Microstructure and mechanical properties of friction-stir welded interstitial-free steel using WC tool

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Abstract. In the present work, interstitial-free steel plates were joined using friction-stir welding. The weld integrity was found to be in excellent condition. This work emphasises the evolution of microstructure and the enhancement of mechanical properties by friction-stir welding. The microstructural characterisation using optical image microscopy revealed the refinement of grains in the nugget zone. Vicker's hardness test stopped to a maximum of ~91 VHN in the nugget zone compared to ~40 VHN in the base material. The tensile test of the welded sample concluded that the samples fractured in the region away from the nugget zone and towards the base material. The results are conclusive that friction-stir welding is an excellent approach for joining interstitial-free steel components for automotive applications.

Keywords: Friction-stir welding, Interstitial-free steel, Microstructural characterisation, Micromechanical behaviour.

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1. Introduction

The interstitial-free (IF) steel was developed commercially in Japan after introducing the vacuum degassing technology in the 1980s [1]. The term 'interstitial free' was coined due to the fact that the interstitial components are present in the range of 30-40 ppm (traces). Thus, this steel is softer than even low-carbon steel due to its alloy chemistry. Currently, the applications of IF steel ranges from the automotive parts, enamel wares, electronic components, and whitegoods industry [2–4]. It has high formability, which is capable of providing a complex geometries as the primary reason [2]. This steel is reported to have the Lankford parameter ≥1.8 and the strain hardening exponent ≥ 0.22 as useful typically for automotive [5]. Carbon and nitrogen are the major interstitial elements. They are found to be negligible in this steel and are further guttered by alloying elements like titanium and niobium due to their strong carbide/nitride forming tendency. It results in the absence of interstices between the solidified iron atoms. This also leads to the absence of yield point or Lüders bands formation during plastic deformation, which gives an excellent surface finish [3,6]. IF steels are known for their excellent ductility and deep drawing properties. These properties are attributed because of a high
plastic strain ratio (r-value). IF steels are clean steels with a predominant ferrite (BCC) microstructural phase at room temperature [1].

IF steels are already soft and easily formable, which is attributed to their single-phase coarse grain microstructure. If conventional fusion welding is applied to these steels for joining, then the grain growth kinetics easily initiates due to the high heat input resulting in a coarser microstructure, further decreasing the strength. Moreover, friction-stir welding (FSW) is categorised as a solid-state joining method leading to grain growth inhibition because of the lower heat input [7-8]. The Welding Institute (TWI) Ltd. was the first to develop the FSW technique in 1991 [9]. The FSW process uses a tool that is generally harder (non-consumable) than the base material. The tool is rotated at a high rpm, and the tip is forced to penetrate into the interface of the two plates. The tool is then moved forward through the work-piece(s) interface, leading to heating and softening of the work-piece(s) due to the frictional heat. A solid-state bond is formed due to the mechanical mixing by the advancing rotating tool. Over time FSW is rapidly gaining industrial prominence and can become a successful alternative to conventional arc welding. In this technical paper, we would discuss the successful joining of IF steel through FSW.

2. Experimental procedures

For the present study, IF steel was used. The samples received were in the form of plates with a commercial-purity of 99.27%. The chemical composition analysis (in wt.%) has been done by optical emission spectroscopy (Perkin Elmer Optima 5300 DV), given in table 1. The thick plates were machined to identical rectangular plates with dimensions 120 mm length x 50 mm breath x 3 mm thickness. A pair of plates were used as base materials (BM) for the welding process. The FSW experiments were performed using a BMacF friction-stir welding machine (Figure 1a). A tungsten carbide (WC) with a 12 mm shoulder diameter dimension was fabricated to accommodate a pin of dimensions (3 mm diameter and 2.8 mm length). The process parameters involved a rotation speed of 720 rpm, traverse speed of 28 mm/min, and a tool tilt angle of 1.5 ° normal to the plate to facilitate effective ploughing in the advancing direction [10]. The process parameters used are of optimised conditions in our previous work, which results in the best properties of the welded joint. They have been selected after trial and errors and a thorough literature survey. The schematics of the FSW process have been shown in Figure 1b.

| Table 1: Composition (in wt. %) of IF steel under current investigation. |
|-----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| C                | Ti            | Mn            | Nb             | Si              | P              | Ni              | Al              | Cr              | Cu              | N              |
| 0.029            | 0.053         | 0.51          | 0.014          | 0.004           | 0.03           | 0.017           | 0.03            | 0.02            | 0.01            | 0.002          |
| 0.009            | 0.001         | 99.271        |                |                 |                |                 |                 |                 |                 |                |
Figure 1: (a) FSW machine, and (b) the FSW setup used for welding.

The transverse section of the welded samples was used for microstructural examination. They were mechanically polished using various grades of SiC abrasive discs in a Stuers TEGRAMIN auto polisher. The final polishing to achieve a mirror finish was done using colloidal silica suspension (OP-U) and NAP polishing disc. The mirror-finish polished samples are then chemically etched with nital for metallographic techniques. The initial microstructures were observed using an optical microscope (Leica DMI 5000 M). The Vicker's macro-hardness of the welded specimens were evaluated at 1 kg load with 10 s dwell time (Model: FIE-VM50, India). The flat tensile samples were prepared by machining along the traverse direction using the schematics shown in Figure 2 [11]. The tensile testing was done at 1 mm/min cross-head speed using an Instron universal testing machine at room temperature.

Figure 2: ASTM E8 flat sub-size specimen schematic[11].

3. Results and discussions

3.1. Microstructural observation

The optical microstructure of the as-received IF steel sample is exhibited in Figure 3. The microstructure reveals a bimodular grain structure of ferrite [12]. At room temperature conditions, the sample is completely ferritic, and the difference in grain size is due to the sample's as-cast condition. Proeutectoid ferrites of finer sizes as the major micro-constituents and coarser grains result
from the slow cooling-rate in the casting process. ImageJ software has been used to calculate the pearlite and ferrite phase volume fraction and average ferrite grains size. The grain size is calculated by ImageJ software. The average grain size ranges between 8 ± 4 μm and 85 ± 15 μm, respectively, for finer and coarser ones. The absence of second phase particles in the microstructure is also visible. As the IF steel is fully ferritic at room temperature, at higher temperatures the ferrite phase transforms to austenite. Austenite is regarded as the mother phase from which various allotropes (martensite, bainite, ferrite) can be obtained by varying the cooling rate [13]. In the case of ferrite more phase transformations can be obtained like wüdmanstätten ferrite, massive ferrite, polygonal ferrite, and diffusional ferrite. All these allotropes alter the mechanical properties of the steel. As the cooling-rate is high in FSW, we would try to obtain at least one of these allotropes to enhance the mechanical properties.

Figure 3. The initial optical microstructure of the IF steel sample (BM).

On observing at lower magnification, the cross-sectional area of the welded region shows sound welding (Figure 4a). The stir nugget zone (NZ) width was estimated to be ~3 mm, which is equivalent to the WC pin diameter. The NZ consist of finer grains (Figure 4b) from the resultant heating due to the friction between the BM and the WC tool. In Figure 5, the grains can be distinguished properly in all the regions. In Figure 5a, the thermo-mechanically affected zone (TMAZ) reveals how the grains from the BM get ploughed into the NZ due to the high rotational speed of the WC tool. Coarse grains are also visible, which has not transformed into fine grains in the TMAZ. The comparatively low heat input and high welding speed in the TMAZ region lead to elongated grain structure formation. In Figure 5b, the NZ shows a refined grain structure at a higher magnification. The refinement was owed to dynamic recrystallisation during FSW. The elongated grains were subjected to severe plastic deformation (SPD) due to the rotational motion of the WC tool pin. This intense mixing and SPD assisted in forming a fine grain structure in NZ [10]. On observing the micrographs of the NZ and TMAZ, considerable formability can be expected. It opens doors to possibilities of welding blanks prior to a deep-drawing operation.
Figure 4. The cross-sectional view of the processed sample.

Figure 5. Micrographs of (a) the interface of NZ, TMAZ and BM, and (b) NZ.

3.2. Hardness

The hardness values were evaluated from the BM and progressing towards the NZ, as shown in Figure 6. The hardness of the BM and NZ was 40 ± 5 VHN and 94 ± 10 VHN, respectively. The increase in hardness was due to grain refinement in NZ. The Hall–Petch equation states that a decrease in grain size will increase the hardness of the material [6]. No phase transformations were observed in the micrographs. Hence, the cooling effect was comparatively low to promote any displacive or diffusional phase transformations. The variation in hardness of different zones is accredited to the grain size of the specific region. The hardness in the TMAZ decreased due to the heat transfer from the NZ to the BM, resulting in elevated temperatures promoting grain growth. It can also be considered that as the heat generation was not as high as conventional arc welding, the HAZ is very lean.
3.3. Tensile Properties

The tensile properties of the processed sample were also evaluated from the transverse direction (Figure 7). The stress vs strain curve represents the tensile properties of the base material and the friction-stir welded joints. The stress-strain curve for IF steel is continuous, so there is no yield point phenomenon in this steel. Three tests were performed and averaged to assess the ultimate tensile strength (UTS), yield strength (YS), elongation, and efficiency of the weld joint. The YS and UTS of the BM are 204 MPa and 271 MPa, respectively, compared to 150 MPa and 219 MPa for the processed sample. The reduction in strength is due to the fact that the failure of the sample occurred from the region of TMAZ/BM. It indicates that NZ has higher strength due to grain refinement and is defect-free with a good weld efficiency. The elongation was also better than the BM due to the formation of stress-free recrystallised grain in NZ. From the stress-strain curve, we can also see that the formability is improved after FSW.
Figure 7. Stress vs strain plots of the as-received sample compared with the processed sample.

4. Conclusions
Friction-stir welding is an excellent technique for the joining of IF steel sheets. FSW of IF steel was successful performed with a WC tool in this work. The rotational speed was set at 708 rpm, and the welding speed of the advancing direction was set at 28 mm/min. The welded sample showed good weld joint integrity. The NZ produced was free from defects. The main conclusions of this work can be drawn as follows:

i. The nugget zone width was measured to be ~3mm, equivalent to the WC tool's pin width.
ii. Dynamic recrystallization was observed in the NZ, leading to grain refinement, which in turn increased the strength of the nugget zone.
iii. The yield strength (150 MPa) and the ultimate tensile strength (219 MPa) of the weld section in the transverse direction is inferior to the base material. This is ascribed to grain growth and heat dissipation from the nugget zone towards the base material.
iv. The hardness profile showed a dramatic increase in the hardness of the nugget zone owing to the fine grain structure.

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