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The microstructure and mechanical properties of FSPed HSLA steel

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ABSTRACT

Purpose: High-strength low-alloy (HSLA) steels have been used in a wide range of applications from automotive to ship building industry due to their low weight, formability and good weldability. However, especially in the automotive industry, it is still attempted to improve this steel for the better formability and strength properties. Grain refinement is a well-known method to improve mechanical properties of metallic materials without changing their chemical compositions. Friction stir processing (FSP) is a new method of enhancing the properties of metals as a result of grain refinement by severe plastic deformation, which is based on the basic principles of Friction Stir Welding (FSW) technique. The purpose of this study is to investigate microstructural alteration and the main mechanical properties of HSLA after friction stir processing.

Design/methodology/approach: HSLA steel sheet with a thickness of 1.5 mm was processed using a tungsten carbide (WC) tool consisting of a cylindrical shoulder and a cylindrical conical pin. The parameters of FSP are kept to a fixed tool rotation speed of 1600 rpm, traverse speed of 170 mm.min^{-1} and downforce of 5 kN. The evaluation after and before FSPed of HSLA steel was performed by optical microscope, scanning electron microscope, tensile test and hardness measurement.

Findings: After FSP, refined microstructure brought about a considerable increase in both hardness and strength values. The increase in the yield and tensile strength after FSP was about 30% and 34%, respectively.

Research limitations/implications: Electron backscatter diffraction (EBSD) mapping could not be done in this study. The EBSD mapping should be performed for detailed microstructural characterization of processed zone such as grain size distribution and misorientation angle distribution.

Practical implications: FSP can be applied to other steel to obtain high strength steel without any decrease in their ductility properties by means of grain boundary strengthening mechanism.

Originality/value: FSP, as a severe plastically deformation technique, is applied to many aluminium alloys and steels. However, only few studies were reported on FSPed HSLA steels. Moreover, further investigations are needed to identify the microstructural and mechanical properties of the FSPed HSLA steels.

Keywords: Friction stir processing; High-strength low-alloy steels; Microstructure; Mechanical properties

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PROPERTIES

1. Introduction

High-strength low-alloy (HSLA) steels, or microalloyed steels, have good engineering properties such as high strength, formability and weldability. HSLA steels replace conventional steel in a wide range of load-bearing applications where low weight and good formability are essential. Thus, they have been widely used especially in the automotive industry to reduce vehicle weight and improve car safety. However, automotive industry still attempts to improve this steel for the better formability and strength properties. The high strength of this steel mainly derives from precipitation hardening by micro alloying elements such as niobium, titanium. Also, thermo mechanical control processes (TMCP) including controlling of phase transformation with temperature control and controlling cooling stage have been used to develop their mechanical properties [1,2]. Nevertheless, severely plastic deformed (SPD) methods provide higher strengthening effects in comparison with the TCMP methods [3]. The mechanical and microstructural properties of these steels can be substantially improved by friction stir processing (FSP), which is one of the severely plastic deformation techniques due to altering in the morphology and grain refinement without changing chemical compositions of HSLA steels [4]. FSP is a new microstructural modification technique based on the basic principles of friction stir welding (FSW) [5]. In FSP, a non-consumable rotating tool with a shoulder and pin is inserted into a metal plate and traversed through a direction of interest. The heat generated by the friction between the rotating tool and metal surface locally softens the volume to be processed. During FSP, workpiece undergoes an intense plastic deformation and high temperature in the processed zone (PZ), and dynamic recrystallized and equiaxed grains occur [6]. Few researchers study on weldability, microstructure and mechanical properties of friction stir welding of HSLA steels [7-9,11,12], but there are no remarkable studies on FSP of HSLA yet. Therefore, the main purpose of this study is to apply FSP on HSLA steel (EN 10149-2 /S315MC), and investigate the effect of FSP on its microstructural and mechanical properties

2. Materials and methodology

Galvanized HSLA steel sheets with the chemical composition given in Table 1 were used in this study. FSP samples with the dimensions of 200 mm × 60 mm × 1.5 mm were machined from the base sheets. They were subjected to FSP using a tungsten carbide (WC) tool consisting of a cylindrical shoulder with the diameter of 12 mm and a cylindrical conical pin with the diameter, angle and length of 4 mm, 200 and 1.3 mm, respectively (Fig. 1.). Galvanize coat in the steel sheet is removed by using acid solution for FSP. FSP was conducted with a tool rotation speed of 1600 rpm and a traverse speed of 170 mm/min.

Table 1.
Chemical composition of the HSLA steel used in this study (wt%)

C	Mn	P	S	Si	Al	Nb
0.12	1.5	0.030	0.030	0.050	0.015	0.015

Fig. 1. Tungsten carbide FSP tool

The shoulder tilt angle was set at 3°, and the tool downforce was kept constant at 5 kN during the process. Scanning electron microscope (SEM) and optical microscope (OM) were used to observe the effect of FSP on the microstructure of steel sheets. The metallographic specimens were sectioned perpendicular to the process direction (Fig. 2) and then etched in 2% Nital (2 ml. HNO_3 + 98 ml. C_2H_6O) for 20 s after standard metallographic preparation. Mechanical properties of the sheets before and after FSP were evaluated by hardness measurements and tensile tests. Hardness measurements were performed using a Vickers micro-hardness tester under a load of 1.96 N for a dwell time of 10s. Tensile properties were determined on dog bone-shaped specimens with dimension of 1.4 mm × 3 mm × 26 mm at a strain rate of 10^{-3} s^{-1}. The tensile axis of the samples was oriented parallel to the processing direction as illustrated in Figure 2.

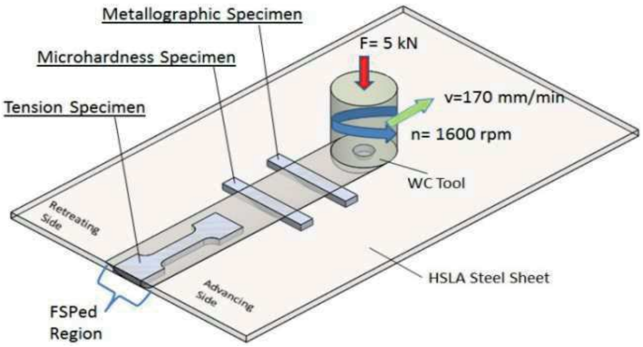

Fig. 2. Schematic illustration of the FSP of the sample and the specimen's positions and shapes inside the processed regions

3. Results and discussion

3.1. Microstructure

The effect of FSP on the microstructure of HSLA steel is shown in Figure 3 and Figure 4. The initial microstructure of HSLA steel sheet consists of fine ferrite grains with an average grain size of 6 μm (Fig. 3 (b)) and carbides distributed inside the grains or along the grain boundaries (Fig. 4 (a)). The processed zone (PZ) is formed by intense plastic deformation and complicated material flow around the rotating pin. FSP resulted in a considerable refinement in the microstructure especially inside the PZ. Carbides in the ferrite grain boundary as seen in Figure 4 (a) are broken by rotating pin and distributed more homogenously in the ferrite matrix (Fig. 4 (b)). The microstructure of the PZ is characterized by fine acicular ferrite with broken carbides. The ferrite and carbides were fragmented and refined by the effect of severe plastic deformation, dynamic recrystallization and temperature during FSP [4].

3.2. Microhardness

Related microstructure and microhardness profiles of the FSPed sample through the longitudinal sections are shown in Figures 5 (a)-(d). As shown, the hardness of the steel increased from 190 HV to mean 250 HV in the PZ after FSP due to the substantial grain refinement and increase in dislocation density [13]. Fine grained microstructure formed around the pin where the highest hardness value is measured as a 320 HV due to the pin's forging effect and intense deformation resulting from the rotation. Ultrafine grained microstructure was formed around the pin due to the dynamic recrystallization and rapid cooling. This region has a high hardness value due to grain size strengthening (Fig. 5 (d)). This region of high hardness around the pin is a very narrow region and has caused inhomogeneity. This is a normal as considering the inhomogeneous distribution of fine grain and particles. During hardness measurement, the indenter coincided with this narrow inhomogeneous region and thus the hardness value is higher than other regions. Increasing in the hardness especially inside the PZ is because of the Hall-Petch effect coming from the substantial grain refinement [14]. Thus, the hardness profile mainly follows this approach. Therefore, the heat-affected zone (HAZ) has the lowest hardness value because of the relatively large grain size (Fig. 5 (c)). Because, only the heat generated through the process is effective in that region without considerable plastic deformation [15]. Microhardness profiles of the FSPed sample through the vertical sections are shown in Figures 6 (a)-(b). As shown, the hardness of the steel increased from 190 HV to mean 250 HV in the PZ.

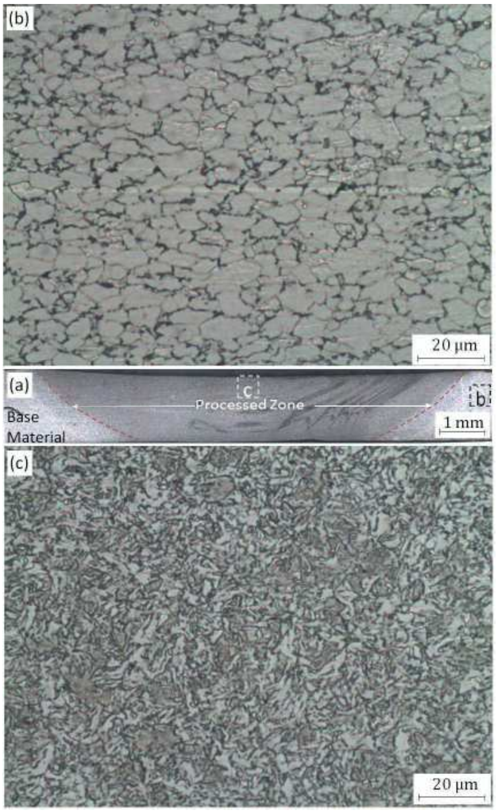

Fig. 3. (a) A general view of cross-section of the FSPed sample, (b) optical micrograph of the base HSLA steel and (c) optical micrograph of processed zone

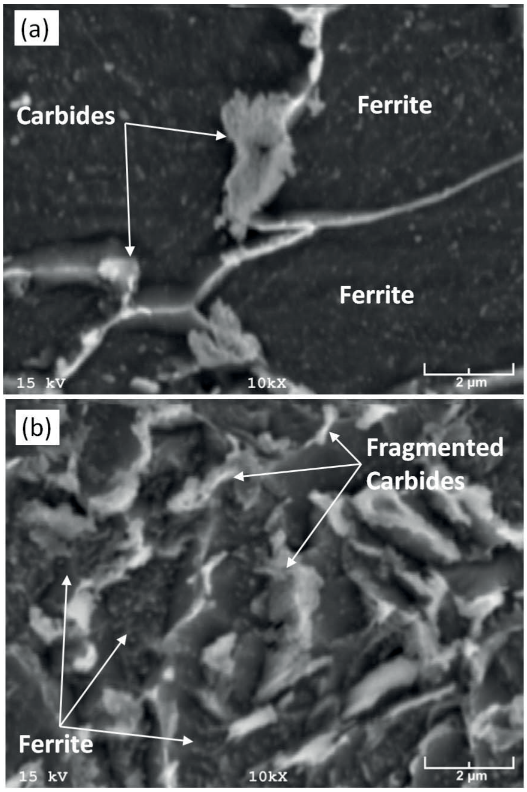

Fig. 4. (a) SEM micrographs of the HSLA steel, (b) SEM micrograph of processed zone

3.3. Tensile properties

The stress-strain curves of HSLA steel sheet before and after FSP are shown in Fig. 7, and the values of strength and ductility obtained from the curves are given in Table 2. Base HSLA steel sheet exhibits a characteristic curve of ductile materials with high strength and high elongation. As clearly seen, FSP caused a considerable increase in strength values with decrease in ductility of steel plates. The sample showed an increase in the ultimate tensile strength (σ_{UTS}) of about 34%, from 523 MPa for the base state to about 704 MPa for the FSPed state. Similarly, the yield strength (σ_Y) increased about 30% after FSP, from 417MPa to 545 MPa. Also, while the σ_{UTS}/σ_Y ratio is 1.25 in the HSLA steel, it increased to about 1.29 after FSP, which means that the strain hardening rate increased with FSP. The uniform and total elongation of the base material are about 19% and 40%, respectively. After FSP, these values decreased down to about 12% and 21%, respectively. After FSP, the increase in strength values can be attributed to the substantial grain refinement (Hall-Petch effect) and increase in dislocation density (strain hardening effect) [16].

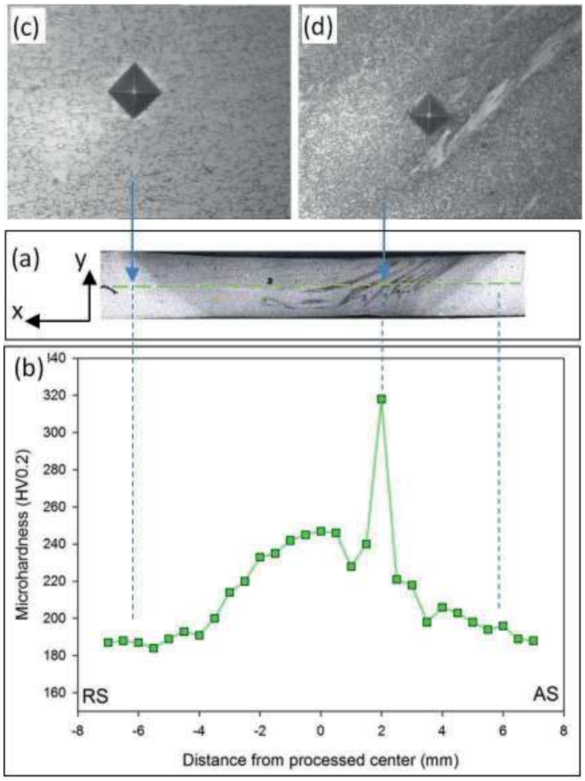

Fig. 5. (a) Optical micrographs and (b) hardness profiles of longitudinal of the FSPed sample, (c) microstructure of HAZ, (d) microstructure of inhomogeneous region in the PZ

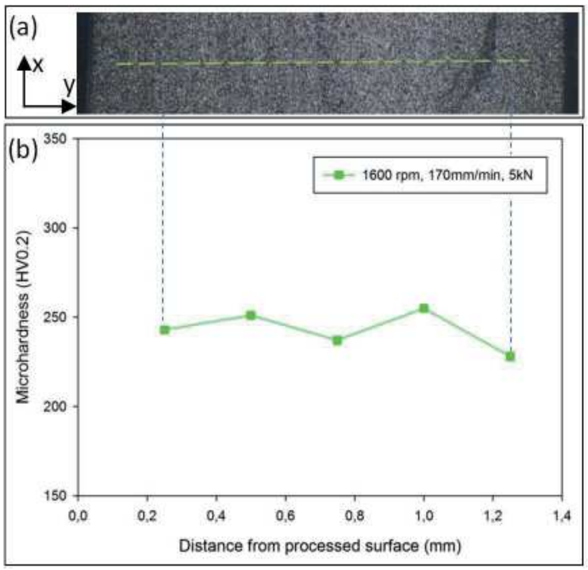

Fig. 6. (a) Optical micrographs showing the cross-sectional view of FSPed sample and (b) hardness profile from the top layer to bottom layer

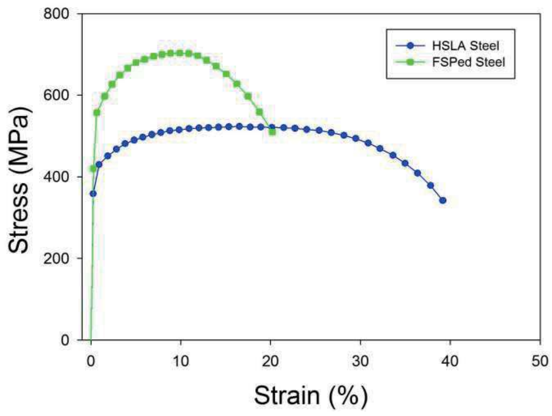

Fig. 7. Stress-strain curves of the HSLA steel and FSPed steel sheets

Table 2.
Main strength and ductility values of HSLA steel before and after FSP

Sample	Yield strength, MPa	Tensile strength, MPa	Uniform elongation, %	Failure elongation, %
HSLA	417	523	19	40
FSPed	545	704	12	19

4. Conclusions

HSLA steel was subjected to friction stir processing and its effects on the microstructure, hardness and tensile properties were investigated. The main conclusions of this study can be summarized as follows:

FSP results in a considerable refinement in the microstructure especially inside the PZ. The microstructure of the PZ is characterized by fine acicular ferrite with broken carbides.

The hardness of HSLA sample increases from 190 HV to mean 250 HV in the PZ after FSP.

FSP results in a considerable increase in strength of the steel sheet. Yield strength and tensile strength values increased from 417 MPa and 523 MPa to about 545 MPa and 704 MPa, respectively, after FSP. The uniform elongation and total elongation decreased from 19% and 40% to 12% and 21%, respectively, after FSP.

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