stainless steels). Since increasing the nickel content is also known to reduce the ferrite number, nickel additions improve the toughness by both means. A research [27] shows a linear increase in strength as the nitrogen is increased from 0.04 to 0.28 wt.%. Lee et al. [28] while investigating the pitting corrosion behavior of welded joints of AISI 304L using flux cored arc welding process, found that tensile and yield strengths were increased with increasing equivalent ratio of Cr_{eq}/Ni_{eq}. Due to these facts, the type of the electrode and its cover remain the same in all tests.

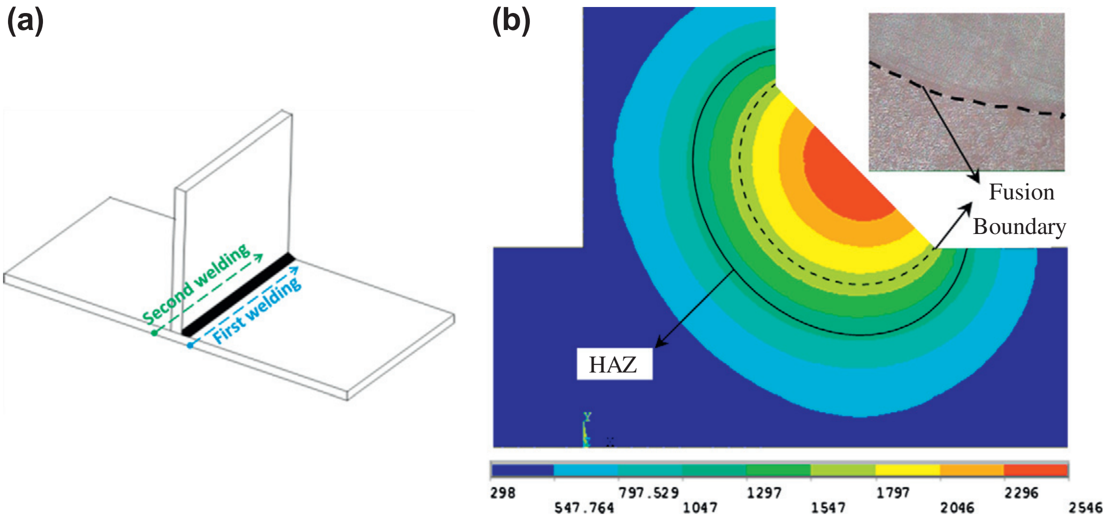

Fig. 1. (a) Schematic diagram of T-shape joint and (b) snapshot of micrographs in the weld zone.