EFFECT OF FRICTION STIR PROCESSING ON FATIGUE BEHAVIOR OF THIN DUAL PHASE (DP600) STEEL SHEETS

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Abstract

In this study, effects of Friction Stir Processing (FSP) on the deformation behavior of Dual Phase (DP600) steel sheets under static and cyclic loading were investigated. Fatigue tests were performed at a frequency of 15 Hz during repeated tension at a cycle asymmetry $R = 0$ and 10^6 loading cycles. DP600 steel reflected yield strength (σ_y) of 301 MPa and ultimate tensile strength (σ_{UTS}) of 621 MPa with uniform elongation of 21.3% and fractured after a total elongation of 34.7% in its as-received condition. After FSP, it was observed that the yield strength increased to 811 MPa and the ultimate tensile strength reached to 1054 MPa. This effective strength enhancement brought an acceptable decrease in ductility of the DP600 steel resulting in uniform elongation and elongation to failure of 6.3% and 13.0%, respectively. Based on obtained ductility values, it can be considered that, FSPed DP600 shows a deformation behavior that mostly dominated by the strain hardening. Static strength enhancement obtained by FSP of DP600 steel also yielded a favorable effect on the fatigue behavior and stress level leading to transition to the infinite life. As a result of the fatigue tests, it was determined that the fatigue limit of the as-received DP600 steel increased from 350 MPa to 480 MPa after the applied FSP. Experimental results obtained in the study mainly indicate that, FSP is an easy to apply and practical procedure which provides significant enhancement on the mechanical performance of DP600 steel under both static and cyclic loading conditions.

Keywords: Friction stir processing, DP steel, fatigue behavior, sheet metal

1. INTRODUCTION

Establishing weight reduction accompanied with superior mechanical strength and enhanced crash safety is one of the most important design strategies of the modern automotive industry [1, 2]. This strategy leads to the increasing adoption of high-strength materials for automobile body parts. Advanced high strength steels (AHSS) are mainly developed to satisfy high strength material needs of the automotive industry [3]. Currently, dual phase (DP) steels in various level of strength is one of the most widely used members of this steel family due to their adequate formability. Their unique microstructure consists of ferrite and martensite phases. Morphologically, martensite phases are mainly distributed within the ferrite matrix like small islands. Hence, volume fraction of the martensite phase mainly, directly related to the strength of the DP steels. Also, increasing strength of the DP steels may provide great advantage considering the lightweighting goals. One of the important approaches that can contribute to the mechanical performance of AHSS can be regarded as supporting their mechanical performance with innovative strength enhancement processes. It has been well shown that, severe plastic deformation methods provide a practical and easy to scale up approach to this goal.

Friction stir processing (FSP) is a relatively new solid-state process to be used to microstructural modification of the metallic materials [4-6]. It has been well documented that, FSP may be considered as an effective and useful tool for microstructural modification and grain refinement. Generally, combined effects of high level of deformation under conditions of warm to hot deformation conditions brings about occurrence of dynamic recrystallization. Hence, resultant microstructure of a FSP processed metal mainly consisted of equiaxed fine grains.

Given the potential technological advantages of this effective and flexible technology, several research efforts have been made to understand the mechanical response and engineering performance of the FSPed materials. To date, considerable attention has been paid especially to the light metals namely wrought and cast Al, Mg, Cu and Ti alloys [4-7]. It has been demonstrated in these studies that mechanical properties of course grain (CG) metallic materials could have been enhanced by microstructural refinement and reorganization [4-7]. Generally, enhanced hardness and strength can be achieved for variety of material groups according to Hall-Petch type strengthening [8, 9]. In limited studies, effect of the FSP on different type of steels such as stainless steels [10-16], interstitial free (IF) steels [9, 17-19], carbon steels [20-24] and high-strength low-alloy (HSLA) steels [25, 26] was investigated. On this point of view, strengthening of the DP steel via FSP may be beneficial to contribute to lightweighting goals of automotive industry. Moreover, to evaluate the contribution of the FSP on the structural integrity of an automobile chassis, one of the most important mechanical behavior that must be questioned may be fatigue [27, 28].

On the point of view outlined above, current study mainly concentrated on the effect of friction stir processing (FSP) on the microstructural evolution, mechanical properties cyclic deformation response and fatigue performance of DP steels.

2. EXPERIMENTAL PROCEDURE

A commercially available plate of tool DP 600 steel was used in this study. The chemical composition of the DP 600 steel is Fe - 0.14 C - 0.5 Mn - 0.1 P - 0.22 Ti - 0.015 Al - 0.09 Nb - 0.0015 S - 0.5 Si - 1.0 Cr (in wt.%). As DP steels are widely used in forming of structural parts of automobile body parts, a relevant thickness of 1.1 mm was selected to investigate possibility of application of the FSP to the thin AHSS. DP steel samples were subjected to one-pass FSP using a wolfram-carbide (WC) tool shoulder having a diameter of 14 mm. The shoulder tilt angle was 3° and the tool plunge depth was kept constant through the process. Tool rotation speed and processing speed was set at 1000 min^{-1} and 1.6 mm/s, respectively. Processing temperature was determined with an infrared thermal imaging camera.

Optical microscope (OM) and scanning electron microscopy (SEM) were used to observe the microstructure of DP steel samples before and after FSP. The metallographic specimens were sectioned perpendicular to the process direction (**Figure 1**) and then etched in 5 % Nital for 10 s after standard metallographic preparation.

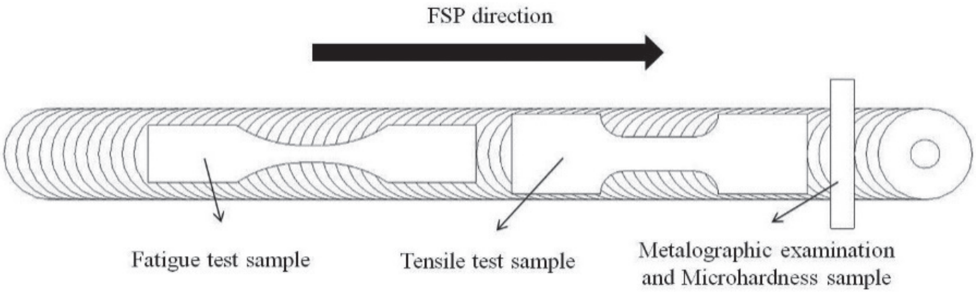

Figure 1 Schematic illustration of the FSPed plate and the position of the specimens inside the FSPed zone

To determine variation of the hardness within the processed regions, vertical and horizontal scans were performed at the geometrical symmetry axis of the sample. Hardness measurements were performed using a Vickers micro-hardness tester under a load of 0.5 g and for 10 s dwell time. Mechanical properties of the samples before and after FSP were determined with tensile test using dog-bone shaped specimens. Tensile test specimens were sectioned parallel to the process direction (**Figure 1**). Dimensions of the samples were determined due to ASTM E8/E8M as 12 mm x 6 mm x 1.1 mm. The tests were performed using a SHIMADZU electro-mechanic tension test machine at a strain rate of 0.001 s^{-1}. Flow curves and basic mechanical properties like yield strength, ultimate tensile strength, uniform elongation and elongation to failure were determined as mean values of the results obtained from at least three companion specimens.

Fatigue tests of as-received and FSPed samples were performed on a SHIMADZU servo-hydraulic machine at a frequency of 15 Hz during repeated tension at a cycle asymmetry $R = 0$ and 10^6 loading cycles. Fatigue test specimens were sectioned parallel to the process direction (**Figure 1**). Dimensions of the samples were determined due to ASTM E446 as 3 mm x 3 mm x 1.1 mm.

3. RESULTS AND DISCUSSION

Selected process parameters did not cause macro damage, cracking or deformation discontinuities. The highest process temperature during the FSP is determined to be 915 ± 20 °C. Microstructure of the as-received DP 600 steel consists of ferrite and martensite phases (**Figure 2**). Morphologically, ferrite phase grains are mainly equiaxed with a mean grain size 15 ± 5 µm (**Figure 2 (a)**). Size distribution of the ferrite grains were somehow homogeneous but finer grains in the size range of 5 - 10 µm were also evident in the microstructure (**Figure 2 (b)**). Very fine martensite phase grains (particles) are placed at the vicinity of the ferrite phase grain boundaries constituting nearly continuous network through the structure (**Figures 2 (a)-(b)**).

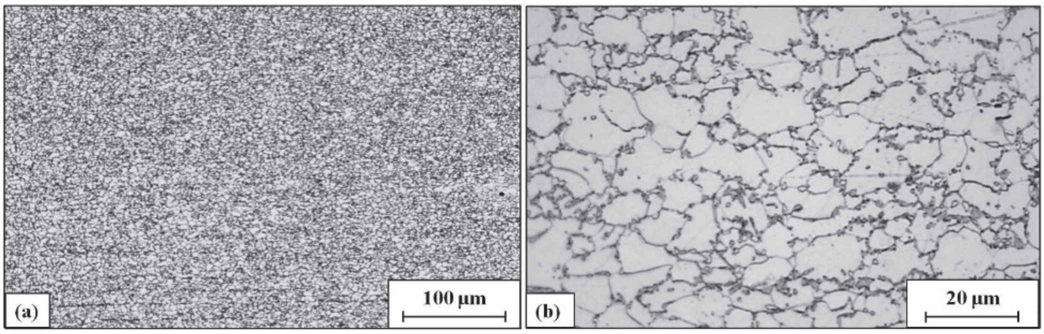

Figure 2 OM micrographs of microstructure of as received DP 600 steel at a different magnifications

The effects on the microstructural properties of the FSPed DP steel are shown in optical microscopy and scanning electron microscopy photographs given in **Figure 3**. FSP considerably affected the as-received microstructure. Also, thermo-mechanical process condition variations based on the changes plastic strain and deformation temperature formed some deformation regions that can be distinguished by the microstructural differences. These deformation regions are well defined and named in previous studies and indicated on the **Figure 3 (a)**. The FSP zone consists of an FSPed DP steel (**Figure 3**), heat affected zone (HAZ) (**Figures 3 (b)-(c)**), thermo-mechanically affected zone (TMAZ) (**Figures 3 (d)-(e)**), and stir zone (SZ) (**Figures 3 (f)-(g)**). In SZ, FSP process mainly reorganized microstructure of the DP steel (**Figures 3 (f)-(g)**). From **Figures 3 (f)-(g)**, it is obvious that martensite phase become more bulky and ferrite grains are somehow refined. It is also obvious that, ferrite grain size was not homogeneous through the microstructure. As can be understood from **Figures 3 (f)-(g)** fine ferrite grains with a size of 4 - 5 µm are formed in the microstructure of DP steel. A transition region between the SZ and the HAZ **(Figures 3 (d)-(e)**) known as thermo-mechanically affected zone (TMAZ) reflect similar microstructural properties with that of the SZ zone. Mainly bulky martensite phase along with refined ferrite phase formed in the TMAZ. Also ferrite phase morphology seems to be somehow elongated (**Figures 3 (d)-(e)**). By the end of the TMAZ, grain morphology gradually became alike with that of as-received material. However, grain size of the ferrite phase somehow coarsened compared to that of the as-received steel. This may be occurred due to deactivation of the dynamic recrystallization at regions farther from the stir pin. These regions are not deformed as effective as the SZ and TMAZ. However, heat generated by the shoulder and pin frictions rapidly transfer in the surrounding material. This leads HAZ to experience a thermal cycle, but not undergo any plastic deformation.

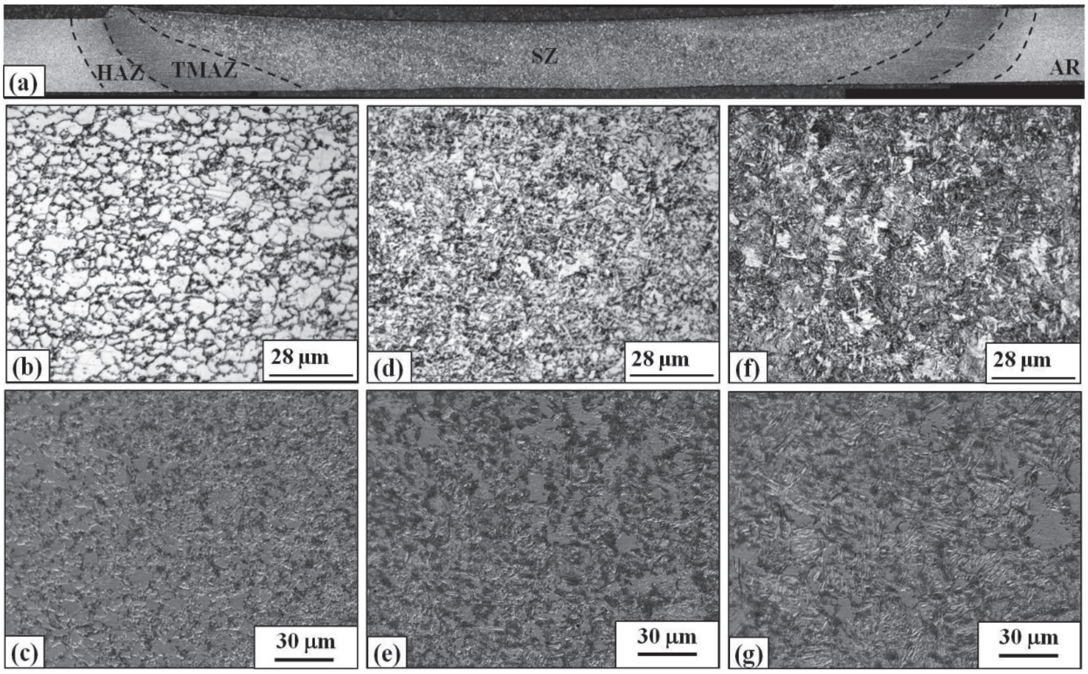

Figure 3 (a) A general view of cross-section of the DP steel after FSP (b)-(c) OM and SEM micrographs of HAZ (d)-(e) OM and SEM micrographs of TMAZ (f)-(g) OM and SEM micrographs of SZ

Hardness evolution of DP 600 steel after FSP is represented in **Figures 4 (a)-(b)**. Generally, FSP considerably enhanced hardness of the steel. As can be seen from the horizontal profile (**Figure 4 (a)**), hardness of the DP 600 steel sharply increase within the thermo-mechanically affected zone and reached to its peak value of 290 ± 20 Hv 0.5 at the SZ. However, hardness values measured at the HAZ are slightly lower than that of the as-received steel. Vertical hardness scan of the FSP processed steel also revealed similar trend of hardness enhancement (**Figure 4 (b)**). As can be understood from **Figure 4 (b)**, peak hardness values were measured at the surface contacting to tool shoulder and hardness of the steel and remained stable through a depth of about 0.6 mm. Beyond this depth, however, hardness values sharply decreased to the levels of the as-received steel (**Figure 4 (b)**). Such increase in hardness of the SZ may be considered as an expected result of the microstructural evolution including both grain refinement of ferrite phase and morphological alteration of the martensite phase. In accordance to the microstructural examination (**Figure 3**), transformation of the martensite phase from uniformly distributed fine particles to more bulky grains may be effective on the local hardness enhancement.

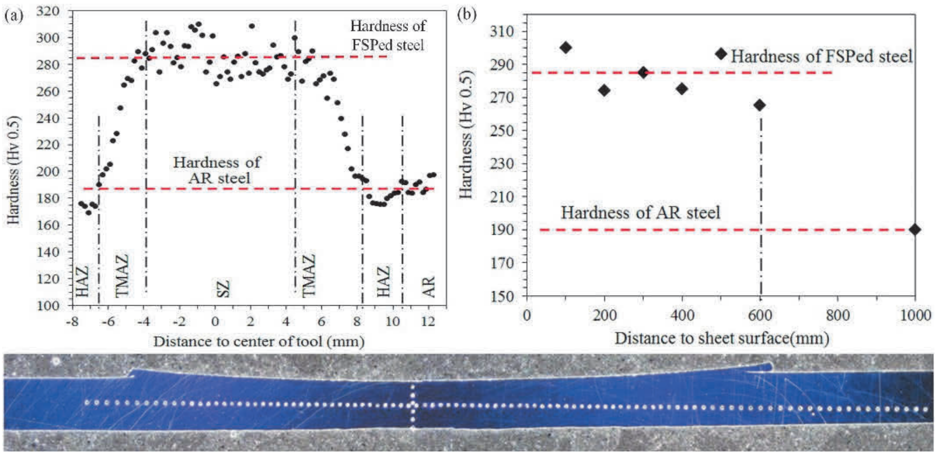

Figure 4 Hardness evolution of DP steel (a) Horizontal profile (b) Vertical (through thickness) profile

Engineering stress - engineering strain curves of the as-received and FSPed DP steel are represented in **Figure 5 (a)**. The yield strength (σ_y), ultimate tensile strength (σ_{UTS}), uniform elongation (ε_u) and elongation to failure (ε_f) taken from this curves are summarized in **Table 1**. As-received DP 600 steel reflected deformation behavior mainly dominated by the strain hardening behavior with a large strain hardening region with constitutes nearly equal to about half of the total elongation. This deformation behavior was somehow changed after the FSP. Generally, as can be observed form **Figure 5 (a)** that, strain hardening region and ductility of the DP 600 steel decreased after FSP. However, strain hardening behavior is still evident in the deformation curve of FSPed and dominated deformation behavior. Yield strength (σ_y) and ultimate tensile strength (σ_{UTS}) of the as-received DP 600 steel was determined to be 301 MPa and 621 MPa respectively. These strength values of as-received DP 600 steel was increased drastically by the effect of single pass FSP to 811 MPa and 1054 MPa respectively. However, uniform elongation and elongation to failure of the as-received material decreased from 21.3% and 34.7% to 6.3% and 13.0% respectively after the FSP process. Such improvement in strength of the FSPed sample is assumed to be primarily from the considerably refined microstructure leading to grain size strengthening and transformation of the uniformly distributed martensite phase particles in to bulky grains. These microstructural changes may also be effective on the decrease in uniform elongation and consequently elongation to failure of the FSPed steel due to the increased cracking tendency of the microstructure.

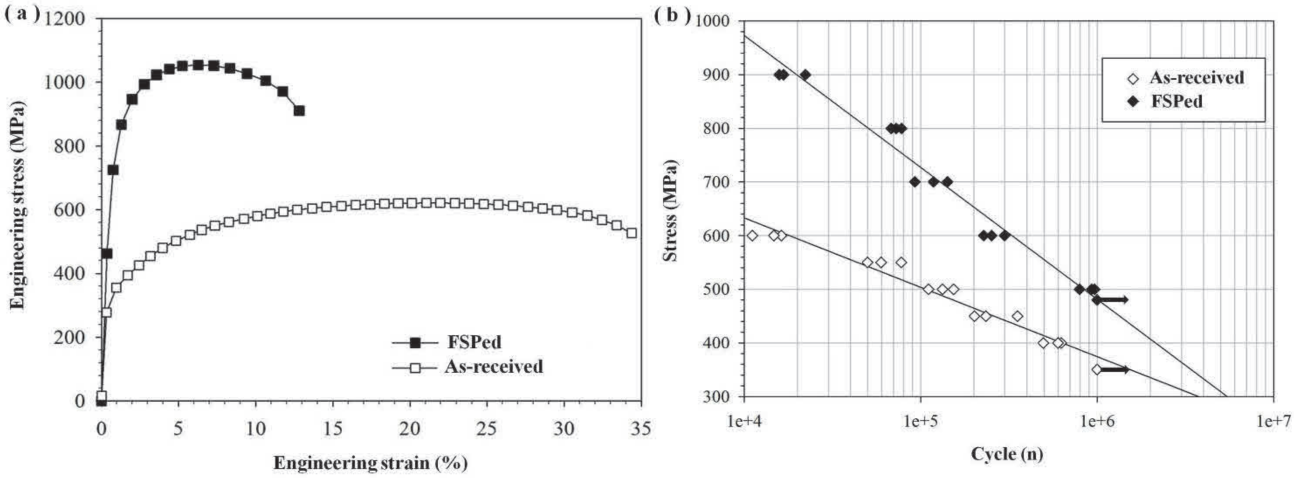

Figure 5 (a) Engineering stress - engineering strain curves of as-received and FSPed DP steel (b) Stress - cycle curves of as-received and FSPed DP steel

Table 1 Mechanical properties of as-received and FSPed DP steel samples

	σ_y (MPa)	σ_{UTS} (MPa)	ε_u (%)	ε_f (%)
As-received	301.0 ± 6	621.1 ± 13	21.3 ± 0.2	34.7 ± 2
FSPed	811.7 ± 48	1053.8 ± 56	6.3 ± 0.1	13.0 ± 2

S-N curves of as-received and FSPed DP steel samples are shown in **Figure 5 (b)**. From Figure **5 (b)** it is understood that, as-received DP steel showed fatigue limit of 350 MPa. When **Figure 5 (a)** and **Figure 5 (b)** examined together, it can be observed that yield strength and fatigue limit of the as-received material are at the same level. Applied FSP causes significant effects on both fatigue behavior and fatigue limit of DP steel. It is observed that FSP increases the slope of the S-N curve of DP steel. This increase in the slope of the S-N curve after the process leads to an increase in the number of cycles to fracture. Consequently, fatigue limit in the processed state was improved to reach a stress value of 480 MPa. The improvement in fatigue behavior can be attributed to the superior strength of the FSPed DP steel. It is noteworthy that, when

Figure 5 (a) and **Figure 5 (b)** examined together, it can be observed that fatigue limit of the FSPed material (480 MPa) is lower than FSPed yield strength (811 MPa). It is understood that FSP shifts the fatigue strength from the plastic deformation zone to the elastic deformation zone. This may be explained with an increased crack initiation tendency of the FSPed microstructure due to the transformation of the morphology of the martensite phase from uniformly distributed fine particles to bulky grains.

4. CONCLUSION

In the present study, the effect of friction stir processing (FSP) on the microstructural evolution, mechanical properties and fatigue behavior of DP steel was investigated. The main results and conclusions of this study can be summarized as follows:

- Thin (1.1 mm) DP steel sheets were successfully processed by position controlled FSP without causing macro damage, cracking or deformation discontinuities.
- In the process region microstructure of DP steel is strongly affected by FSP and fine grained microstructure having mean ferrite grain size of 5 μm and bulky martensite phase were obtained.
- Microstructural modification obtained by intense thermo-mechanical treatment of FSP increased hardness of the DP 600 steel from 190 Hv 0.5 to about 290 Hv 0.5.
- Deformation behavior of DP 600 steel found to be strain hardening dominated. This behavior remained unchanged after the FSP. FSP also strongly enhanced steel yield strength and tensile strength of DP 600 steel from 301 MPa and 621 MPa to 811 MPa and 1054 MPa, respectively. However, uniform elongation and elongation to failure values contracted from 21.3% and 34.7% to 6.3% and 13.0%, respectively.
- FSP process applied to the DP 600 steel favorable increased as-received fatigue limit of 350 MPa to 480 MPa.

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