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# Microstructure feature of friction stir butt-welded ferritic ductile iron

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This study conducted friction stir welding (FSW) by using the butt welding process to join ferritic ductile iron plates and investigated the variations of microsturcture in the joined region formed after welding. No defects appeared in the resulting experimental weld, which was formed using a 3-mm thick ductile iron plate and tungsten carbide alloy stir rod to conduct FSW at a rotational speed of 982 rpm and traveling speed of 72 mm/min. The welding region was composed of deformed graphite, martensite phase, and dynamically recrystallized ferrite structures. In the surface region and on the advancing side (AS), the graphite displayed a striped configuration and the ferritic matrix transformed into martensite. On the retreating side (RS), the graphite surrounded by martensite remained as individual granules and the matrix primarily comprised dynamically recrystallized ferrite. After welding, diffusion increased the carbon content of the austenite around the deformed graphite nodules, which transformed into martensite during the subsequent cooling process. A micro Vickers hardness test showed that the maximum hardness value of the martensite structures in the weld was approximately 800 HV. An analysis using an electron probe X-ray microanalyzer (EPMA) indicated that its carbon content was approximately 0.7–1.4%. The peak temperature on the RS, 8 mm from the center of the weld, measured 630 °C by the thermocouple. Overall, increased severity of plastic deformation and process temperature near the upper stir zone (SZ) resulted in distinct phase transformation. Furthermore, the degree of plastic deformation on the AS was significantly greater than that on the RS, and relatively complete graphite granules and the fine ferrite grains resulting from dynamic recrystallization were observed on the RS.


## 1. Introduction

Friction stir welding (FSW) is a novel solid-state welding technology that adopts the heat generated by the friction that results from a stir rod rotating at high speed and penetrating a base material, subsequently achieving the joining effect during the feeding process through the metal plastic flow phenomenon created by stirring [1–8]. During the welding process, the temperature remains below the melting point of the welding material. In contrast to traditional welding methods, the absence of melting renders FSW applicable to materials that are difficult to weld such as age-hardened aluminum alloys [9–11]. Several recent studies have employed FSW to join carbon steel and stainless steel [4–8,12–20]. The rotating tools must tolerate high temperatures (1000 °C), which are required to create plastic flow when welding iron-based alloys. The complex phase transformation of steel materials varies substantially with the carbon content of the base material. Furthermore, temperature changes that occur during welding and the cooling rate after welding significantly influence the microstructure of the welding regions, altering the mechanical properties of weldments [4,5,16–20]. Fujii et al. performed FSW on 0.12% carbon steel by using welding parameters of 400 rpm and 100 mm/min, and observed relatively small ferrite grains (3 μm) that resulted from dynamic recrystallization at the bottom of the weld [16]. Furthermore, Fujii et al. extensively investigated how welding temperature affects structural changes in various weld regions. By using 0.85% carbon tool steel for FSW, Chung et al. reported that martensite structures formed in the weld when the welding temperature exceeded that at the eutectoid transformation point ($A_1$) [17]. A welding temperature lower than that of the $A_1$ transformation temperature prevented martensite formation in the ferrite matrix and simultaneously induced grain refinement; the weldment also demonstrated superior toughness and ductility. Because Chung et al. exercised joint material which is a ferrite matrix with globular cementite, the structure characteristic obtained proper plastic flow in lower temperature by FSW. Consequently, the base material was joined by friction stir effect, and without any phase transformation produced in the joint region. Sun et al. indicated that performing FSW using a 3.2-mm thick, 0.45% carbon steel at a rotational speed of 600 rpm and a traveling speed greater than 300 mm/min produces martensite and bainite structures in the weld; however, a traveling speed lower than

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300 mm/min inhibits the formation of martensite and bainite [5]. Lakshminarayanan et al. identified very fine ferrite and martensite structures in the weld when performing FSW at 1000 rpm and 50 mm/min and using ferrite-based stainless steel, which contains 0.026% carbon, 11.4% chromium, and 0.4% nickel [6]. According to the aforementioned studies, the chemical composition of iron-based alloys and changes in welding temperature extensively alter the microstructure of welds, affecting the mechanical properties of weldments.

Compared to traditional fusion welding technologies, FSW provides a feasible method for joining ductile irons. Previously, welding methods were rarely adopted for joining ductile irons because of various problems that could not be overcome during the welding process. The carbon content of ductile iron is considerably higher than that of carbon steel, causing poor weldability; thus, during high-temperature fusion welding, carbon in the graphite dissolves into the surrounding melted region and diffuses across the unmelted regions that contain austenite phase. Consequently, the hard and brittle carbide and martensite developed during the cooling and solidifying processes reduce the mechanical properties of the weldments [2,21,22]. To resolve this problem, several studies have employed FSW to join ductile irons. By conducting dissimilar welding using ductile iron and low-carbon steel, our previous studies observed martensite and pearlite structures in the weld, and found that proper heat treatment removes martensite and improves the tensile properties of the weldments [2,3]. Fujii et al. and Imagawa et al. conducted friction stir processing with ferritic ductile iron, pearlitic ductile iron and flake graphite cast iron for surface hardening processing that rendered the hardening effect by forming martensite transformation in the stir zone. Their studies indicated that the carbon atom is more difficult to diffuse in the ferritic matrix of ductile iron, so that the optimal condition of friction stir processing was narrower than that of other two materials [23–25]. Furthermore, Cheng et al. applied friction stir surface hardening to ductile iron by using a stir rod without a pin and rotating and traveling speeds of 2200 rpm and 60 mm/min, respectively. Mixtures of structures containing ferrite, bainite, martensite, and retained austenite were found in the stirred region, and this hardened layer improved the resistance of ductile iron to erosion [26]. Based on previous studies, martensite forms in the joined region of ductile iron after FSW; however, the mechanism related to this formation process has not been investigated. Therefore, this study employs FSW to join ductile iron by using the butt welding technique, investigating the morphological and microstructural changes in the graphite surrounding the weld.

## 2. Experimental procedure

The base material in the current experiment comprised a 3-mm thick ferritic ductile iron plates that contained 2.0% carbon, 2.5% silicon, 0.09% manganese, 0.006% sulfur, 0.034% phosphorous, 0.039% magnesium, and iron. Based on the experimental requirements, the ductile iron plate was processed to the desired dimensions (95 mm × 40 mm × 3 mm). Before welding, the oxidized layer on the ductile iron surface was sanded, washed with acetone, and blow-dried. Fig. 1 presents a schematic of the relative positions of the base material and stir rod during the butt welding process. Furthermore, Table 1 lists the dimensions of the stir rod, which equips with columnar probe without threads. During the welding process, the stir rod was tilted 0.5 degrees from the normal direction of the plate. To determine the optimal parameters for the welding process, pilot tests were performed by different rotational and travelling speed. The preliminary results showed that rotational and traveling speeds of 982 rpm and 72 mm/min, respectively, were favorable for joining. After welding, the weld surface was smooth and lacked defects, the ductile iron plate was not deformed, and the rotating tool (i.e., stir rod) presented no wear. To explore how temperature changes near the weld affected the microstructure of the ductile iron, the K-type thermocouples were installed near the retreating side (RS) 8, 13 and 18 mm from the center of the weld. These thermocouples were embedded into three holes, each 5 mm apart, to record the temperature changes that occurred during welding. Subsequently, a section of the weld region was sliced to facilitate an observation of its microstructure, and the specimen was polished before being etched using Nital etchant. The microstructural changes in the weld of the etched specimen were observed using an optical microscope and scanning electron microscope (SEM).

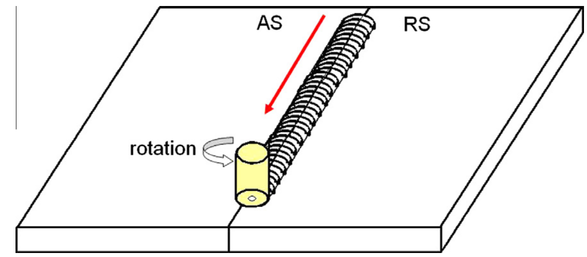


**Fig. 1.** Schematic illustration of friction stir butt-welding.

**Table 1**
Original size of welding tool, mm.

| Tool material | Shoulder diameter | Pin diameter | Pin length |
|---|---|---|---|
| WC-Mo | 12 | 3.6 | 2.8 |

After FSW, variation in the hardness of the joined region was first measured by polishing the cross-section of the sliced specimen and then conducting micro Vickers hardness tests, which were performed as per ASTM: E384-11e1 specification. The measurement conditions were a load of 200 g and a hold time of 15 s. To determine the variation in hardness values of different regions, a microhardness distribution curve was plotted using the data obtained from the following procedure: dividing the cross-section of the specimen into three regions (surface, middle, and bottom) from top to bottom and using the welding line as the center, microhardness was measured every 0.2 mm on each side of the center point. Additionally, to verify the phenomenon by which carbon atoms diffuse from graphite during welding, the current study adopted JEOL JXA-8200 electron probe X-ray microanalyzer (EPMA) for quantitative and line scan analyses. In addition to the EMPA results, the microhardness values and phase transformation results were employed to explore potential factors that caused the formation of various weld phases and structures.

## 3. Results and discussion

### *3.1. Microstructural characterization*

Fig. 2 shows the microstructure of ductile iron used as the FSW base material. The graphite nodules (approximately 20–25 μm in diameter) were evenly distributed within the ferrite matrix, which were in the state of equiaxed crystals approximately 30–40 μm in diameter. Fig. 3 presents a cross-sectional schematic of the weld regions. The sub-surface region of the weld is the area where the stir rod shoulder acts on the base material and is approximately the width of the stir rod shoulder. The spindle rotation creates friction between the shoulder and base material; thus, the location