metals

Communication

Friction Stir Welding of Dissimilar Materials Aluminum AL6061-T6 to Ultra Low Carbon Steel

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Abstract: In this study, the microstructure and strength properties of friction stir welded 6061-T6 aluminum alloy to ultra-low carbon steel have been investigated using different advancing speeds of 100, 200, and 400 mm·min^{-1} at constant rotation rate. Microstructure observations have been conducted by optical and scanning electron microscopy. The joint strength was evaluated on a tensile testing machine. The effect of advancing speed on the shear load of a joint has been found, as well as a relationship between microstructures and mechanical properties.

Keywords: friction stir welded; aluminum; steel; microstructures; mechanical properties

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1. Introduction

Friction stir welding (FSW) is potentially a practicable joining process for dissimilar materials. It is a solid state process where a non-consumable rotating tool with a specially designed pin and shoulder is inserted into the abutting edges of sheets or plates to be joined and subsequently traversed along the joint line [1]. Heat is generated by the friction between the tool and the work pieces, as well as the plastic deformation [2–6]. It is an ideal process for producing low-cost and high performance joints. The practical approach is to use a non-consumable rotating tool consisting of two parts: a shoulder and a pin. Rotational speed, traverse speed, and vertical pressure on the plates during welding are the main process parameters [7].

Many studies of the friction welding of dissimilar materials have been conducted by various researchers. Ozdemir et al. [8] investigated the effect of rotational speed on the interface properties of friction-welded AISI 304L and steel. They found a correlation between the tensile strength of the joint and joining rotational speed. Dehghani et al. [9] investigated joining aluminum alloy to mild steel, and looked into the effect of various FSW parameters such as traverse speed, plunge depth, tilt angle, and tool pin geometry on the formation of intermetallic compounds (IMCs), tunnel formation, and tensile strength. Watanabe et al. [10] investigated the effect of pin rotation speed and pin offset on the mechanical and microstructural behavior of AA5083 aluminum alloy and SS400 low-carbon steel dissimilar joint.

The previous works on the friction welding of steel to 6061 aluminum alloy using a lap joint configuration were limited to a few investigations [11–13], but these studies were focused on coated steel for a specific application.

The objective of this work is to focus on the effect of traverse speed on the mechanical properties and microstructural characteristics of the welded FSW 6061 aluminum alloy to ultra low carbon steel with a lap joint configuration. The tool used is made from X40CrMoV51 steel, which is an economical tool steel.

2. Materials and Methods

2.1. Base Materials

The 6061-T6 aluminum alloy and ultra-low carbon steel sheets with thicknesses of 3 mm and 0.8 mm, respectively, were used. The chemical composition is shown in Tables 1 and 2.

Table 1. Chemical composition of 6061-T6 aluminum alloy.

% (wt)	Al	Cr	Cu	Fe	Ga	Mg	Mn	Si
6061-T6 Al alloy	97.8	0.19	0.24	0.44	0.015	0.92	0.05	0.56

Table 2. Chemical composition of ultra low carbon steel.

% (wt)	C	Mn	Si	S	P	N
Ultra low carbon steel	0.013	0.136	0.01	0.005	0.0132	<0.008

2.2. Weld Production

The dissimilar materials were joined (Figure 1) with a lap joint configuration. (1) Two lapped plates (steel and aluminum alloy) were clamped; (2) a rotating tool was vertically plunged through the upper plate and partially into the lower plate (steel), and traversed along the desired direction, joining the two plates. The rotating pin (pin Ø = 5 mm) was gently pushed into the Al-6061-T6 sheet until the pin tip entered (tool offset) −0.1 mm into the ultra-low carbon steel; (3) with a specific traverse speed. Three traverse speeds (100, 200, and 400 mm/min) were applied along the joint, with constant rotation speed of 1200 rpm.

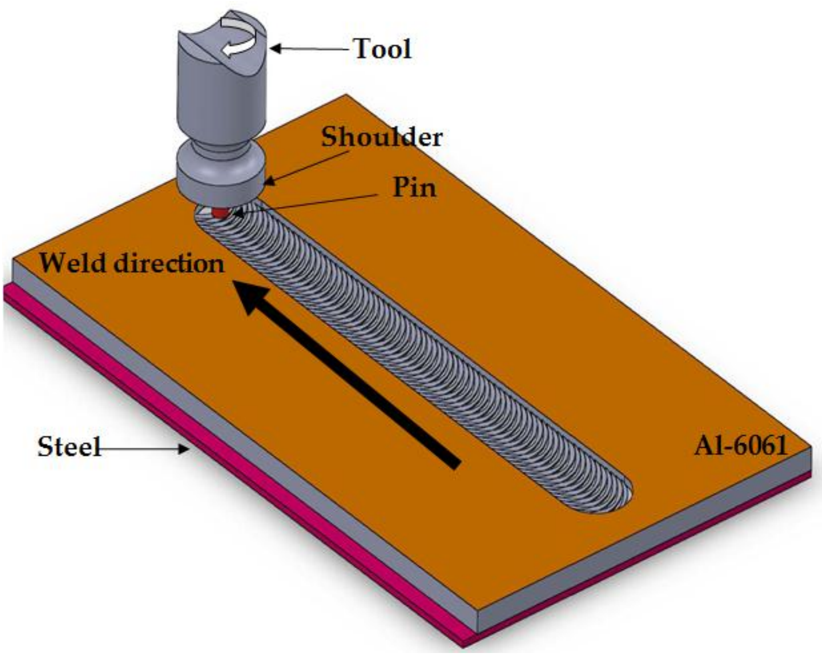

Figure 1. Friction stir welding (FSW) process with a lap joint configuration.

The tool (Figure 2) used for FSW was made from X40CrMoV51 steel (quenched and tempered with 50 HRC).

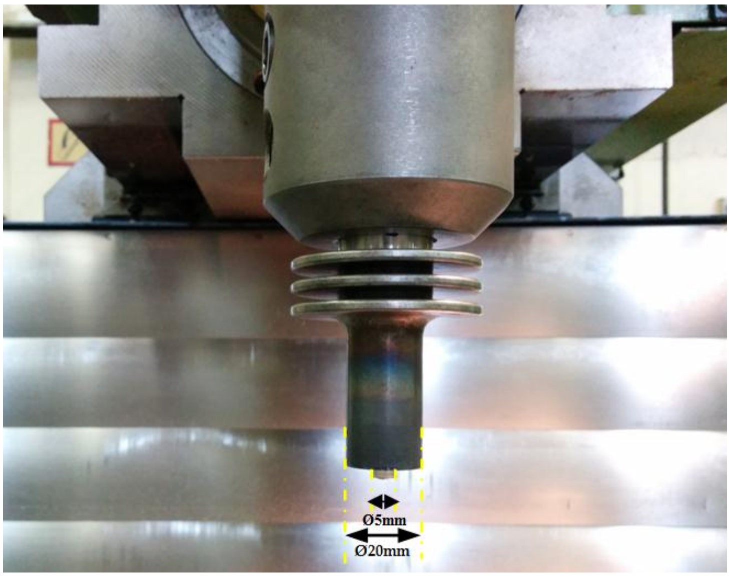

Figure 2. The tool used for FSW.

The macrograph of welded dissimilar materials—6061-T6 aluminum alloy and ultra low carbon steel—lap welds is shown in Figure 3. There are the "metallurgical bands" or "onion rings" in a friction stir weld.

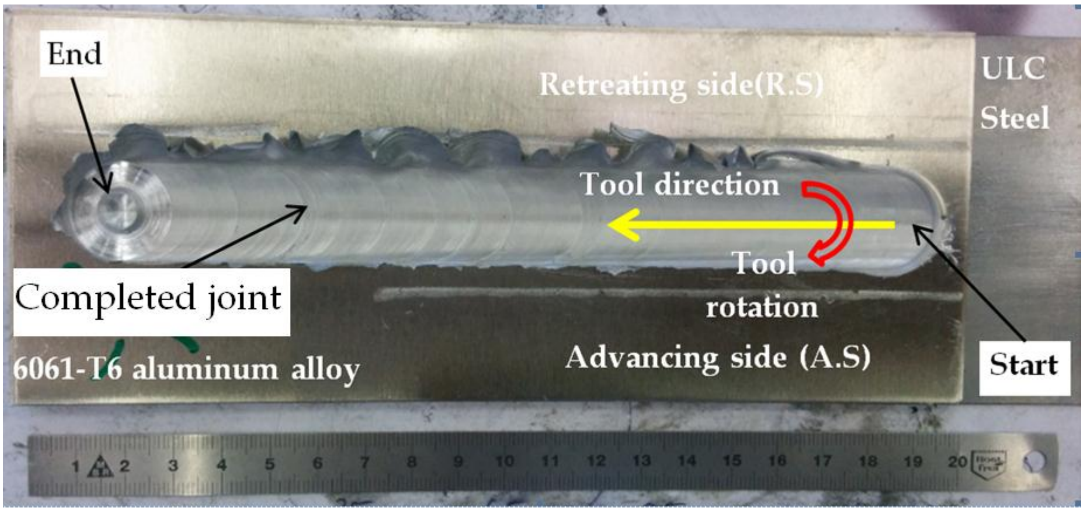

Figure 3. Macroscopic view of a completed joint. ULC: ultra-low carbon.

For microstructural analysis, the FSW samples were cross-sectioned perpendicular to the welding direction, polished, and then etched with a solution of a standard metallographic procedure. The aluminum side was etched by a Killer's solution (HCl: 22.5%, HF: 7.5%, HNO_3: 7.5%, H_2O: bal.). The microstructure and quantitative chemical analyses of the joints were performed by an optical microscope (Olympus, Beijing, China) and scanning electron microscope (SEM, Zeiss Ultra55, Carl Zeiss AG, Jena, Germany) with Energy-dispersive X-ray spectroscopy EDS capability. The joint strength was evaluated with a tensile testing machine (Zwick 50 kN, Zwick company, Ulm, Germany) using a cross-head speed of 0.5 mm/min at room temperature. The tensile shear specimens had an overall length of 80 mm and width of 10 mm (Figure 4). The tensile properties of each joint were evaluated using five lap shear specimens cut from the same joint.

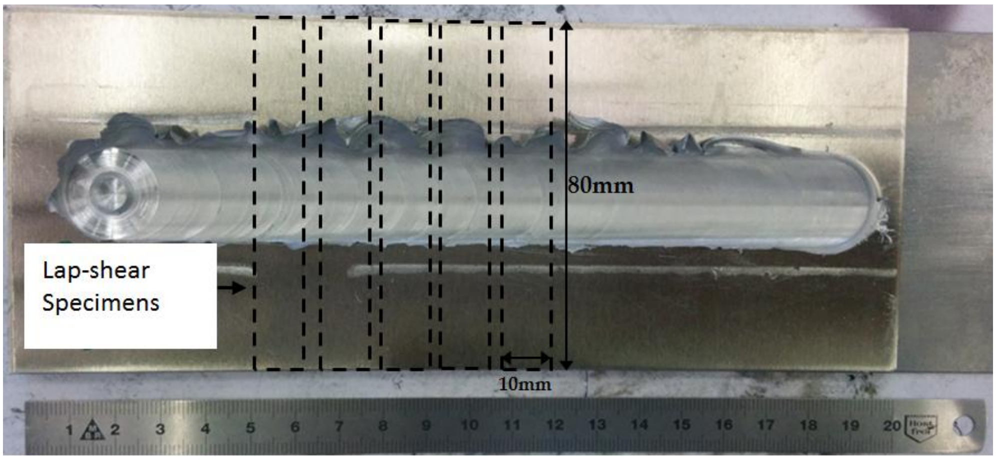

Figure 4. Five tensile shear specimens cut from the same joint.

3. Results

3.1. Microstructures

Figure 5 shows the initial microstructure of the 6061-T6 aluminum alloy before welding. The microstructure of the base metal was formed by homogeneous microstructure with elongated grains. This microstructure is a result of the manufacturing process.

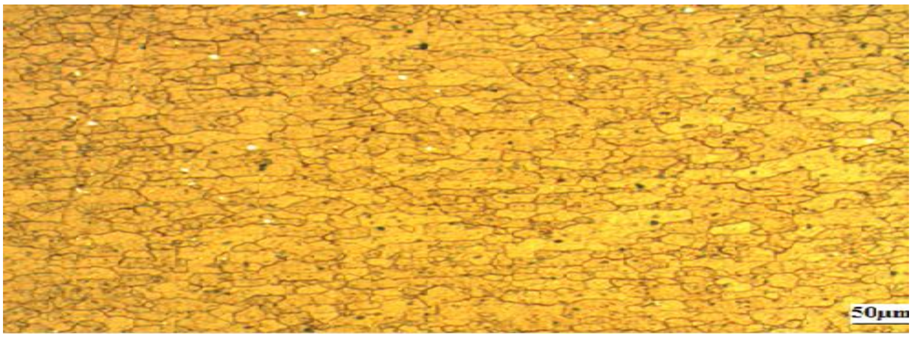

Figure 5. Microstructure of the 6061-T6 aluminum alloy.

Micrographs of a joint cross-section of the 6061-T6 aluminum alloy and an ultra low carbon steel lap welds after welding by FSW process is shown in Figure 6. It is clear that all of the deformation and transformation during the welding process occurs on the aluminum side of the joint, because the aluminum is a softer material compared to the steel. A distinct region from the advancing side to the retreating side in the aluminum part can be observed. This heavily deformed region is called the Nugget or Stir zone, which is the main area in the welded aluminum side. This recrystallized zone is the result of a severe plastic deformation, in which tool pin rotates and produces frictional heat [14,15]. The grains within the stir zone are roughly equiaxed, and often with an order of magnitude smaller than the grains in the parent material [16].

The effect of traverse speed on the microstructural evolution of the friction stir welded 6061 aluminum alloy to ultra low carbon steel is shown in Figure 7. The main phenomenon produced in the welded joint was the grain refinement in the aluminum side. Generally, the increase of the advancing speed generates plastic deformation and heat treatment in aluminum side, which leads to dynamic recrystallization. The average grain size of the welded zone of the aluminum side was about 10 µm. However, the average grain size of the base metal was 50 µm, which confirms the recrystallization reaction after welding. The interface microstructure examination showed an intermetallic compound which was formed at the joint interface.

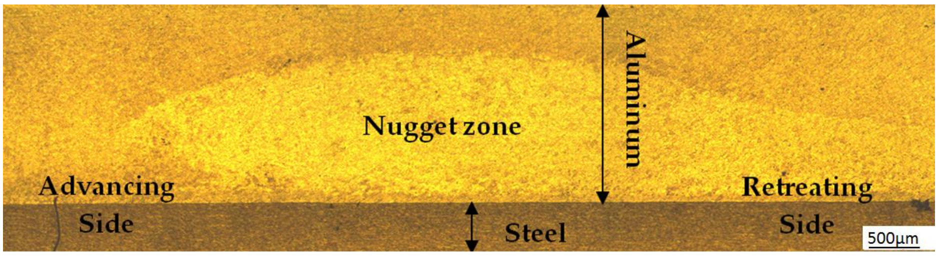

Figure 6. Optical microscopy of welded joint by friction stir welding of aluminum alloy AL6061-T6 to ultra-low carbon steel. Advancing speed of 200 mm/min.

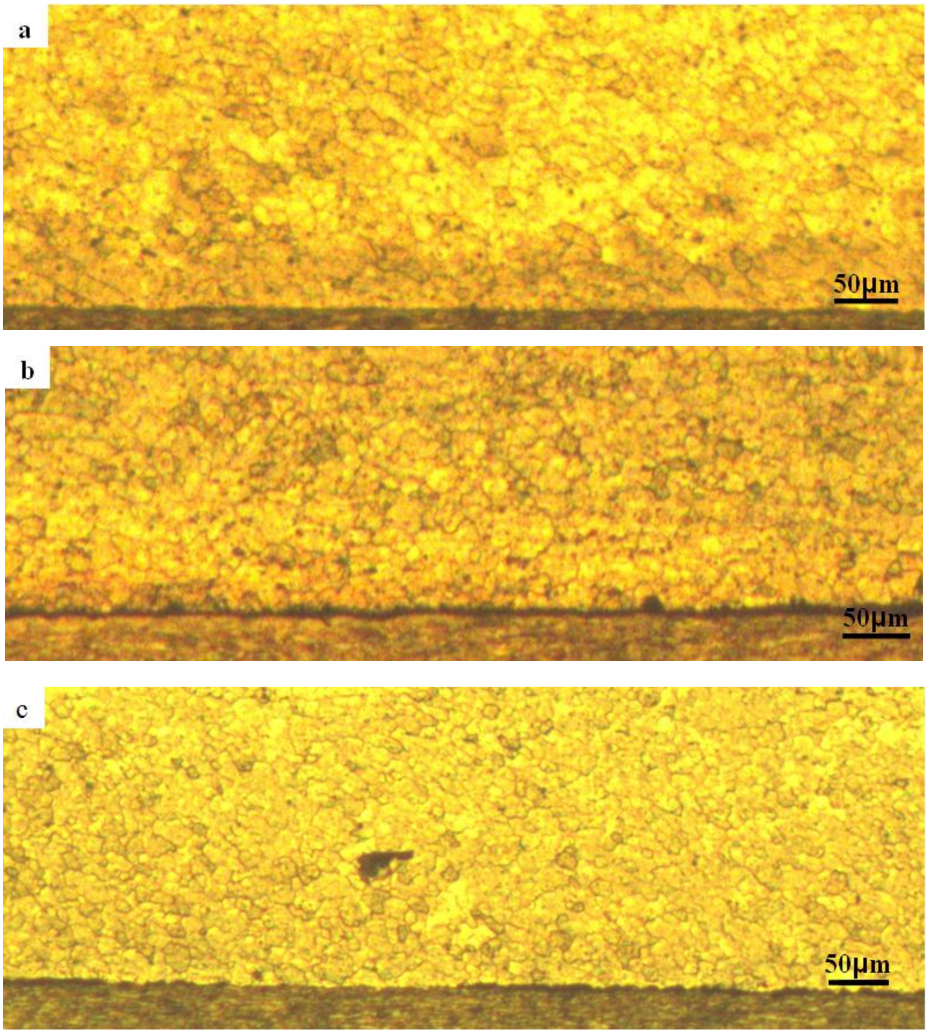

Figure 7. Microstructural evolution in welded joint by friction stir welding of aluminum alloy AL6061-T6 to ultra-low carbon steel after different advancing speed: (**a**) 100; (**b**) 200; and (**c**) 400 mm/min.

Figure 8 shows SEM observation of the joint cross-section of the 6061-T6 aluminum alloy and ultra-low carbon steel lap welds after welding. The interface structure of the joint showed that an intermetallic compound layer (IMC) was formed along the interface, and it was not uniform. The EDS analysis of the chemical composition inside the IMC layer is shown in Table 3. The concentration of the main dominant elements—Fe and Al—was measured. In addition, X-ray diffraction analysis has been performed on the critical region (nugget zone and IMC layer) to determine the main phases. The XRD diffractogram (Figure 9) indicates that this region is formed mainly by two phases: $AlFe_3$ and $Al_{13}Fe_4$. These phases have been observed in other investigations [17].

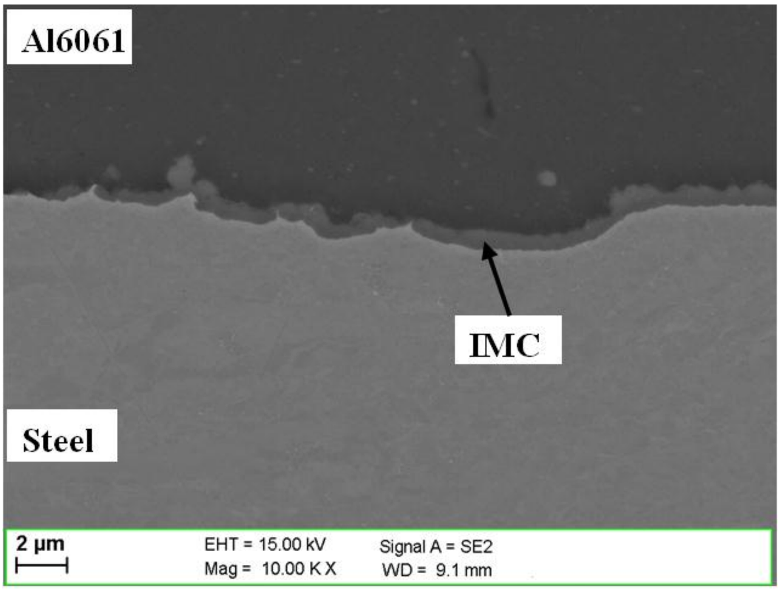

Figure 8. SEM observation of welded joint by friction stir welding of aluminum alloy AL6061-T6 to ultra-low carbon steel. Advancing speed = 200 mm/min. IMC: intermetallic compound.

Table 3. Chemical composition of IMC layer.

% (wt)	Al	Fe	Si	Mg
6061-T6 Al alloy	76.00	23.106	0.94	-

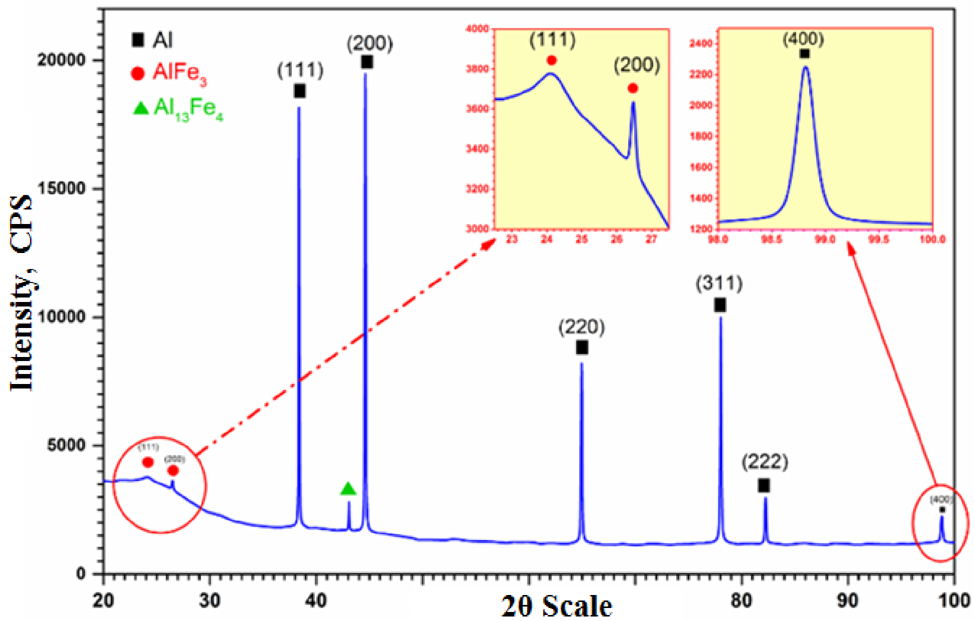

Figure 9. XRD diffractogram of aluminum side of welded joint by friction stir welding of aluminum alloy AL6061-T6 to ultra low carbon steel.

The relationship between the thickness of the intermetallic compound layer (IMC) and advancing speed is presented in Figure 10. The thickness of the IMC layer decreases from 2 µm to 0.1 µm with increasing welding speed, which significantly affects the strength of the joint. The decrease of the thickness of IMC layer with increasing the advancing speed is mainly due to the decreasing time of the interaction between the two adjacent dissimilar materials. The decrease of the interaction time induces a low time of inter-diffusion process [18].

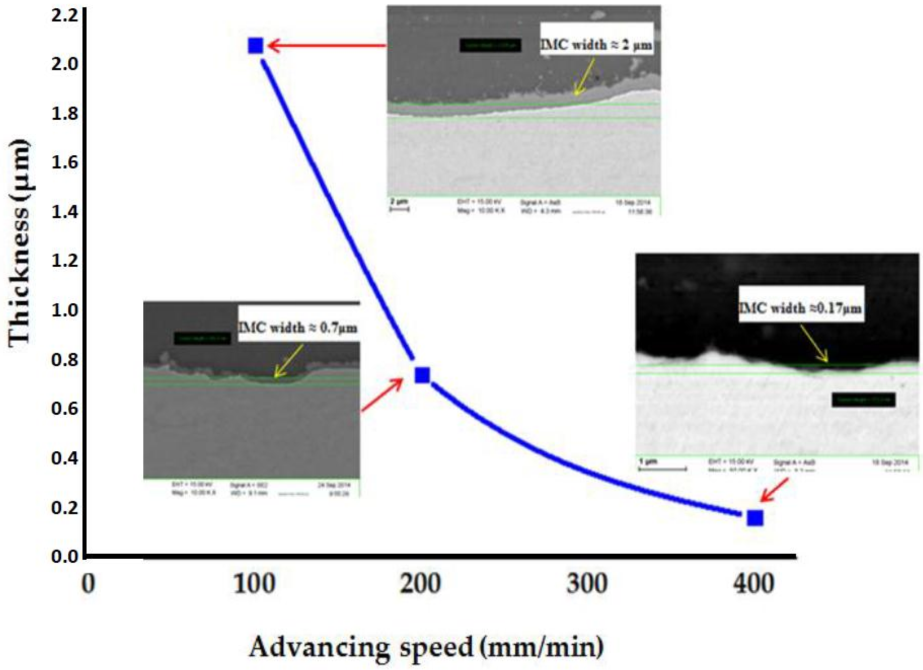

Figure 10. Thickness variation of the intermetallic compound layer IMC formed after different traverse speed in welded joint by friction stir welding of aluminum alloy AL6061-T6 to ultra low carbon steel.

3.2. Lap Shear Testing

Figure 11 shows the specimen after lap shear test of friction stir welded 6061-T6 aluminum alloy to ultra-low carbon steel. The fracture zone was developed in the center of the welded joint.

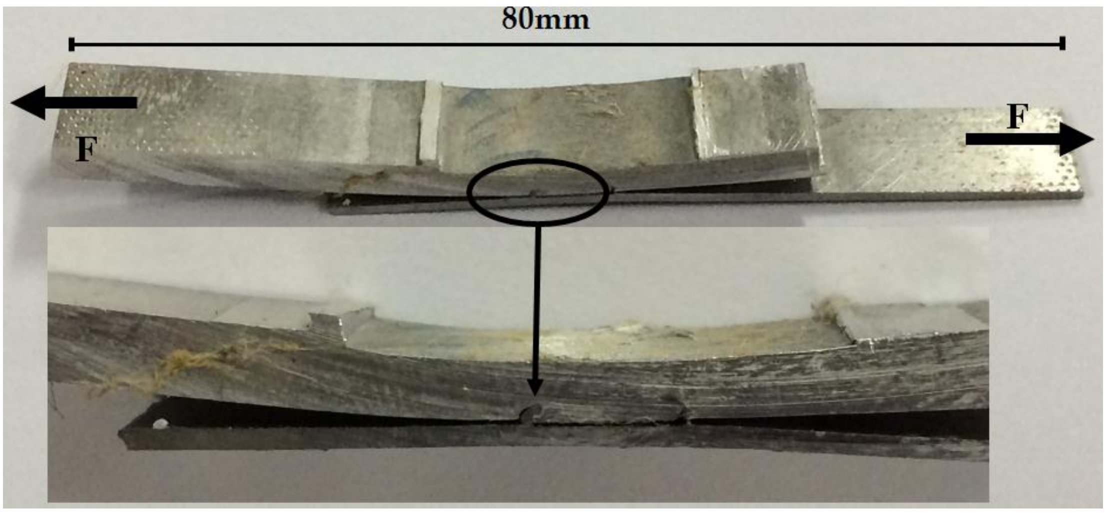

Figure 11. Specimen after tensile test of friction stir welded 6061-T6 aluminum alloy to ultra low carbon steel. F: Force used during a test. Fractured zone is presented.

The effect of advancing speed on the shear strength of the welded joint is presented in Figure 12. It is clear that the shear strength increases with increasing advancing speed. This can be explained by the relationship between shear strength and IMC thickness formed in welded join, and also with grain refinement in the aluminum side.

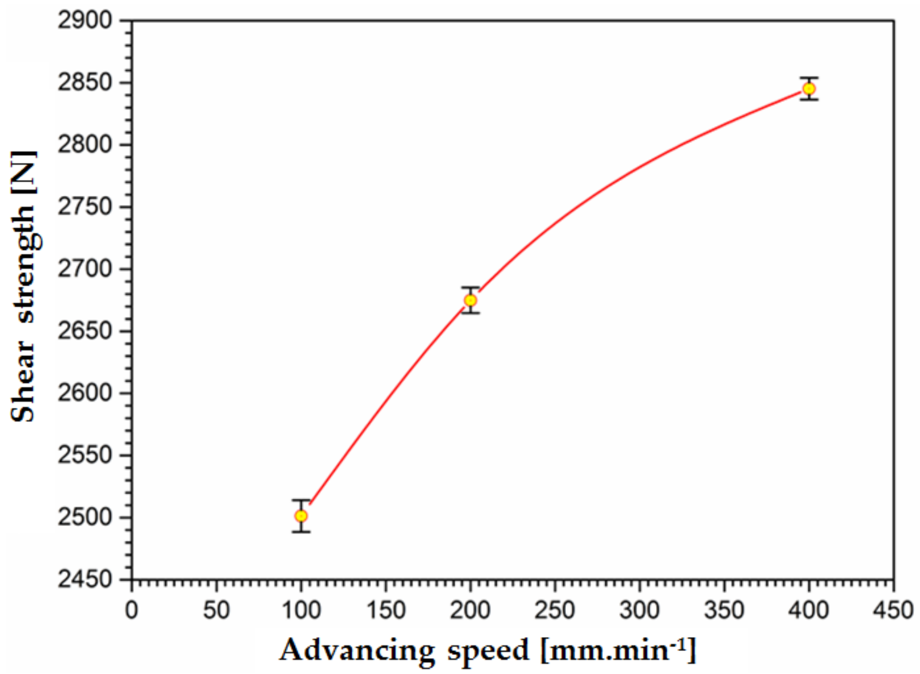

Figure 12. Curve of shear strength vs. advancing speed using welding conditions: rotational speed of 1200 rpm; tool offset of −0.1 mm of friction stir welded 6061-T6 aluminum alloy to ultra low carbon steel.

4. Conclusions

The microstructure and strength properties of friction stir welded 6061-T6 aluminum alloy to ultra low carbon steel have been investigated. The results show that friction stir welding can be used for the joining of dissimilar 6061-T6 aluminum alloy to ultra low carbon steel. The advancing speed effect on the microstructure and strength properties of the welded dissimilar materials has shown that:

- A phenomenon of grain refinement is developed in the aluminum side; i.e., the nugget region NG is dominated by a dynamically recrystallized grain structure.
- The thickness of the IMC layer decreases with increasing welding speed, which significantly affects the strength of the joint; i.e., the shear strength increases by increasing the traverse speed.

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Conflicts of Interest: The authors declare no conflict of interest.

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