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Formability of friction stir processed low carbon steels used in shipbuilding

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ABSTRACT

The stretch formability of a low carbon steel processed by friction stir processing (FSP) was studied under biaxial loading condition applied by a miniaturized Erichsen test. One-pass FSP decreased the ferritic grain size in the processed zone from 25 μm to about 3 μm, which also caused a remarkable increase in strength values without considerable decrease in formability under uniaxial loading. A coarse-grained (CG) sample before FSP reflected a moderate formability with an Erichsen index (EI) of 2.73 mm. FSP slightly decreased the stretch formability of the sample to 2.66 mm. However, FSP increased the required punch load (F_{EI}) due to the increased strength by grain refinement. FSP reduced considerably the roughness of the free surface of the biaxial stretched samples with reduced orange peel effect. The average roughness value (Ra) decreased from 2.90 in the CG sample down to about 0.65 μm in fine-grained (FG) sample after FSP. It can be concluded that the FG microstructure in low carbon steels sheets or plates used generally in shipbuilding provides a good balance between strength and formability.

1. Introduction

Designing of light-weight, safe, durable and low-cost constructions is one of the most important and essential design criteria of the modern transportation industries including shipbuilding, automotive and railway to be able to introduce energy saving, high performance vehicles with affordable prices. To satisfy these design criteria, high strength materials with good formability and low-cost are desired.

Low carbon steel sheets/plates have been widely used in transportation industries due to their high availability, good formability and excellent weldability. However, they have low strength, hardness and fatigue resistance due to their low carbon content. This is an important drawback of these steels sheets/plates for light-weight and energy saving design strategies of the transportation industries. Hence, any attempts providing strengthening of such steels without a considerable decrease in their formability may contribute to their performance by satisfying industrial needs. In addition, such attempts should be applicable in the industrial scales.

It has been well established that grain refinement (Hall-Petch effect) is an effective way for strengthening low carbon steels without changing their chemical composition. Advanced thermo-mechanical processing (ATMP) and classical severe plastic deformation (SPD) methods have been developed to dramatically refine the microstructure and produce fine grained (FG) or ultrafine-grained (UFG) steels [1]. Steels produced through these routes are generally characterized with high strength accompanied with inferior ductility and limited formability. This is mainly because of severely deformed microstructure having very high dislocation density leading to a remarkable loss of strain hardenability after the processing [2] Thus, new approaches or methods are needed to improve strength of the ordinary low carbon steels without considerable scarifying their ductility and formability.

Friction stir processing (FSP) is a recently developed microstructural modification technique for plate or sheet types of metallic materials based on the basic principles of friction stir welding (FSW)

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[3,4]. This method can also be considered as one of the new generation SPD techniques, and more detailed information regarding its principles and applications can be found elsewhere [5–8]. But shortly, a non-consumable rotating tool with a shoulder and pin is inserted into a metal plate or sheet and traversed through a direction of interest during FSP. Heat generated by the frictional effect between tool and surface of the material during processing locally softens the processing volume [9]. The material in the processed zone (PZ) undergoes severe plastic deformation at elevated temperatures which caused a remarkable grain refinement by dynamic recrystallization [7,10,11]. In general, dynamically recrystallized grains with mainly equiaxed morphology and large fraction of high angle grain boundaries (HAGBs) in the PZ form as a result of processing [7,9,10,12].

FSW/P have been generally apllied low melting point aluminium alloys due to their easy workability [13–22]. However, as a result of improvement in high temperature resisting tool materials FSP have been successfully applied to several type of steels including ultra-low carbon steels (IF-steel) [23,24], low carbon steel [1], medium carbon steels [25], high carbon steels [26–28], high strength low alloy (HSLA) steels [29,30], dual phase steels [31], tool steels [32–34] and stainless steels [35–39]. These studies have shown that an effective strengthening can be achieved without a considerable decrease in uniaxial uniform elongation after FSP [6,23]. However, formability of the FSPed steels has been rarely investigated.

Considering the engineering applications, formability is an essential property, and any changes in its characteristics under uni- and bi-axial loading conditions should be well characterized by connecting microstructural alterations occurring during processing. Therefore, the aim of this work is to investigate the effect of FSP on the formability of low-carbon steels under biaxial loading conditions. Also, the microstructural evolution and uniaxial tensile properties after FSP processing were investigated to clarify the relationships between uniaxial and biaxial deformation behavior of the low carbon steels after extensive grain refinement.

2. Experimental procedure

A low carbon hot rolled steel used generally in ship building with the chemical composition given in Table 1 was utilized in the present study. For FSP, samples having the dimensions of 200 mm × 40 mm × 6 mm were machined from the steel plates. FSP was performed using a WC 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. This processing parameters were chosen according to the preliminary studies in order to be able to obtain the optimized property outcomes. For this purpose, a range of tool rotation rates from 500 rpm to 800 rpm and traverse speeds from 35 mm/min to 55 mm/min were scanned, and the values of 635 rpm and 45 mm/min were determined as they gave better property outcomes then others regarding the mechanical properties of FSPed steel. The shoulder tilt angle of 3^0 was set, and the tool plunger downforce was kept constant at 11 kN during processing.

Scanning electron microscopy (SEM) and optical microscopy (OM) were utilized for examining microstructural evaluation of steel samples prior and after FSP. Samples for metallographic investigations were sectioned perpendicular to the processing direction (Fig. 1(a)) and then etched in 3% Nital after standard metallographic preparation.

Mechanical properties were obtained using a uniaxial tensile test. Tensile properties of steel samples were determined with dog-bone shaped specimens with dimensions of 2 mm × 3 mm × 26 mm. The tensile specimens were extracted from the processed samples where their tension axis is parallel to the processing direction (Fig. 1(a)). The tests were done with an Instron-3382 electro-mechanical load frame having a video type extensometer at a quasi-static strain rate of $5.4 \times 10^{-4}\ \mathrm{s}^{-1}$.

Erichsen test technique was used for evaluation of stretch formability of the samples under biaxial strain conditions before and after FSP. For this purpose, the specimens with the dimensions of 13 mm × 0.7 mm were sectioned from the SZ of FSPed sample and also unprocessed sample (Fig. 1(a)). A miniaturized Erichsen die system which was constructed as 25% of standard Erichsen test fixture as shown in Fig. 1(b). This system was attached to the Instron 3220 universal testing machine and the tests were performed at a punch speed of $0.01\ \mathrm{mm\,s}^{-1}$ without using any lubricant. In order to avoid from crack initiation effect of the tool scars, specimen surfaces were prepared by grinding and polishing before Erichsen test.

SEM was used for investigation of the dome free surfaces of stretched FSPed and unprocessed samples. Also, 2D and 3D scanning of the dome surfaces were also undertaken by a Nanofocus μscan in order to determine the morphological features and specify the surface roughness of dome surface before and after FSP.

3. Results and discussion

3.1. Microstructure

The initial microstructure of the steel plate before FSP is a typical structure for a plain low carbon steel consisting of coarse ferrite (white in color) and perlite (black in color) phases as shown in Fig. 2(a)–(b). The pearlitic phase located along the boundaries of ferritic grains is elongated or banded due to the initial hot rolling process. In general, the ferritic phase has equiaxed coarse grains with 25 μm average grain size.

FSP had a remarkable effect the microstructure of processed zone. Optical and SEM micrographs showing the effect of FSP on the global microstructure of global steel plate and at different regions of Erichsen test samples are shown in Fig. 3(a)–(d). In general, a remarkable grain refinement in the microstructure occurred especially inside the stir zone (SZ) (Fig. 3). After FSP, the average grain size inside the ferritic phase decreased from 25 μm down to 3.0 μm. In the processed region, the coarse-grained (CG) structure of as-received steel transformed to the fine-grained (FG) structure. The coarse ferrite and perlite grains in the as-received steel were fragmented and refined by combined effect of severe plastic deformation and dynamic recrystallization during FSP [1].

As looking at the global view of the processed plate, it is clear that the FSPed region consists of two distinct zones; stir zone (SZ) and heat affected zone (HAZ) as in the case of conventional welding of such steels (Fig. 3(a)). The SZ exhibits a characteristic nature of dynamic recrystallization [3,4,40,41]. This zone undergoes both severe plastic deformation and frictional heating during FSP. Optical and SEM micrographs representing the microstructure in the middle of the SZ (also the region where the Erichsen samples were taken) are shown in Fig. 3(b)–(d). In that zone, the microstructures consist mainly of grain boundary ferrite (GBF), Widmanstatten ferrite (WF) and aggregates of ferrite + cementite (FC). Widmanstatten ferrite usually forms as colonies of coarse side-plates with aligned microstructure that grows from prior austenite because of elevated temperature caused by FSP.

3.2. Uniaxial tensile behavior

The engineering stress-strain curves of steel before and after FSP are shown in Fig. 4, and corresponding mechanical properties