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Residual stress modeling of narrow gap welded joint of aluminum alloy by cold metal transferring procedure

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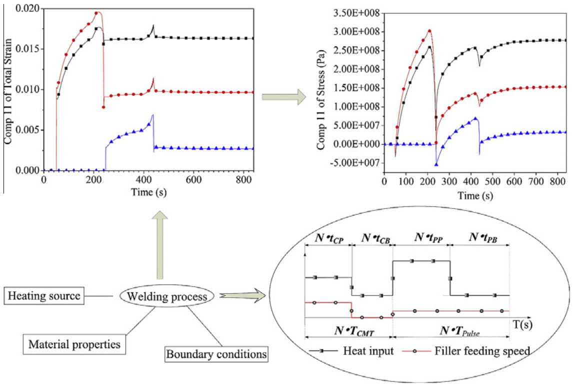
HIGHLIGHTS

- A novel FEM model for narrow gap CMT welding was established.
- Impulse input of weld wire and weld heat was simplified.
- Global stress distribution changed little after cooling down of the first weld pass.
- Bigger strain resulted in shaper decreasing of residual stress in re-melted zone.
- The vulnerable areas of the joint were obtained.

GRAPHICAL ABSTRACT

Cooperation between wire feeding and heat input was simplified so that the CMT welding process could be simulated. The evolution of residual strained was obtained, then the mechanism of residual stress evolution was observed with the assistance of mechanical properties.



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ABSTRACT

Research on FE method simulation of CMT + P MIX welding process has been suspended because of the absence of qualified model for characterizing cooperation between wire feeding and heat input. A novel 3D FE thermo-mechanical model was established, in which impulse input of weld wire and weld heat was simplified by decreasing the impulse frequency. Materials were modeled as elastic-perfectly-plastic with composite heat sources utilized. Numerically simulated results were validated by thermal cycle curves and residual stress distribution obtained with infrared photography instrument and X-ray diffraction tester, respectively. The numerical residual stress distribution also got well supported by the tested results obtained by the blind-hole method. Residual stress evolution was analyzed, whereas special attention was paid to the influences on residual stress distribution by the subsequent weld passes. Based upon this was the vulnerable area of the joint identified under the conduction of different strength theories. The global stress distribution was found to be dominated by the first weld pass while more residual stress in the re-melted zone than that in the HAZ could be released by the last two welding passes. The mechanism was studied through the yielding process of residual strain which was divided into two steps.

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1. Introduction

The benefits including thin heat affected zone, little distortion and improved productivity made the cold metal transferring (CMT) process incomparable when applied in welding thin plates and weld-brazing, as reported by Shang et al. [1] and Cao et al. [2]. However, the application of CMT technology was limited due to insufficient heat input. Bright foreground turned up with pulse current adopted into the CMT process. The CMT mixed with pulses (CMT + P MIX) process could make up heat input insufficiency yet preserved all the advantages of the CMT process. Particularity of the CMT process was the backward drawing of weld wire and its synchronous conjunction with the sharply dropped weld heat input. Pulses were added independent of CMT cycles and the heat input could be adjusted by setting the parameters including peak current, base current and duty cycle, as reported by Pickin et al. [3].

Low heat input and high welding speed in narrow-gap welding contributed to the excellent joint properties. It was found in 1976 by Henderson and Steffens [4] that the critical region of the narrow-gap joint was the weld metal rather than the heat affected zone (HAZ) or the weld metal-parent metal boundary. Narrow-gap welding was common in welding thick steels by submerged arc welding [5], electron beam welding [6] and gas tungsten arc welding (GTAW) [7]. The double-V groove was recommended by ASME according to the industry standards in the process piping part, although, none of the groove types were proved to be with absolute advantages. Negligible change in magnitude of residual stress was found between U groove and V groove in thick pipe welds according to the work by Sattari-Far and Farahani [8]. The I type groove and the U type groove were firstly proposed by the Battelle Institute in 1963 [9]. Narrow-gap I type joint could also be obtained with the assistance of magnetic field as reported by Starling et al. [10]. With regard to gas tungsten arc welding, the dynamic molten pool behavior of the joint was significantly influenced by the angle of the groove. Bigger angle gave birth to better penetration, but problems such as overheating and underfilling might be caused simultaneously as indicated by Cho et al. [11] and Chen et al. [12].

Residual stress was one of the major concerns that might be either beneficial or detrimental to the performance of the welded structures. For instance, compressive residual weld stress would decrease crack growth rate while tensile residual stress contributed to the high local stress concentration factor (SCF) that often led to inter-granular stress corrosion cracking (IGSCC) during service life [13]. However, fatigue strength of as-welded specimens was found higher than that of heat-treated specimens due to compressive residual stresses induced at the weld toe areas according to the work by Kang et al. [14]. Attentions have been paid to the distribution of tensile and compressive residual stress in welded joint. Compressive residual stresses could be obtained on the surface of the joint. Compressive residual stress could also be obtained in the HAZ with the most tensile stress situated away from the weld center in the fusion zone, as was found in welded aluminum plates with thickness of 12 mm by variable polarity plasma arc welding in single pass [15]. However, according to the numerical investigation upon residual stresses in a multi-pass steel weld joint [16], peak tensile stress was identified in the heat affected zone (HAZ) adjacent to the weld bead, which was validated by experimental results with X-ray diffraction method. Kong et al. [17] studied the stress distribution of the welded joint obtained by hybrid heat sources of laser and arc. Numerical simulation indicated that higher residual stress is distributed in the weld bead and the adjacent heat affected zone (HAZ). Longitudinal and normal components of residual stress showed a bimodal distribution across the welded joint with a low trough at the weld centre, as was indicated by the experimental results by Kumar et al. [18]. However the axial stress on the outside surface exhibited a double-valley distribution and the peak of tensile stress was located at the weld center. The width of the central trough was indicated to be significantly greater for higher heat input weld.

Evolution process of stress field became complex under multi-pass welding situation. Finite element (FE) method has been a practical, effective and non-expensive way of capturing the immediate and detailed stress distribution during and after welding process. With regard to the steel joints, the stress distribution could be explained by the strains related to the austenite to martensite solid-state transformation while cooling down as indicated by Kumar et al. [18]. Deng and Kiyoshima [19] focused their attentions on the weld start/end side as numerically investigating residual stress distributions induced by tungsten inert gas arc welding in a steel pipe. It was found that both the hoop and axial stresses strongly varied with weld passes and the last two passes seemed to contributed most to the final stress distribution. Brown [20] found that the tensile strength was reduced by 7% after the entire weld passes, in addition, weld metallurgy was only slightly changed in the HAZ due to the overaging caused by the following passes. The peak longitudinal residual stress was reduced with increasing number of passes, which could also be found in the work by Jiang et al. [21]. Mark [22] studied the evolution of residual stress in a three-pass steel weld. It was found that the peak tensile residual stresses in the weld became lower as the subsequent weld passed was finished. The longitudinal residual stress in the weld bead changed from compressive in the one-pass specimen to tensile in the three-pass specimen, which was supposed to result from the increase in transformation start temperature.

Due to the immaturity of the novel welding method, there is little information available about immediate and detailed stress distribution and its evolution in welds by the CMT + P MIX procedure. The study adopted the CMT + P MIX procedure into welding thick aluminum plates with narrow gap multi-pass welding method. A model of cooperation between wire feeding and heat source was established under the principle of equivalent input. Composite heat source model was proposed for the three weld passes. A symmetric elastic-perfectly-plastic FE model based upon the CMT + P MIX welded butt joint was established. The stress field was predicted and the thermal mechanical behavior of the joint was analyzed, based on which the vulnerable areas were obtained.

2. Experiments

The AA7A52 plates with a size of 100 mm × 50 mm × 20 mm were welded by three passes with a CMT + P MIX weld source and automatic weld robot. ER5356 with a diameter of 1.6 mm was chosen as filler metal and argon with a purity of 99.99% was chosen as shielding gas. The chemical composition of the base material was shown in Table 1. The plates were assembled with an initial gap of 2 mm. A simple type of narrow-gap groove with high practicability was made by a groove machine. The two plates were horizontally fixed and the dimension of the groove was shown in Fig. 1.

Prior to welding, the surface of the specimen was degreased by wiping with acetone and then cleaned with a brush that had stainless bristles. All the three weld passes were carried out in the same direction along the positive *Z* axis. The cooling time was set as 140 s, 140 s and 150 s in sequence after each weld pass so that the inter-pass temperature was kept below 50 °C, thus the whole welding procedure could be depicted as Fig. 1. Welding thermal cycle of the welded plates was recorded with infrared (IR) camera.

Table 1
Chemical composition (wt.%) of the base plates AA7A52 aluminum alloy.

Zn	Mg	Cu	Mn	Cr	Ti	Zr	Fe	Si	Al
4.0–4.8	2.0–2.8	0.05–0.20	0.20–0.50	0.15–0.25	0.05–0.18	0.05–0.15	⩽0.30	⩽0.25	Bal.

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