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Achieving ultrafine-grained ferrite structure in friction stir processed weld metal

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ABSTRACT

Ultrafine-grained (UFG) ferrite phase was the desired structure in the weld metal of high strength low alloy (HSLA) steel joints. In this study, submerged arc weld metal of a HSLA steel was subjected to friction stir processing (FSP) under a very low rotation rate of 80 rpm. The original coarse bainite structure was changed into UFG ferrite structure after FSP, and the grain sizes were refined to about 500 and 300 nm in the upper and lower parts of the processed zone, respectively. This study provides an effective strategy to preparing UFG ferrite structure in the weld metal of HSLA steel joints, and also a potential welding method.

1. Introduction

In the fabrication of high strength low alloy (HSLA) steel structures, the integrity and reliability of structures are extremely dependent on the microstructure of the welded joints [1,2]. Generally, coarse martensite and bainite phases were achieved in the weld metal in the fusion welding process [3]. These transformed phases are usually characterized as brittle microstructure, which plays a vital role in deteriorating the mechanical properties of the welded joints. In this case, ferrite is the most desired phase structure in the weld metal, due to its excellent toughness [4].

However, the ferrite phase usually exhibit lower strength compared to the bainite and martensite phases. As the Hall–Petch relationship indicates, the decrease of grain size will improve the mechanical properties, including the hardness and yield stress. Therefore, the grain refining of the ferrite phase has attracted considerable interest in the fabrication of HSLA steel joints, which is an essential strengthening method that enhances both the strength and the toughness simultaneously [5]. Inclusion assisted microstructure control is the most encouraging method of refining the weld metal, but the grain size of the achieved intragranular acicular ferrite structure is still as large as several micrometers [3–5]. In fact, ultrafine-grained (UFG) ferrite is a desired structure of the weld metal to join HSLA steels with ultrahigh strength, so new methods are still needed to refine the ferrite further.

Friction stir processing (FSP) is a new thermo-mechanical processing technology based on the principles of friction stir welding (FSW) [6]. During this process, the material in the processed zone undergoes intense plastic deformation at elevated temperatures, resulting in significant grain refinement. Recently, FSP has been successfully used to prepare bulk UFG materials [7–10]. After FSP, the microstructure was greatly refined in the processed zone, resulting in sound mechanical properties. Therefore, FSP should be a very effective method of preparing UFG microstructure in the weld metal of HSLA steel joints. More importantly, it can provide a new welding method of HSLA steels, based on the similar principles between FSW and FSP.

However, investigations on the preparation of UFG steels by FSP are still lacking, due to the complex phase transformation in FSW/P of steels [11–13]. Previous studies mainly chose high heat inputs with high tool rotation rates in FSW/P of steels, and transformed phases, such as martensite and bainite were still formed in the weld metal [11,12]. In the present study, FSP was performed at a very low rotation rate of 80 rpm on a weld metal with coarse bainite structure. The aim of this study is to investigate whether the UFG ferrite structure can be achieved in the weld metal after FSP, and to elucidate the mechanism of the grain refinement.

2. Experimental procedures

The materials used in this study were HSLA steel weld plates 2 mm in thickness fabricated by the submerged arc welding, and the chemical composition of the weld metal is shown in Table 1. In

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Table 1
Chemical composition of the weld metal (in wt%).

Element	C	Si	Mn	P	S	Cu	Ni	Cr	Ti	V	Nb	B	Al	O	N
Content	0.057	0.30	1.51	0.010	0.005	0.18	0.11	0.12	0.017	0.03	0.023	0.0030	0.034	0.027	0.0045

order to greatly reduce the processing temperature, FSP was performed on the weld metal at a very low rotation rate of 80 rpm with a traverse speed of 80 mm/min. The processing tool was made of a tungsten carbide based material with a shoulder diameter of 12 mm and equipped with a columnar pin without threads, and the pin diameter and the length were 4 mm and 1.8 mm, respectively.

Microstructural observations were conducted by optical microscopy (OM), electron backscatter diffraction (EBSD), scanning electron microscopy (SEM), and transmission electron microscopy (TEM). The specimens for OM and SEM observation were machined perpendicular to the welding direction, and were etched with a 4% nital solution. EBSD specimens were prepared by the electro-polishing at room temperature using a solution of 92% acetic acid and 8% perchloric acid under a potential of 30 V.

3. Results and discussion

The initial weld metal exhibited a typical fusion welded structure with many coarse columnar grains, as shown in Fig. 1a. Defect-free processed zone was successfully achieved after FSP, and the microstructure was refined apparently (Fig. 1b). Usually, an enlarged nugget/processed zone was obtained during FSW/P of steels, which was attributed to the strong effect of the shoulder [11,12]. In the present study, however, the effect of the shoulder weakened due to the very low rotation rate. Therefore, two significant parts labeled as PZ-1 for the upper part and PZ-2 for the lower part were observed in the processed zone, which was mainly effected by the tool shoulder and the pin, respectively.

Fig. 1c shows the detailed microstructure of the weld metal. Many large bainite laths divided by the carbide strips could be observed in the coarse grains, which was characterized as a typical bainite structure. It could also be observed that coarse grain boundary ferrite phase formed at the prior austenite grain boundaries during the phase transformation of the welding process. Moreover, many fine inclusions dispersed in the matrix of weld metal, which is a normal phenomenon in fusion welding [4].

After FSP, totally different microstructure was obtained in the weld metal, as shown in Fig. 1d–f. Clearly, UFG ferrite microstructure was successfully prepared in both PZ-1 and PZ-2 of the weld metal by FSP, indicating a peak temperature of below Ac_1 during FSP, and PZ-2 exhibited finer grain size than that of PZ-1. The microstructure in PZ-1 and PZ-2 was characterized by a uniform equiaxed ferrite, and the average grain sizes were about 500 and 300 nm, respectively. Usually, the tool shoulder produced most of the heat at the top, and the bottom of the workpiece was in contact with a backplate which acted as a heat sink that lowered the peak temperature and reduced the time at high temperature [14,15]. Further, more sufficient dynamic recrystallization was achieved in the bottom of the processed zone due to the severe stirring action of the pin. Thereby, the grain size of PZ-2 was finer than that of PZ-1.

In the present study, it is clear that the grains could be further refined around the inclusions, as shown in Fig. 1e, and this should be related to a typical phenomenon of particle stimulated

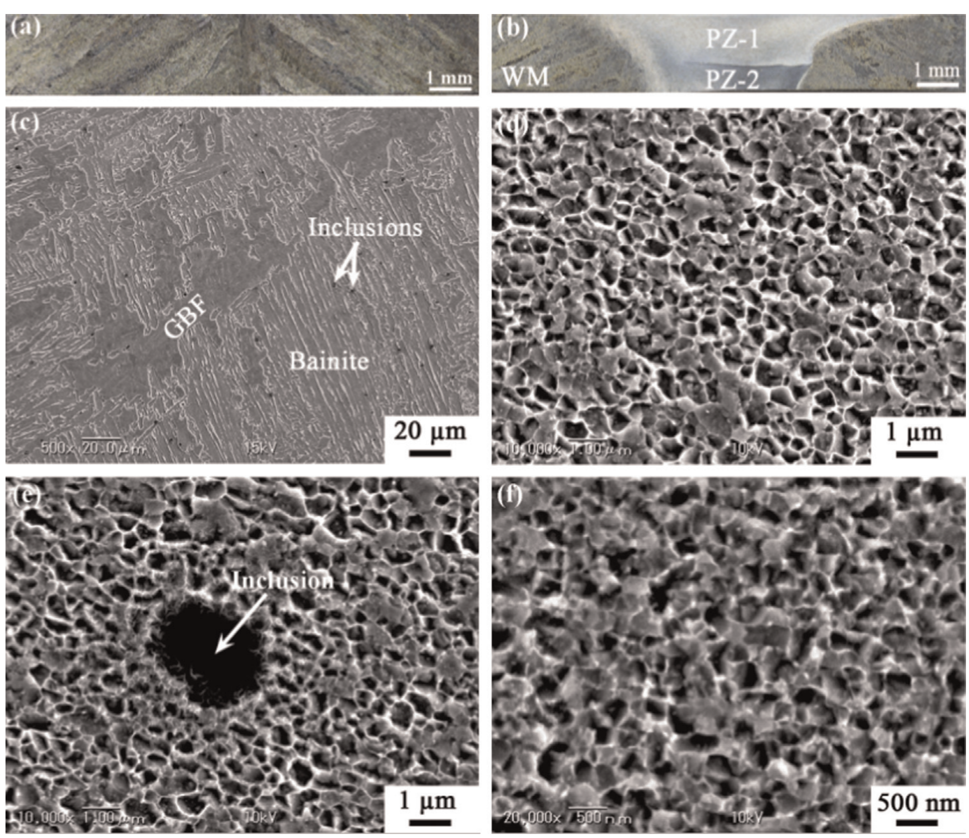

Fig. 1. Macrostructure of weld metal (WM) (a) before and (b) after FSP, and SEM microstructure of (c) weld metal, (d) (e) PZ-1, and (f) PZ-2.

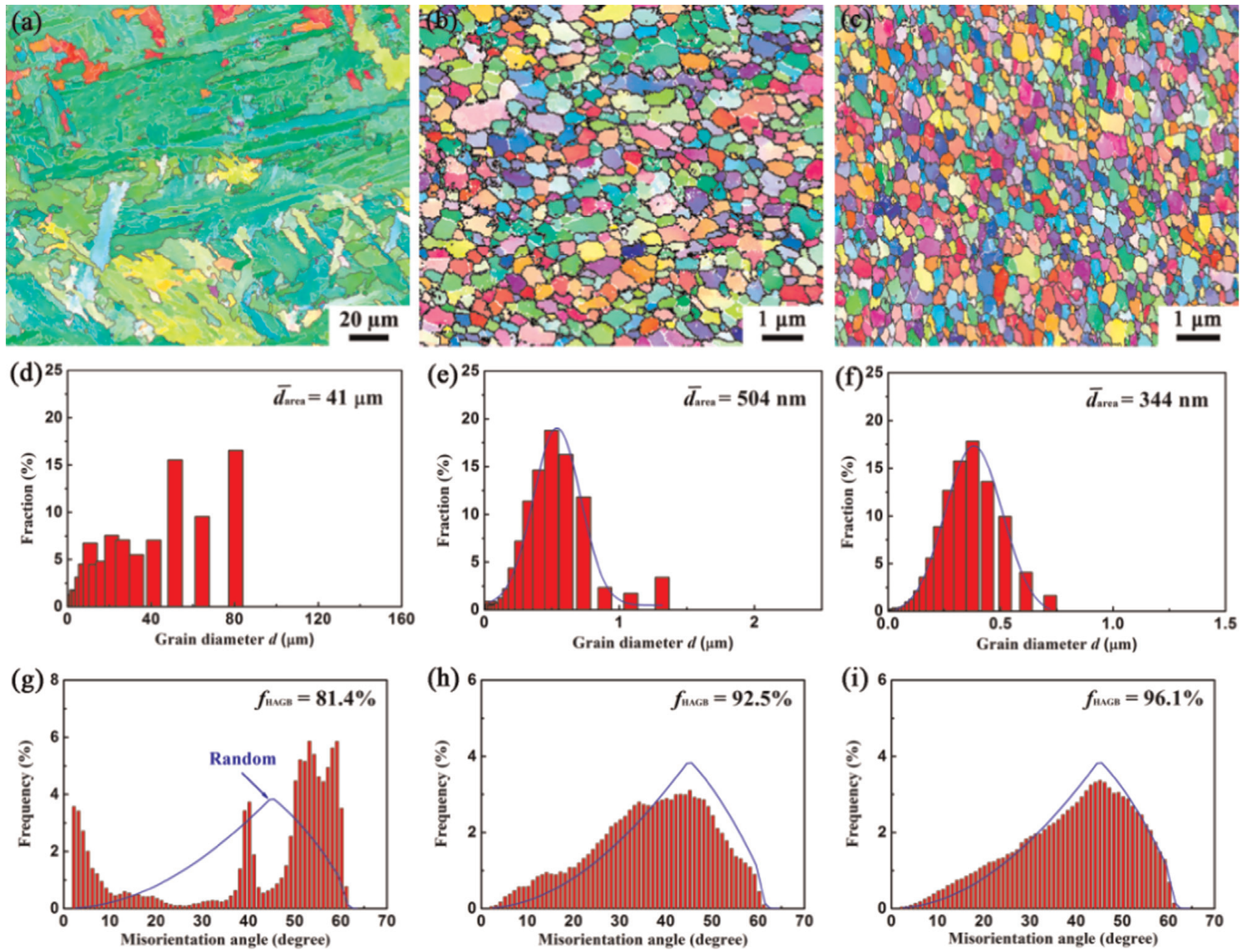

Fig. 2. EBSD maps of (a) weld metal, (b) PZ-1 and (c) PZ-2, grain size distributions of (d) weld metal, (e) PZ-1 and (f) PZ-2, and misorientation angle distributions of (g) weld metal, (h) PZ-1 and (i) PZ-2.

nucleation. During or after deformation, inclusion has usually been a nucleus to stimulate new recrystallized grains to nucleate, which leads to the formation of finer recrystallized grains. Similar phenomenon has been reported in the previous papers [16,17]. On the other hand, the original long carbide strips disappeared in the processed zone after FSP, were replaced by the dispersed carbide particles with very fine scales. This indicates that a strong stirring action was achieved in the processed zone, though a very low rotation rate of 80 rpm was chosen in this study.

Fig. 2 shows the analysis results of the microstructures of the weld metal and processed zone by EBSD. Coarse bainite grains were observed in the weld metal, and many low angle grain boundaries (LAGBs, misorientation angle $<15°$) distributed in the coarse grains (Fig. 2a), which coincided well with the OM and SEM results. Most of the LAGBs should be the bainite lath boundaries with very low misorientation angles according to the previous studies [3,18]. However, many high angle grain boundaries (HAGBs, misorientation angle $\geq 15°$) were observed for the fine equiaxed ferrite structure in both processed zones (Fig. 2b and c).

The distributions of the grain sizes for the weld metal and processed zones are shown in Fig. 2d–f. The average grain sizes were about 41 μm, 504 and 344 nm for the weld metal, PZ-1 and PZ-2, respectively, calculated automatically by the grain area determination method of the EBSD analysis software. The misorientation angle of the weld metal concentrated at the LAGB area and 50–60° range compared to the random distribution of the cubic metals (Fig. 2g), which originated from the bainite phase transformation [3,13]. However, the misorientation angles of both processed zones exhibited random distributions of the cubic metals, as shown in Fig. 2h and i. The fractions of HAGBs for the weld metal, PZ-1 and PZ-2 were calculated as 81.4%, 91.7% and 96.1%, respectively, considering all the misorientation angles larger than 2°.

Fig. 3 shows the detailed TEM bringht-field images of the processed zones. It is clear from Fig. 3a and b that the grains in both processed zones were equiaxed and most grain boundaries were sharp, clear, and relatively straight with clear contrasts between neighboring grains, indicating that they were the grain boundaries with higher misorientation angles [9,10]. This could also be confirmed by the typical electron diffraction pattern shown in the top right corner of Fig. 3b, which exhibted near continuous rings. Many dislocations could be observed in the present ultrafined grains (Fig. 3c), which is attributed to the severe plastic deformation process during FSP. Further, many fine carbide particles of several tens of nanometers could be found in the ultrafined grains, as shown in Fig. 3d.

It is clear from the observations that the UFG structure in both processed zones exhibited recrystallized grains, therefore, the grain refinement is referred to the dynamic recrystallization, which is a regular refining mechanism for FSW/Ped materials [6–10]. In the present study, the grain growth should be strongly inhibited during dynamic recrystallization, due to the significantly decreased processing temperature under the very low rotation rate of 80 rpm [11,12]. On the other hand, the dispersed inclusions

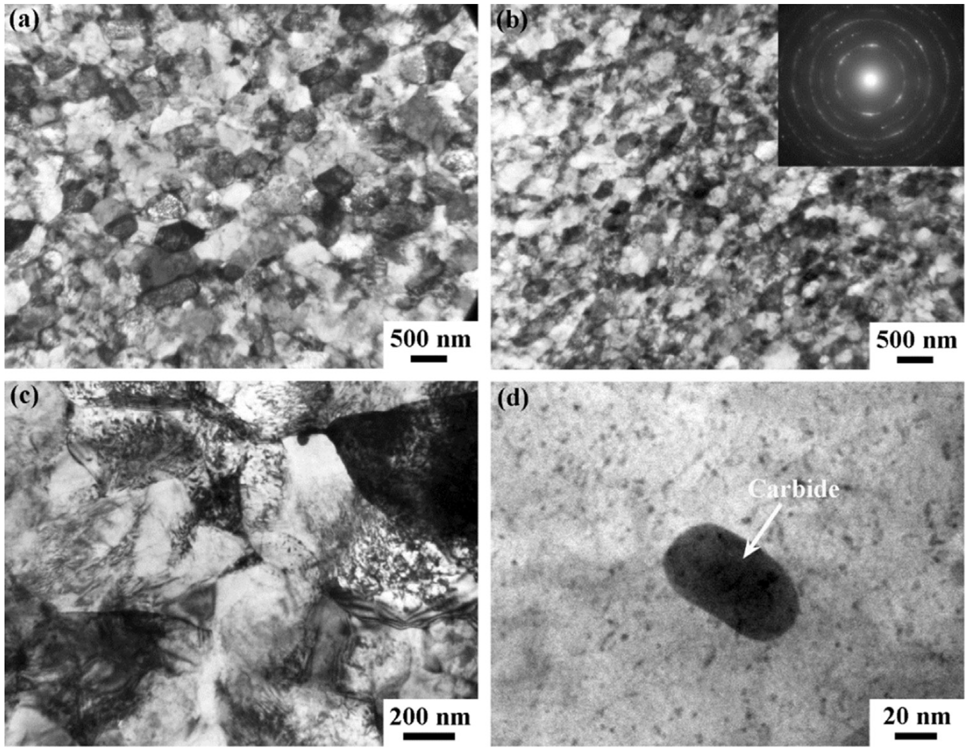

Fig. 3. TEM microstructure of (a) PZ-1, (b) (c) PZ-2, and (d) typical carbide particle in PZ-1.

and the carbide particles provided abundant nucleation sites for the new grains and also inhibited the grain growth during dynamic recrystallization, resulting in the UFG microstructure in the processed zone.

4. Conclusions

In this study, the submerged arc weld metal was subjected to FSP at a very low rotation rate of 80 rpm, and UFG microstructure was successfully achieved in the processed zone, which could be devided into PZ-1 and PZ-2 for the upper and lower parts, respectively. Due to the very low heat input and abundant nucleation sites by the inclusions and the carbide particles, ultrafine equiaxed grains with average grain sizes of about 500 and 300 nm were obtained by dynamic recrystallization in PZ-1 and PZ-2, respectively.

Acknowledgments

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