



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.

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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 Content	C	Si	Mn	P	S	Cu	Ni	Cr	Ti	V	Nb	B	Al	O	N
	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 A_{c1} 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

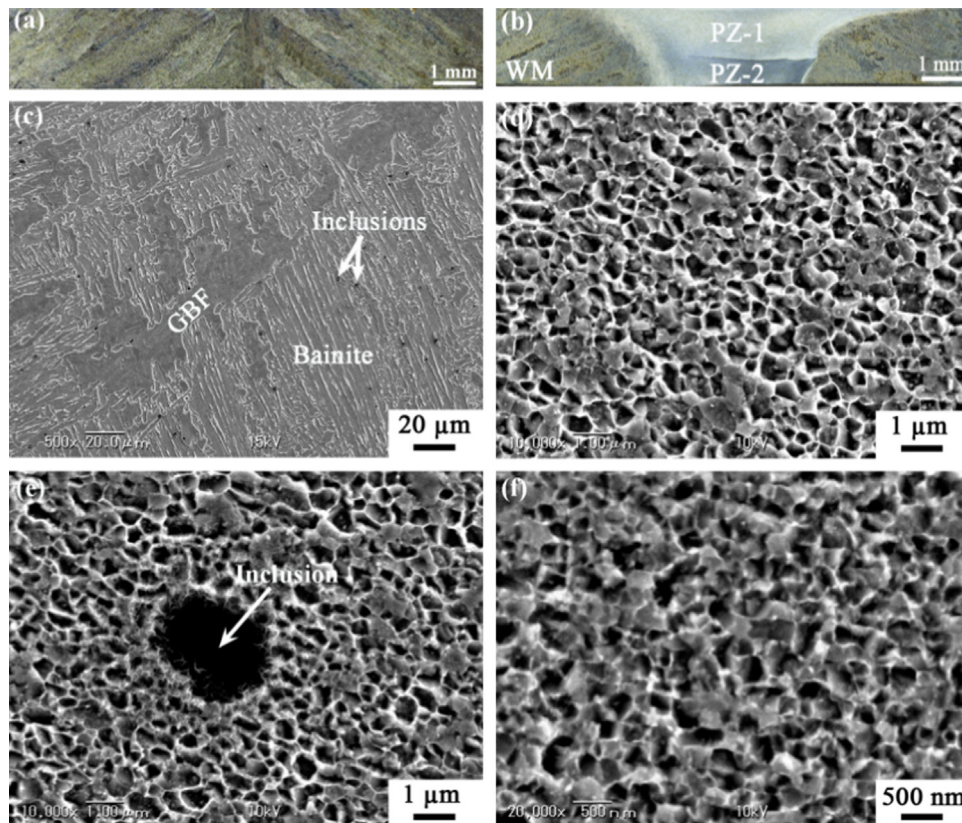


Fig. 1. Macrostructure of weld metal (WM) (a) before and (b) after FSP, and SEM microstructure of (c) weld metal, (d) (e) PZ-1, and (f) PZ-2.

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