IOP Conference Series: Materials Science and Engineering

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Abstract. A low carbon structural steel was surface-hardened by friction stir processing (FSP) through 4 mm thickness from the surface. The hardness of the alloy increased from 140 Hv0.1 to about 240 Hv0.1 after single-pass FSP. This improvement came from the substantial microstructural refinement due to both severe plastic deformation and dynamic recrystallization. Both yield and tensile strength of the alloy increased without a considerable decrease in ductility after FSP. Friction and wear behavior of the alloy before and after FSP was investigated by a pin-on-disk type tribometer according to ASTM-G133. The substantial increase in both hardness and yield strength resulted in a considerable improvement in wear resistance of the alloy depending on applied pressure. In this study, metallurgical and mechanical reasons for such improvement in wear behavior and any change in wear mechanisms after FSP were investigated.

1. Introduction

Low carbon steels have been used in a wide range of applications from automotive sector to ship building industry due to their low cost, high workability and good weldability [1]. However, they have relatively low hardness and strength compared to high carbon steels which restricts their broader industrial applications. On the other hand, it is well known that harder materials provide lower wear rate and friction coefficient [2]. There are various ways to enhance hardness and strength of steels [3-4]. Heat treatment may be an effective way to enhance their hardness. Also, various thermomechanical [5-7] and plastic deformation treatments [6-8] are used to enhance the bulk and surface properties of low-carbon steels. Recently, much attention has been paid on surface modification techniques like friction stir processing (FSP). It is a new solid-state surface processing technique that can be used for surface hardening through microstructural modification, which was developed based on the principle of friction stir welding [9-11]. The basic concept of FSP is that a rotating tool including a pin and a shoulder is penetrated into a material surface and traversed along the desired path to cover the region of interest. During FSP, workpiece undergoes intense plastic deformation and high temperature during process, and dynamic recrystallized grains take place occur through that zone. Severe plastic deformation and thermal exposure of the material result in significant changes in the surface microstructure. As a result, three main zones form: the nugget zone (NZ), the thermos-mechanically affected zone (TMAZ) and the heat-affected zone. By the combined effects of severe plastic deformation and dynamic recrystallization bring about a microstructure with refined and equiaxed grains in the size range from 1.0 to 10 µm. The FSP has been used for many studies and thus more detailed information related to its processing principles and advantages can be obtained in earlier literatures [9, 12-16].

There are limited studies on the FSP of steels [17-21]. They mainly focused on the changes in both microstructural and mechanical properties. Also, no studies have been undertaken on tribological properties of FSPed steels.

It is well known that the wear resistance of steels depends mainly on their bulk and surface properties. It is accepted that the wear resistance of a material can be increased by increasing its surface hardness. FSP seems to be a simple way to enhance the mechanical properties of surface material. Thus, the main purpose of the current study is to apply FSP to a low carbon steel for modifying the microstructure and evaluate the changes in wear and friction behavior by the effect of FSP.

2. Experimental Procedure

In this study, a hot rolled low carbon steel (ABS-P2-96 Gr A) was used (table 1).

Table 1.Chemical composition of the low carbon steel (ABS-P2-96 Gr A) used in this study.

Elements	C	Mn	P	S	Si	Cu
Chemical Composition (%)	0.2	0.6	0.03	0.03	0.45	0.15

Samples with the dimensions of 200 mm x 40 mm x 6 mm were cut from the steel plate for FSP. FSP was performed with a processing tool having a convex shoulder with the diameter of 18 mm and a cylindrical pin with the diameter and length of 8 mm and 3 mm, respectively. FSP was conducted with a tool rotation of 635 rpm and a traverse speed of 45 mm/min. The shoulder tilt angle was set at 30, and the tool plunger downforce was kept constant at 11 kN during process.

Optical microscope (OM) was used to observe the microstructure of the samples before and after FSP. The specimens for OM were cross-sectioned on the processed sample perpendicular to the processing direction (figure 1), polished with standard techniques and then etched in %3 Nital (3ml. HNO3 + 97 ml. C2H6O) for 15 s.

Mechanical properties of the samples before and after FSP were determined using tensile test and hardness measurements. Tensile properties of the samples were determined using dog-bone shaped specimens with the dimensions of 2 mm x 3 mm x 26 mm using an electro-discharge machining (EDM). The tensile specimens were cross-sectioned parallel to the process direction (figure 1). The tests were performed using an Instron-3382 electro-mechanical load frame with a video type extensometer at a strain rate of 5.4×10^{-4} s^{-1} to be able to stay into the quasi-static deformation range. Hardness measurements were performed using a Vickers micro-hardness tester with a load of 300 g and a dwell time of 10 s. Hardness values were scanned along the cross-section of the sample as shown figure 1.

The dry sliding tests were carried out in a ball-on-disk type wear testing device (UTS Tribometer T10-20) at room temperature (20°C) and a relative humidity of about 75%. The samples (15 mm x 15 mm x 5 mm) were cut from processed an unprocessed material using an EDM. The wear experiments were conducted using an Al2O3 ball (6 mm in diameter). The wear test was carried out at sliding speeds of 0.125 m/s under normal loads of 5, 10 and 15N for a sliding distance of 250 m corresponding to a period of 30min. Prior to wear testing, all the specimen surfaces were ground with 1200 grit emery paper, cleaned with alcohol and then dried. The wear resistance was determined primarily by measuring the weight loss using a microbalance with an accuracy of ±0.1 mg. For the measurements, the samples were cleaned before and after each test with acetone in an ultrasonic bath for 5 min and subsequently dried with hot air. Also, 2D and 3D scanning of the worn tracts were also undertaken by a Nanofocus µscan in order to clarify the morphological features and determine the volume of the worn tracts (grooves).

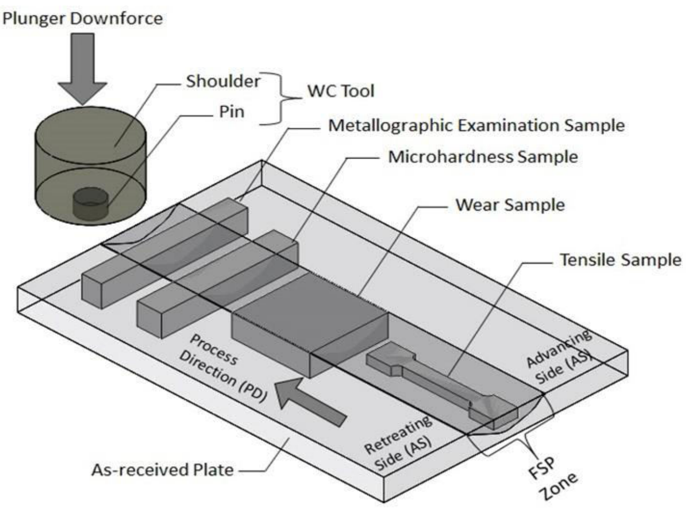

Figure 1. Schematic illustration of the FSP of the sample and the position and shape of specimens inside the processed regions.

3. Results and Discussion

3.1. Microstructure

Optical micrographs showing the microstructures of base and FSPed samples of the steel are given in figure 2. The initial microstructure of base steel plate is consisted of coarse ferrite+perlite grains with an average grain size of 25 µm (figure 2(a)). FSP resulted in a considerable refinement in the microstructure especially inside the nugget zone (NZ) (figure 2(b-c)). After FSP, the average grain size decreased from 25 µm down to about 3.0 µm in the NZ. The coarse ferrite and perlite grains were fragmented and refined by the effect of both severe plastic deformation and dynamic recrystallization during FSP [22]. TEM micrograph given in figure 2(c) showed that dislocation density increased during FSP into the stir zone. Also, most of the dislocations are accumulated at grain boundary regions, and the amount of dislocation decreases through the grain interiors.

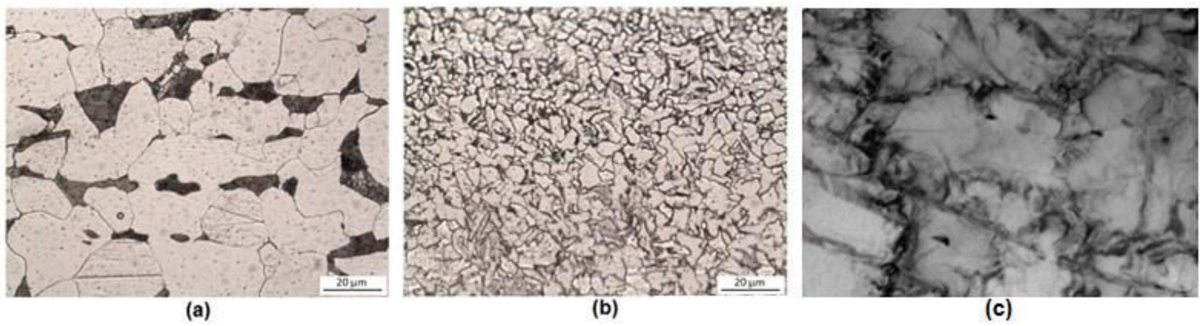

Figure 2. Micrographs showing the microstructures of: (a) based material and (b-c) FSPed region.

3.2. Mechanical Properties

The hardness profile taken from the vertical cross-section of the FSPed samples is shown in figure 3(a)-(b)). As shown, the hardness of steel increased from 140 Hv0.3 to about 200 Hv0.3 in the NZ after FSP due to the substantial grain refinement and increase in dislocation density [23]. However, the top most surface layer just beneath the shoulder has relatively low hardness. This may be due to the early recrystallization and grain coarsening effect due to the high pressing effect of shoulder [24]. Ultrafine grained microstructure formed around the pin increased the hardness to about 245 Hv in that zone (figure 3). This probably originates from the effectiveness of the pin end which not only rotate but also behaves like a forging affect and causes more refined microstructure in that zone compared to other region of NZ. After peak value around the pin end, the hardness starts decreasing through the rest of FSPed plate. However, the hardness value is still higher than that of the base material in the TMAZ (figure 3(a)-(b)). Because, only temperature-induced structural alteration without intense deformation is valid in that zone. After then, the hardness continuous to decrease and reaches a stable level near the other surface of the plate with the hardness values higher than that of the base material. As considering the sheet thickness, this result is normal. As seen from the cross-sectional micrographs (Fig. 3(a)) of the plate-type sample, all cross section of that sample was thermo-mechanically affected. So the effect of plastic deformation and also temperature generated during deformation caused grain refinement even up to other side of the steel plate. Thus, this microstructural alteration brings about higher hardness even opposite surface of the sample compared to the un-processed sample.

The strength and ductility values taken from the stress-strain curves of steel are given in table 1. As clearly seen, the steel before FSP exhibited low yield strength, good ductility due to the CG microstructure. FSP of the steel increased considerably its strength values without considerable decrease in ductility into the NZ. Both yield and tensile strength values increased from 256 MPa and 435 MPa to about 334 MPa and 525 MPa, respectively (table 1). FSP decreased slightly the elongation to failure from 44% to about 32%. The increase in strength values after FSP can be attributed to the substantial grain refinement (Hall-Petch effect) and increase in dislocation density (strain hardening effect) (figure 3(c)) [25]. It is well known that an increase in dislocation density occurs during FSP, and this formation make a further effect on strengthening of the FSPed microstructure [23]. Such microstructural changes also brought about a decrease in the ductility of the materials due to decreasing in their strain hardening effect [26]. However, it should be noted that ductility of the steel sheet was not radically decreased although the strength values increased considerably.

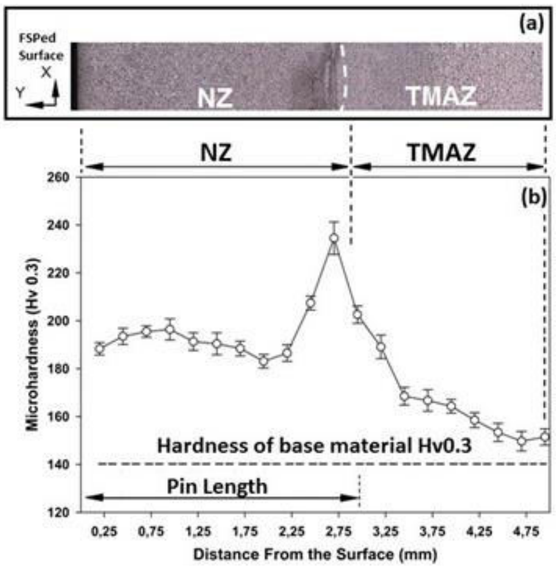

Figure 3. (a) Optical micrograph of vertical cross-section of FSPed sample and (b) hardness profile through the thickness of the plate.

Table 1. Mechanical properties the low carbon steel before and FSP.

Condition	Yield Strength (MPa)	Tensile Strength (MPa)	Uniform Elongation (%)	Failure Elongation (%)
Base	256±07	435±06	18.4±0.3	44.2±2.4
FSPed	334±06	525±13	13.9±0.6	32.4±1.7

3.3. Friction and Wear Behavior

Figure 4 shows the changes in friction coefficient of low carbon steel as a function of sliding distance before and after FSP. The curves indicate a sharp increase in friction coefficient during the initial sliding period with steady-state levels reached after about 50 m for both conditions. As carefully investigate, the FSPed sample shows slightly lower friction coefficient values inside the state-state period. Also, the scatter or variation in the friction coefficient values is relatively higher in the sample without FSP. After FSP, the sample exhibits more steady variations. The average coefficient of friction values in the state-steady-condition are 0.46 for the un-processed sample and 0.42 for FSPed sample.

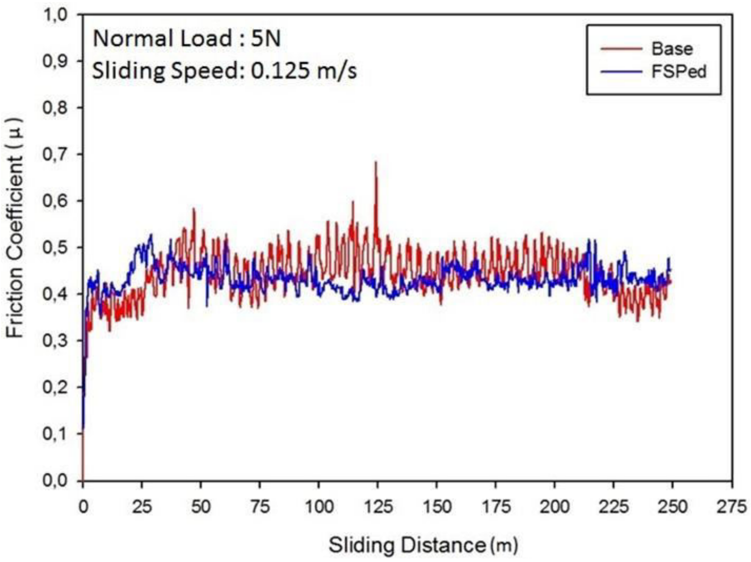

Figure 4. The coefficient of friction vs. sliding distance curves for the low carbon steel before and after FSP at room temperature and under 5N load.

Figure 5 shows a typical relationship between the weight loss and applied normal load for the base and FSPed samples of low carbon steel. Generally, it can be seen that amount of wear in both conditions increased with increasing normal load. The FSP increased the wear resistance and decrease the weight loss of steel under all loads. The difference in weight losses between base and FSPed samples is more pronounced under low loads, and it decreased with increasing normal load. The 2D and 3D profilometric views of wear tracts of base and FSPed samples are also shown in figures. 6(a)-(d). These profilometric results also confirm the results given in figure 6. Both diagrams demonstrate the same variation under all loads. As shown the wear depth increases with increasing applied load for all conditions. Also the depth of wear in the base material is higher than that of FSPed sample. This result is expected as considering the hardness and also yield strength of both conditions. As explained above, the hardness and strength increased substantially after FSP especially inside the NZ. This increase brings about an increase in resistance against to plastic deformation during rubbing, and thus the wear resistance of material increases [27]. Also, this improvement in wear resistance is higher under low normal loads. As the loads increases, the heat generated by the rubbing action increases which may cause recrystallization of processed zone. This microstructural alteration decreases the hardness of the rubbing surfaces with deterioration of the wear behaviour

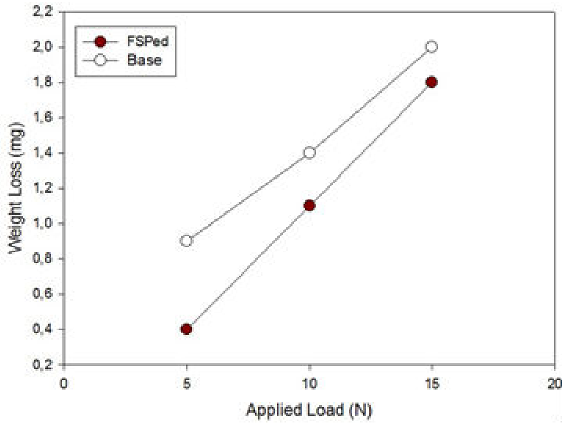

Figure 5. Weight loss of low carbon steel before and after FSP as a function of applied loads.

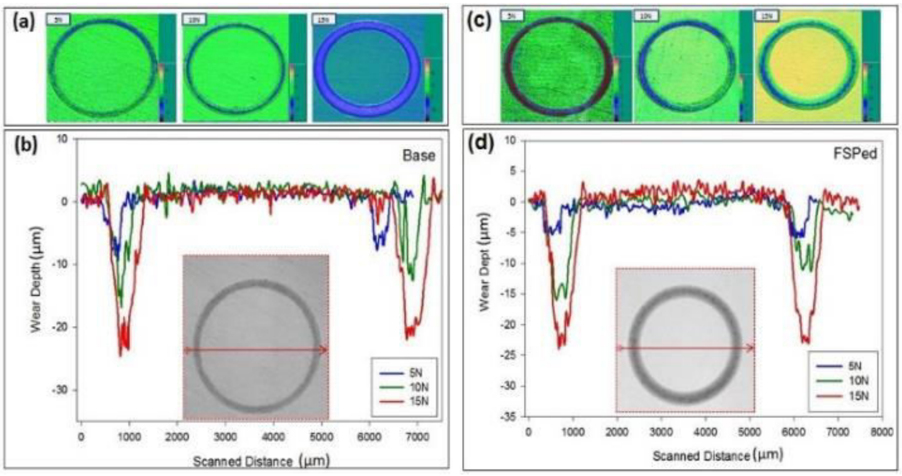

Figure 6. 3D profilometric view of wear tracts of steel under different loads and 2D view of worn tracts took place under different loads: (a)-(b) Base sample before FSP and (c)-(d) FSPed sample.

4. Conclusions

In the present study, the effect of friction stir processing (FSP) on the microstructure, mechanical properties and friction and wear behavior of a low carbon steel was investigated. The main results and conclusions of this study can be summarized as follows:

- A fine grained microstructure having mean grain size of 5 μm were obtained from the CG (grain size: 25 μm) steel with FSP. Such grain refinement leads to a significantly enhancement in strength and hardness without notably sacrificing the elongation to failure.
- FSPed sample has slightly lower coefficient of friction than un-processed sample. The average coefficient of friction values in the steady-steady-condition are about 0.46 for un-processed sample and 0.42 for FSPed sample.
- FSP increases the wear resistance of steel. This is associated with a considerable increase in its strength and hardness values after one-pass FSP.

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