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Reinforcement of laser-welded stainless steels by surface mechanical attrition treatment

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ABSTRACT

The laser-welded stainless steel was treated by surface mechanical attrition treatment (SMAT) in order to improve its mechanical properties. The microstructure was characterized by X-ray diffraction (XRD), scanning electron microscopy (SEM) and transmission electron microscopy (TEM). Mechanical properties were measured by means of microhardness and tensile tests. Results show that the microstructure of weldment after SMAT is composed of ultra-fine grains, multiscale twins, and residual dendrites. The mechanical properties of laser-welded stainless steels after SMAT are significantly improved. The strengthening of weldment can be attributed to the refinement of dendrites and formation of multiscale twins during SMAT. The influence of dendrites on the formation of twins is discussed.

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1. Introduction

Austenitic stainless steels (SS), such as type 304, are widely used in chemical, automotive, and nuclear industries due to their good fracture toughness, tensile ductility, and corrosion resistance. In general, austenitic SS are easily weldable, and many welding methods have been developed to meet requirements of the practical applications, such as gas tungsten arc welding [1,2], resistance spot welding [3], friction stir welding [4], and laser welding [5]. However, any welding technology can induce some negative metallurgic changes, such as micro-segregation, precipitation of secondary phases, presence of porosities, solidification cracking, and abnormal grain growth in the heat-affected zone (HAZ) [2,6–8]. These metallurgical changes usually deteriorate mechanical properties. For example, the conventional arc-welding formed coarse grains and intergranular Cr-rich carbides along grain boundaries in HAZ [9]. A comparative study by Yan et al. [10] exhibited that laser welding could obtain relatively higher tensile strength and smaller dendrite size than tungsten inert gas welding. The degradated mechanical properties of SS weldments limit their wide applications. However, the strengthening method of weldment is seldom reported due to the small joint gaps and special shape of weld zones (WZ).

Surface mechanical attrition treatment (SMAT) is an effective technology to obtain nanocrystallines (NC) and ultra-fine grains (UFG) at surface by means of repeated multidirectional impact of small balls with high energy [11]. The metallic materials after SMAT exhibit improved mechanical properties, such as high hardness and strength, and enhanced tribological properties [11,12]. One of the most prominent characteristics of SMAT technology is that it can strengthen the specific zone of complex-shaped parts, such as irregular pipes or pressure vessels. The refinement mechanisms of SS impacted by SMAT have been reported [12–14]. However, microstructure changes after welding, including phase separation and formation of dendrites, will influence deformation mechanisms, and thus deserve more detailed studies. In the present work, 304 SS sheets were first welded by spot laser welding and then treated by SMAT, microstructure and mechanical properties of weldments after SMAT are investigated. The influence of dendrites on the formation of twins is discussed.

2. Experiment

The chemical compositions of AISI 304 SS sheets used in this study are given in Table 1. The 304 SS sheets were cut into pieces with dimension of $100 \times 35 \times 1\ \mathrm{mm}^3$, and then welded by the spot laser welding on both sides. An OR LASER CAB-200-type welding machine was employed with a working medium of ND:YAG. The optimized welding parameters are tabulated in

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Table 2. The laser-welded (LW) 304 SS sheets were treated by SMAT on both sides, referred to as LW-SMAT samples. Detailed processing parameters of SMAT are listed in Table 3.

The surface morphologies were observed by Nikon C1 Plus laser confocal microscopy and HITACHI S-4200 field emission scanning electron microscopy (SEM). A Philips Xpert X-ray diffractometer (XRD) with Mo K_{α} radiation was used to determine the phase constitution under a working voltage of 40 kV and working current of 40 mA. Nanoscale microstructure analysis was carried out by a JEM 2010 transmission electron microscopy (TEM) with an operating voltage of 200 kV. The TEM foils were prepared and ion-thinned at low temperature. The statistical distribution of grain size at surface was calculated from dark-field TEM images. The twin density at different depths was determined by the area fraction of grains with twins, according to integrated results of TEM and SEM images. Tensile tests were carried out by three specimens at a strain rate of $8.3 \times 10^{-4}\,s^{-1}$ using a ZWICK I250 Materials Testing System. Vickers microhardness was measured by a MVK-H21 Hardness Testing Machine with a 50 g load under 15 s loading time.

3. Results and discussion

3.1. Surface morphologies

The LW sample exhibits two distinct zones, a weld zone (WZ) with fan-shaped patterns and base material (BM), where the WZ can be subdivided into two regions, i.e. a fusion zone (FZ) and HAZ, as shown in Fig. 1(a). The dendrites, as indicated by arrows in the inset of Fig. 1(a), grow in sectors around the WZ. The fan-shaped growth of dendrites is caused by heat flow diffusion direction during solidification. Similarly, the LW-SMAT sample also can be divided into two regimes (in Fig. 1(b)), the simple SMAT zone and WZ plus the SMAT zone of the BM and WZ in the LW sample, respectively. The interfaces of WZ are not very clear, and the dendrites formed in welding disappear in LW-SMAT sample, while a relatively flat surface is observed, as shown in Fig. 1(b).

The determined locations of surface roughness are drawn in Fig. 1(a) and (b), and the roughness profiles of LW and LW-SMAT samples are given in Fig. 1(c) and (d), respectively. The scanning line length is approximate 1.5 mm to include four fusion spots for the purpose of reproducibility and accuracy. Fig. 1(c) and (d) shows a very detailed distribution of roughness and also contains some scatters along the scanning lines. These scatters originate from noises of confocal microscopy, which are induced by two reasons [15]. One is the high resolution of 0.05 μm in the *y* direction, and the other is the intensity difference of the laser beam reflected by the physical surface. For example, bright parts in the confocal image can produce strong reflection intensity; therefore, the relatively smooth and bright surface of the LW-SMAT sample exhibits more scatters than the LW sample, as shown in Fig. 1(c) and (d). Comparing the analysis of the two roughness profiles of LW and LW-SMAT samples, waviness is observed along the scanning line in the LW sample, and surface roughness, *Ra*, is as high as 9 μm, as shown in Fig. 1(c). However, the roughness profile of LW-SMAT sample exhibits a planar characteristic, and the corresponding *Ra* is 3 μm, lower than that of the LW sample, as displayed in Fig. 1(d). These observations are confirmed with SEM images.

3.2. Phase analysis

Fig. 2 shows XRD patterns of LW and LW-SMAT samples. The BM of LW sample is composed of γ austenite (fcc) phase; however, a small diffraction peak of the α'-martensite phase occurs after welding, as indicated by the arrow in Fig. 2. The formation of α'-martensite in the LW sample is caused by the rapid cooling of the WZ. Furthermore, the α'-martensite transformation occurs both in the WZ plus SMAT and the SMAT zones of the LW-SMAT sample, as indicated by the arrow in Fig. 2. The occurrence of α'-martensite in the LW-SMAT sample can be attributed to the strain-induced martensite transformation in the process of SMAT [11,12]. Since the treatment time is short, the quantity of α'-martensite phase is relatively low. In addition, the peak broadening of the LW-SMAT sample is observed both in WZ plus SMAT and SMAT zones, which originates from integrated effects of grain refinement and lattice distortion [11].

3.3. Microstructure of weld zones

The cross-sectional morphologies of LW-SMAT and LW samples are shown in Fig. 3(a). The WZ presents a semi-round shape, the fusion interface is bonded very well, and no void is observed in both LW and LW-SMAT specimens. Fig. 3(b) is a magnification of zone “b” in Fig. 3(a), to give the morphologies of dendrites (indicated by arrows) in the WZ of the LW sample. The LW-SMAT sample exhibits a non-uniform deformation microstructure, as shown in Fig. 3(c). Fig. 3(c) is the enlarged picture of zone “c” in Fig. 3(a) to show the deformed structure close to the surface of the WZ plus SMAT zone. The severe plastic deformation occurs within 20 μm depth and grains in this regime are refined to ultrafine scale, as marked in Fig. 3(c). Many fine shear bands occur in deeper locations, as indicated by arrows in Fig. 3(c). It should be pointed out that the dendrites are seldom observed in this zone since the dendrites are fragmented to UFG or transited to shear bands by the high impacting strain at the surface. However, residual dendrites are observed at a deeper location due to the attenuation of impacting strain along depth, as given in Fig. 3(d). Fig. 3(d) is a magnification of zone “d” in Fig. 3(a) to show the subsurface microstructure of the WZ plus SMAT zone, where shear bands and dendrites co-exist, as indicated by dashed and solid arrows in Fig. 3(d), respectively. The inset in Fig. 3(d) is an enlarged picture to show the detailed morphologies of residual

Table 1
Chemical composition of AISI 304 stainless steel (wt%).

Elements	C	Si	Mn	P	S	Cr	Ni	Fe
wt%	0.04	0.49	1.42	0.023	0.006	16.8	7.8	Balance

Table 2
Parameters of spot laser welding.

Laser power (kV)	Pulse frequency (Hz)	Pulse width (ms)	Welding speed (mm/s)	Diameter of beam (mm)	Protect atmosphere
230	6	8.0	0.2	0.5	Ar

Table 3
Processing parameters of surface mechanical attrition treatment.

Vibrating frequency (kHz)	Impact velocity (m/s)	Ball material	Diameter of ball (mm)	Treatment time (min)
20	~10	Bearing steel	3	3

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