Effect of Notch Position on Impact Toughness of Friction Stir Processed Low Carbon Steel

Dursun Murat Sekban[1], Semih Mahmut Aktarer[2], Zongyi Ma[3] and Gençağa Pürçek[4]*

purcek@ktu.edu.tr

[1]*Department of Naval Architecture and Marine Engineering, Surmene Faculty of Marine Sciences, Karadeniz Technical University, Trabzon, Turkey*

[2]*Department of Automotive Technology, Recep Tayyip Erdogan University, Rize, Turkey*

[3]*Shenyang National Laboratory for Materials Science, Institute of Metal Research, Chinese Academy of Sciences, Shenyang, China*

[4]*Department of Mechanical Engineering, Faculty of Engineering, Karadeniz Technical University, Trabzon, Turkey*

Abstract

The effect of single-pass friction stir processing (FSP) on the room temperature impact toughness of a low carbon steel was investigated via Charpy impact test. A fine-grained (FG) microstructure was achieved into the processed zone by large deformation and simultaneous dynamic recrystallization during FSP. The average grain size decreased from 25 µm down to 3.0 µm after FSP. Grain refinement by FSP increased the impact energies as a result of refined grains separated mostly by high-angle of misorientation. Toughness of steel before FSP was about 8.7 J, and it increased up to 11.2 J after processing depending on the notch positions of the samples. The peak impact toughness value of 11.2 J was achieved with the notch position located at top of the surface of processed steel plate.

Keywords*:* Impact toughness, low carbon steel, friction stir processing.

1. Introduction

Low carbon steels are well-known ones among the traditionally employed construction materials. General requirements imposed on such steels are high strength, good corrosion resistance, satisfactory weldability and low susceptibility to cold embrittlement. Grain refinement is known to suppress material susceptibility to cold embrittlement. Grain refinement by severe plastic deformation (SPD) techniques are the promising ones considering their applications and refinement capacity. Among them, friction stir processing (FSP) is one of the best severe plastic deformation (SPD) techniques as considering the processing of large scale plate or sheet type materials (Aktarer et al., 2015). This is a novel microstructural modification method based on the basic principles of friction stir welding (FSW) (Mishra and Ma, 2005) & (Ma, 2008). In many cases, FSP leads to the transformation of the coarse-grained (CG) initial microstructure into equiaxed fine grained (FG) or even ultrafine-grained (UFG) structures consisting mostly of high angle grain boundaries (HAGBs) (Mishra and Ma, 2005) & (Su et al., 2005) & (Ma et al., 2008).

It is, on the other hand, well known that the mechanical properties are more-or-less depending on the orientation or position of the sample inside the FSPed zone. This effect would be more pronounced considering the notched impact behavior of steels (Ray et al., 1995) & (Joo et al., 2013). Till now, no considerable study has been performed on the impact toughness of FSPed low carbon steels. Also no investigation has been undertaken on the effect of notch position on the impact toughness of FSPed steels. Thus, the main purpose of this study is to investigate the effect of FSP on the room temperature impact toughness of a low carbon steel. Also, the effect of the notch position through the processed zone on the impact toughness of the processed sample was studied.

2. Experimental procedure

A well-known carbon steel sheets initially hot-rolled (0.16 wt % C, 0.18 wt % Si, 0.7 wt % Mn, 0.11 wt % S, 0.18 wt % P, 0.09 wt % Cr , 0.14 wt % Mo, 0.04 wt % Cu, 0.04 wt % V and balance Fe) was used in this study. Samples with the dimensions of 200 mm x 40 mm x 6 mm were cut from the steel plates for performing 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 3^0, and the tool plunger downforce was kept constant at 11 kN during process.

Optical microscope (OM) and transmission electron microscope (TEM) were 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, polished with standard techniques and then etched with a %3 Nital (3ml. HNO3 + 97 ml. C_2H_6O) for 15 s. The TEM was performed using an FEI Tecnai F20 microscope, operated at a nominal voltage of 200 kV.

The impact toughness of the specimen was evaluated at room temperature by measuring the total absorbed energy using Charpy impact test before and after FSP. The samples with the dimensions of 3 mm x 4 mm x 27 mm with a V-notch depth of 1 mm and a radius of 0.1 mm were cut from the FSPed plate with different notch position (NP) according to DIN50115 (Fig. 1). The fracture surfaces of the fractured specimens were observed using a JEOL 6400 scanning electron microscope (SEM) operated at 15 keV in the secondary electron image mode.

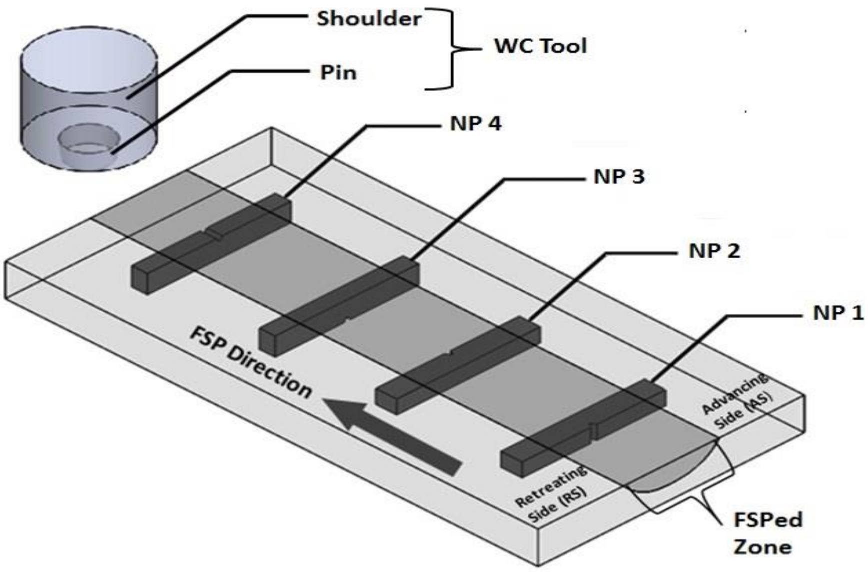

Figure 1. Schematic illustrations showing the FSPed samples and the geometry and position of the impact test specimens inside the processed sample.

3. Results and discussion

3.1. Microstructure

The initial microstructure of base steel plate before FSP is well-known and consists mainly of coarse-grained (CG) ferrite with an average grain size of 25 µm and smaller grains of fine pearlite (Fig. 2(b)). FSP resulted in a considerable refinement in the microstructure of steel inside the processed zone (NZ) (Fig. 2(c)-(f)). A fine-grained (FG) microstructure formed after FSP with decreasing the grain size from 25 µm down to about 3.0 µm in that zone. The coarse ferrite and perlite grains in CG sample were fragmented and refined by the effect of both severe plastic deformation and dynamic recrystallization during FSP (Xue et al., 2013). The microstructure of the stir zone was characterized by the presence of ferrite with aligned and nonaligned second phase of perlite, grain boundary ferrite, and a ferrite/carbide aggregate that appears to be fine pearlite (Lienert et al., 2003). As shown in Fig. 2(e), the top most surface layer just beneath the shoulder has relatively coarser grain size. This may be due to the early recrystallization and grain coarsening effect due to the high pressing effect of shoulder (Prangnell and Heason, 2005). Finer microstructure formed around the pin due to pin's behaves like a forging affect as well as rotation (Fig. 2(f)). From the TEM micrograph (Fig. 2(c)), refined grains are separated mostly by high-angle grain boundaries. TEM micrographs also show that the FG microstructure includes dislocations. However, the dislocations in the microstructures are unevenly distributed in such a way that some grains in their central parts are rather free of dislocations, and most of the dislocations are accumulated and tangled with others around grain boundaries (Fig. 2(e)).

Such distribution of the dislocations is normal, because dynamic recovery and partly recrystallization occurs during deformation, which spreads the trapped lattice dislocations into grain boundaries.

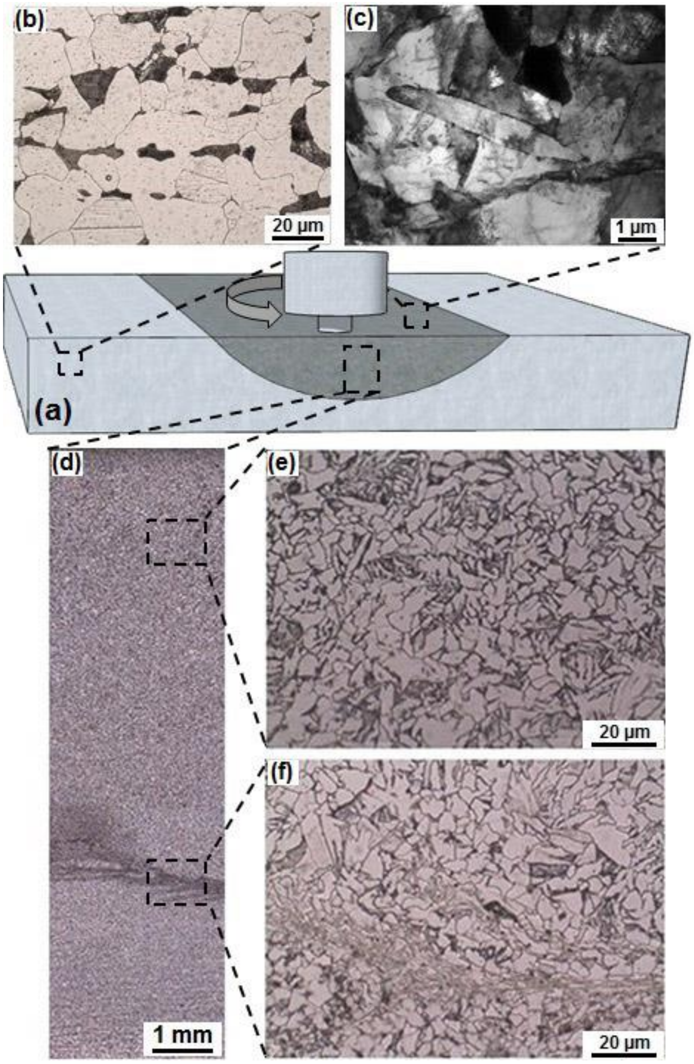

Figure 2. (a) Schematic illustrations of the FSPed plate. (b) Optical micrographs showing the microstructures of un-processed coarse grained steel plate. (c) TEM micrographs showing the microstructures of FG FSPed low carbon steel. (d)-(f) Optical micrographs showing the microstructures of FG FSPed low carbon steel in detail.

3.2. Impact toughness

Room temperature impact toughness values of all specimens before and after FSP are given in Fig. 3. Toughness of the CG steel before FSP is about 8.7 J, and it increased up to 11.2 J after grain refinement by FSP depending on the notch position inside the FSPed sample. The increase in toughness at low temperatures was attributed mainly to the substantial microstructural refinement with grains separated mostly by high angle of misorientation (Saray et al., 2012). The grain refinement from 25 μm down to 3 μm by FSP significantly increased the amount of grain boundaries and brought about an improvement in impact toughness. More grain boundaries mean more barriers in front of the crack propagation. As the cleavage crack propagates along several grains, both the crack tip dislocations and the formation of cleavage facets are interrupted by these boundaries (Song et al., 2005). The peak impact toughness value of 11.2 J was achieved with the notch position located at top of the surface of processed steel plate (Fig. 3). The other notch positions of NP1 and NP2 (the notch located along the processed directions) gave more or less the same toughness values (10.4 J), while the NP3 (the notch located backside of the processed plate) resulted in a slightly higher value (10.8 J) compared to NP1 and NP2 (Fig. 3). In literature, three basic factors were underlined for clarifying the reasons of toughness anisotropy: non–uniform distribution in the size and shape of inclusions, microstructural anisotropy due to chemical segregation with banding or elongated grain structure and crystallographic texture (Ray et al., 1995) & (Joo et al., 2013). Top-most surface and around of the pin have finer grains compared to other processed regions. This is coming from the effectiveness of the pin and shoulder in that region where both rotation and forging effects are working together leading to more refined microstructure in that zone compared to others. Thus, the specimen with the notch position in NP4 showed the highest toughness among the others. The other specimens followed the same behavior with the change in grain size.

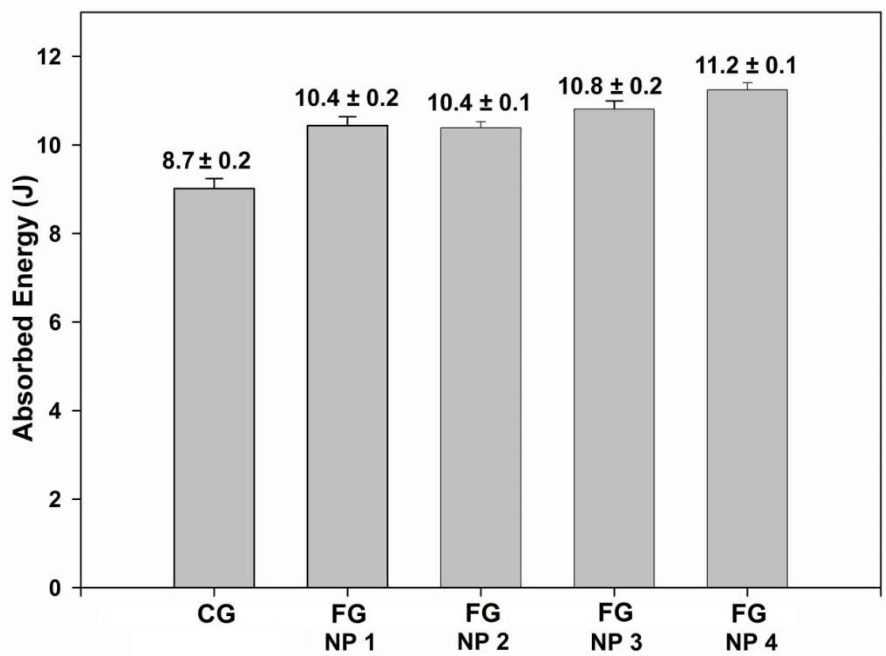

Figure 3. (a) The impact toughness values of both CG and FG specimens. The impact toughness of FG specimens were given depending on notch position inside the friction stir zone.

Morphological features of the fractured surface were also investigated, and representative ones for the specimens before and after FSP were shown in Fig. 4((a)-(b)). In general, a shear-type future morphology without fine dimples is more pronounced in the CG specimens before FSP (Fig. 4(a)). Also, large size voids or fractured valleys is coming from the coarse grained microstructure of initial steel.

FSP changed considerably the fracture surface morphology of the specimen (Fig. 4(b)). As clearly seen, mostly fine dimple-like fracture surface becomes effective due to the more refined microstructure, which also validates relatively high toughness value after FSP.

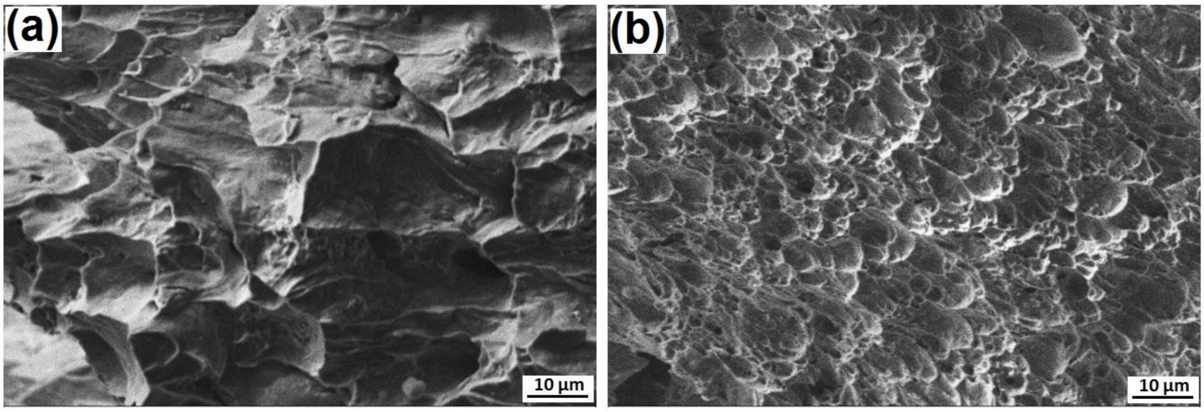

Figure 4. SEM micrographs showing the impacted fracture surfaces of: (a) CG base and (b) FG FSPed steel plates.

4. Conclusions

Room temperature impact toughness of a low carbon steel processed by single-pass FSP was investigated considering the effect of notch position of the samples inside the processed zone. The main results and conclusions of this study can be summarized as follows:

1. A fine-grained (FG) microstructure with an average grain size of about 3 µm was obtained from a coarse grained (25 µm) microstructure of low carbon steel by a single-pass FSP.
2. The microstructural modification by FSP increased room temperature impact toughness of the steel plate at all notch positions. Toughness of CG steel was about 8.7 J before FSP, and it increased up to 11.2 J depending on the notch position. The peak impact toughness was achieved with the notch position located at top of the surface of processed steel plate because of the finest grain size compared to other positions.
3. Ductile fracture mode becomes more effective under impact loading after grain refinement by FSP with decreasing dimple size and increasing amount of the dimples on the fracture surface.

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