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Grain refinement of HAZ in multi-pass welding

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ABSTRACT

A technique named Impacting Trailed Welding (ITW) was proposed, aimed at refining the grain size of the HAZ in multi-pass welding. The key idea of ITW is to obtain a large deformation in the HAZ during one weld pass, and get it recrystallized during the next weld pass. Theoretical analysis suggests that the deformed HAZ can get completely recrystallized and the degree of the successive grain growth is lower than the normal grain growth, so that the grains can be dramatically refined. The average grain size was reduced by a factor 2 through the application of the ITW technique, and remained close to the grain size of the base material. The results are consistent with the theoretical analysis.

1. Introduction

Coarsening grains will significantly degrade the mechanical properties of the welded joint. Kong et al. (2009) reported that the coarsening grains in HAZ can seriously degrade the fracture toughness of the welded joint. Esterling (1983) reported that the lowest toughness exists in the coarse grained heat affected zone (CGHAZ) in single-pass welded steels. Davis and King (1993) found that during multi-pass welding, the most degraded part in the HAZ is the intercritically reheated coarse grained heat affected zone (ICCGHAZ). Therefore, for both single-pass welding and multi-pass welding, grain refinement is a necessary way to improve the microstructure and increase the toughness of HAZ. Technologies for grain refinement mainly focus on changing the constituent of the base materials and the weld materials. Kojima et al. (2004) reported that by the appropriate addition of Mg and/or Ca into steel, fine oxides and/or sulfides with sizes of several 10 nm to several 100 nm can be dispersed in steel, so that γ grain growth in a HAZ is retarded and the HAZ grains are refined. Kimura et al. (2005) reported that the "JFE EWEL" technology for increasing the HAZ toughness has been applied to the welding of the SA440 steel plates for architectural constructions. This technology refines the HAZ grains through controlling TiN particles by using BN and Ca inclusions as nucleation sites. Both of the techniques refine the HAZ grains by changing the chemical composition of the materials, so they cannot be widely adopted in the welding.

Hong and Park (2003), successfully predict the grain refinement effect of a rolling pass schedule. Belyakov et al. (2000) reported that the fine grain evolution could be achieved by plastic deformation and recrystallization in many metallic materials. Both their works testify that under appropriate parameters high strain can lead to a relatively small grain size during recrystallization. Noting this, a technique named Impacting Trailed Welding (ITW) is proposed to refine the HAZ grains in multi-pass welding. This technique takes advantage of the high temperature of the welding environment to generate large deformation by using an impacting hammer, and then the deformed area can get recrystallized with the help of the next welding pass. For deformation, since the high temperature shows a distinct reduction effect on the yield strength of the materials, the impacting hammer can generate more plastic deformation and higher dislocation density to the much deeper sheet thickness direction. If the deformation provides sufficient stored energy as driving force of recrystallization, the latter welding pass mainly works as heat treatment, during which the deformed grains become small equiaxed grains again.

2. Experimental procedure

According to the study of Salvatori et al. (2002), austenitic stainless steels with a low value of stacking fault energy (~21 J/mol at room temperature) had always been an important model alloy for recrystallization investigations, so AISI 304 austenitic stainless steel was chosen as the base material. The materials used in the

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Table 1
Chemical composition of the experimental steel (wt%).

C	Si	Mn	Cr	Ni	S	P
≤0.07	≤1.0	≤2.0	17.0–19.0	8.0–11.0	≤0.03	≤0.045

Table 2
Welding parameters.

Welding current	Welding voltage	Welding speed	Shielding gas flow (argon)
160 A	20 V	90 mm/min	12.5 L/min

experiment was 4 mm thick AISI 304 austenite stainless steel sheet in hot-rolled state with an average grain size of $D_0 = 41\ \mu m$, the chemical composition is shown in Table 1.

The whole ITW procedure is illustrated in Fig. 1. To simplify the experiment, a two-pass welding process was used. Gas tungsten arc welding (GTAW) process was used in the experiments, and the two welding passes were of the same processing condition, as listed in Table 2. During the first welding pass, a spinning hammer with the working power of 528 W was placed 30 mm behind the welding gun to impact the welding HAZ, and the deformation temperature was about 1000 °C. The rotation frequency of the hammer was about 8 Hz, and the impacting frequency was about 25 Hz. In order to compare the grain-refinement effect of ITW with the grain coarsening effect of HAZ better, only one side of the HAZ was impacted. The centerline of the second welding pass was placed 3 mm away from the centerline of the first pass on the other side of the impacted area. The inter-pass temperature was slightly higher than room temperature. Furthermore, to better investigate the metallography process of the ITW method, the microstructure of the deformed HAZ specimen after the first welding pass was also studied.

The specimens were cut by spark wire cutting machine. To observe the microstructure distribution of the welded joints, the transverse section of the welded joint specimens were polished using standard metallographic procedure. The polished specimens were then etched with CrO_3 aqueous solution (~10 wt%) by electrolytic corrosion. The microstructure distribution of the HAZ was observed and studied under optical microscope (Olympus GX71). The average grain size of the specimens was measured by the mean linear intercept method, and the annealing twins were omitted from measurements.The hardness distribution of the welded joint along the transverse section was measured using a Vickers hardness tester (HXD-1000TM) with the load of 200 g.

3. Results and discussion

3.1. Theoretical analysis

The static recrystallization kinetics during hot interrupted deformation can be described by the usual Avrami equation:

$$X_{SRX} = 1 - \exp\left[-0.693\left(\frac{t}{t_{0.5}}\right)^n\right] \quad (1)$$

Here,

$$t_{0.5} = A\dot{\varepsilon}^p \varepsilon^q D_0 \exp\left(\frac{Q}{RT}\right) \quad (2)$$

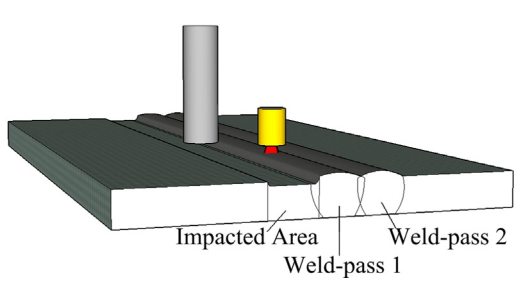

Fig. 1. Schematic diagram of the processing procedure of ITW.

where n is Avrami time constant, $t_{0.5}$ is the time for 50% recrystallization, $\dot{\varepsilon}$ is strain rate, ε is strain, D_0 (~41 μm) is initial grain size, T is deformation temperature and A, p and q are constants.

Cho and Yoo (2001) have studied the static recrystallization mechanism during hot interrupted deformation of 304 stainless steel. For 304 stainless steel, the time for 95% recrystallization can be described as:

$$t_{0.95} = 1.9 \times 10^{-8} \varepsilon^{-1.63} \dot{\varepsilon}^{-0.76} D_0 \exp\left(\frac{173000}{RT}\right) \quad (3)$$

The following equation is suggested for the recrystallized grain size dependence on the process parameters and the austenite grain size prior to deformation:

$$D = 430.7 \varepsilon^{-0.428} \dot{\varepsilon}^{-0.093} D_0^{0.146} \exp\left(\frac{-4461.5}{T}\right) \quad (4)$$

Here T is the deformation temperature (equal to annealing temperature in hot interrupted deformation).

Eqs. (3) and (4) are confined that the deforming temperature is equal to the annealing temperature. However, in the real temperature cycling of welding, the annealing temperature can be much higher in a certain period of time (see Fig. 2), leading to a shorter $t_{0.95}$. But the annealing temperature has little effect on the final grain size after complete SRX compared with the rapid grain growth after SRX, according to Humphreys and Hatherly (2004).

It could be estimated from the appearance of the welded joint and the impacting frequency of the hammer that $\dot{\varepsilon}$ and ε are about 20/s and 0.6, respectively. Due to the high strain rate, the start of DRX is blocked in the experiment. Supposing that the heat treatment temperature is 1000 °C, then the calculated $t_{0.95}$ is about 2.2 s, and the recrystallized grain size d is about 19 μm. While in the real temperature cycling, the time required for complete recrystallization will be shorter that 2.2 s, with recrystallized grains of about the same size. That means after a certain time, which is a function of strain and temperature, most of the deformed microstructure is replaced by newly formed grains and grain growth occurs with longer annealing time and the average grain size increases with increasing the time.

Grass et al. (2003) have studied the grain growth calculation after static recrystallization. After SRX is completed, austenite grain

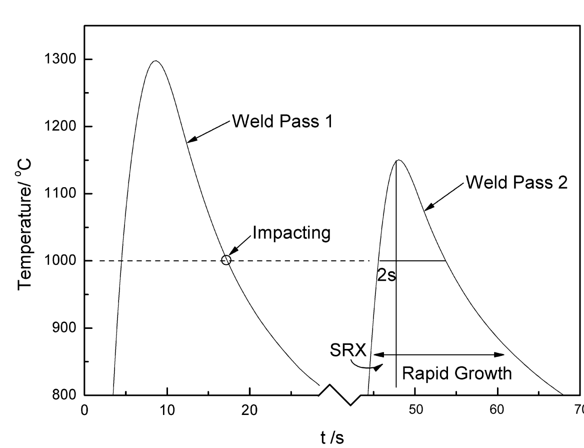

Fig. 2. Temperature cycling of the deformed HAZ.