EFFECT OF TOOL ROTATIONAL SPEED ON MICROSTRUCTURE AND MECHANICAL PROPERTIES OF FRICTION STIR WELDED JOINT OF ULTRAFINE-GRAINED AA 5083 ALLOY

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Abstract. Ultrafine-grained (UFG) materials are widely used as a structure material owing to their unique microstructure and mechanical properties. In this study, friction stir welding (FSW) was used to weld UFG AA 5083 alloy. The effect of tool rotational speed on microstructure and mechanical properties of ultrafine-grained AA 5083 alloy was investigated. Different rotational speeds of 410, 600, 865, 1140, and 1500 rpm, a fixed travel speed of 264 mm/min and tool tilt angle of 2° were used as processing parameters. Visual inspection, macroscopic and microscopic analyses, microhardness and tensile properties using camera, optical microscope, Vickers hardness tester and universal testing machine were used to assess the weld quality and strength. The heat generation and material flow during FSW welding was influenced by rotational speed. At low rotational speed, insufficient heat and material flow caused many defects and reduced the mechanical properties of welded joint. In contrast, high rotational speed caused high heat generation and excess material flow. Hence optimum heat generation is obtained at the rotational speed of 865 rpm. The smooth welded surface, defect-free weld, and finest grain within nugget zone (NZ) were obtained at 865 rpm tool rotational speed that result in high microhardness (91.78 HV) and tensile strength (145.14 MPa).

Keywords: Cryorolling, welded joint, nugget zone, tensile strength, AA 5083 alloy

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Introduction

Cryorolling has been found as a significant severe plastic deformation (SPD) technique for generating ultrafine-grained (UFG) structure with grain sizes less than 1 µm in the metal alloys [1, 2]. SPD technique capable of creating high plastic strains that greatly deforms the materials by transforming the grain size to UFG to increase the strength of material. Dynamic recovery suppression during deformation at cryogenic temperatures preserved a large number of dislocations, which served as recrystallization sites to form UFG structure. However, because cryorolled and other SPD processed materials are limited in size and form, their applicability in the manufacture of large parts, such as car bodywork, is limited [3]. The joining of these types of materials is critical for the development of their applications. The main issue limiting the use of UFG materials in welding is their low thermal stability. Fusion welding techniques in a liquid state are incompatible with UFG materials because the intense welding temperature damages the UFG structure and results in significantly larger grain size [4]. Lower-temperature friction stir welding (FSW) techniques are more efficient because smaller grain sizes can be preserved [5].

FSW has several advantages over other joining methods. The temperature generated did not exceed the melting point of the materials. As a result, there are no issues with re-solidification. Furthermore, the deformation and residual stress in FSW joints are lower than in other techniques [6]. However, when joining UFG material using FSW technique, the welded zone had a lower hardness than the base metal (BM) due to coarsening of the grain structure [4]. Generation of high heat generation would result in an increase in temperature, leading to the excess material flow as well as grain coarsening of the UFG structure. On the other hand, insufficient heat generation may occur during the welding process, resulting in less material flow and recovery of the UFG structure. Despite the difficulty of retaining the original UFG structure within the nugget zone (NZ), mechanical property also loss after welded using FSW [7, 8].

Several studies have been conducted on joining UFG aluminium alloys like AA 1050, AA 6016 using FSW technique [4], [8-11]. Nevertheless, there are no works reported on joining UFG AA5083 alloy using FSW. Since heat generated by the friction between the rotation tool and the workpiece led to a temperature rise, it might bring the risk of recrystallization and coarsening of the UFG materials. Therefore, the selection of FSW parameters for joining UFG AA5083 alloy is critical in achieving good weld joint properties. The aim of the present work is to investigate the effect of various tool rotational speed on microstructure and mechanical properties of UFG AA 5083 alloy produced by cryorolling using FSW process.

Material and Methods

Plate of AA 5083 alloy (122 mm x 105 mm x5 mm) was used for the FSW. It is classified as a wrought aluminium alloy and contains approximately 4.00-4.90 wt% magnesium as major alloying element. The samples were heat treated for 2 hours by annealing at 300 °C at a rate of 10 °C/min. To obtain the UFG structure, the annealed samples were cryorolled using two high roller mills at 20 rpm. Cryorolling was performed with total of 50 passes with approximately 10% thickness reduction in each 10 passes. Each

10% thickness reduction is achieved by adjusting the roll gap by 0.5 cm. Prior to cryorolling, the samples were immersed in a liquid nitrogen (LN) bath for one hour to achieve the required cryogenic temperature (-196 °C). Between each 10 passes, the samples were dipped in an LN bath for a shorter period of time until the LN bubbles vanished, and the temperature returned to saturation. The cryorolled samples then were welded using FSW technique. As shown in Figure 1, a tool with a shoulder diameter of 2 cm and a cone-shaped pin with height and diameter of 0.15 cm and 0.1 cm was used. Five different rotational speeds of 410, 600, 865, 1140 and 1500 rpm [12] were used to weld the samples at a fixed travel speed of 264 mm/min [9] and tilt angle of 2° [12]. Visual inspection method was performed to observe the top surface roughness of the welded joint using camera. Meiji optical microscope equipped with image analyzer (OM-IA) was used to observe and investigate the macrostructure (defect) and microstructure of the UFG welded zone. The samples were subjected to a standard metallographic sample preparation method, which included cutting, mounting, grinding, polishing and etching. The samples were chemically etched with Wecks's reagent containing 4 g of KMnO4, 1 g of NaOH and 100 mL of distilled water to reveal the microstructure. LECO micro-indentation hardness tester LM248AT was used to perform the Vickers microhardness test. The test load was set at 300 gf with dwell duration of 10 seconds. Indentations were made along the entire FSW-joints with a minimum separation of 1 mm between subsequent indentations. The average microhardness of welded zone was calculated. The tensile test was performed on the sample according to the ASTM E8 with 50 mm gauge length. The tensile test was conducted with constant crosshead speed at 1 mm/min until rupture. Three test pieces were tested for each sample, and the average values were calculated. Hitachi TM3030Plus table top scanning electron microscope (SEM) was used to assess the fracture surface of the tested tensile samples.

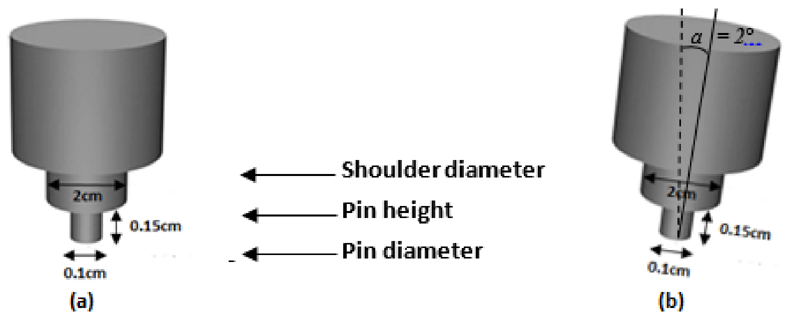

Figure 1. (a) FSW tool dimension and (b) tilt angle

Results and Discussion

Microstructure of ultrafine grained structure. Figure 2 shows the microstructure of as received and UFG AA5083 alloy. The microstructure of the as-received material consists of equiaxed grain while cryorolled alloy has severe elongated grains along the rolling direction. The plastic deformation from cryorolling process caused the increasing in number of the dislocation density and hence reduced the grain size. Cryogenic rolling suppressed dynamic recovery, effectively limiting the cross-slip or climb dislocations resulting in high dislocation density and grain refinement [13].

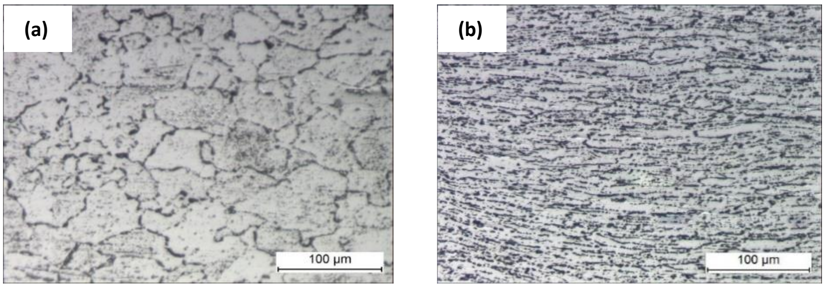

Figure 2. Optical micrographs of a) as-received and (b) UFG AA 5083

***Visual Inspection*.** Figure 3 shows the top surface image of friction stir welded joints of cryorolled AA5083 alloy at various rotational speeds. At low rotational speeds of 410 and 600 rpm, the surface of the welded joint exhibited a rough surface with circular traces of tool rotation. This could be attributed to the low welding heat generated during the welding process, which caused insufficient material flow of the welded joint and leading in a rough surface with visible circular traces [14]. A smooth welded surface with less traces of tool stirring was observed on the surface of the welded joint in the sample welded at 865 rpm. A sufficient heat generated produced better weld consolidation and better surface finish. The surface of the welded joints, on the other hand, showed an excessive flash defect at higher rotational speeds of 1140 and 1500 rpm (Figures 3d and 3e). This could be attributed to the excessive welding heat generated during welding, which caused the material flow of the welded joint to be excessive, resulting in flash defects caused by the outflow of severely plasticized material from beneath the rotating tool shoulder [15].

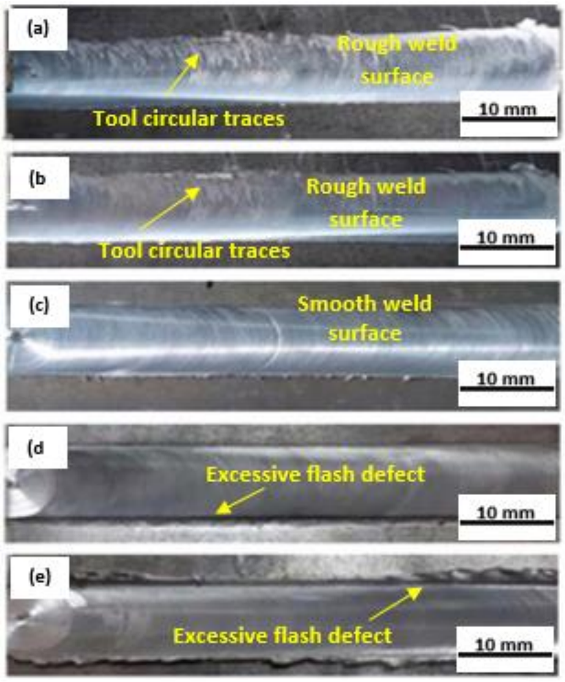

Figure 3. Top surface image of FSW joints at various rotational speed (a) 410 rpm (b) 600 rpm (c) 865 rpm (d) 1140 rpm and (e) 1500 rpm

Macrostructure observation. Figure 4 shows the macrostructure of a welded zone at various rotational speeds. The welding defects were formed within the NZ at low rotational speeds of 410 and 600 rpm (Figures 4a and 4b). The zig-zag welding defect formed within NZ due to low frictional heat generated during welding process that led to insufficient flow of material [14]. Welded joints with no welding defects were produced at a rotational speed of 865 rpm. Within the welded zone, no zig-zag or welding tunnel defects were formed. This could be due to the optimal amount of heat generated within the weld nugget zone (NZ) during welding, which contributed to proper material flow and a defect-free welded joint [16]. Tunnel defects, on the other hand, were formed within the weld zone at high rotational speeds of 1140 and 1500 rpm. The excessive frictional heat causes the material to flow excessively and produced tunnel defects.

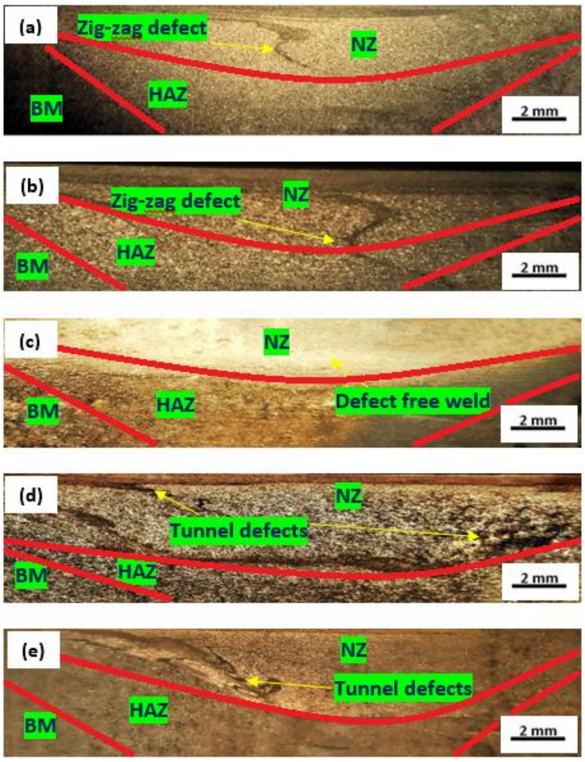

Figure 4. Macrostructure of welded zone at different rotational speed a) 410 rpm, b) 600 rpm, c) 865 rpm, d) 1140 rpm and e) 1500 rpm

Microhardness and Microstructure observation at Nugget Zone (NZ). Figures 5(a) and (b) present the Vickers micro-hardness and microstructure at nugget zone for various tool rotational speed. For all welded parameters, the BM of UFG cryorolled AA5083 alloy had the highest average micro-hardness value as compared to NZs. The high mechanical strength attained through cryorolling [17] can be attributed to the formation of UFG structure with a significant density of dislocations as shown in Figure 2(b). All welded samples showed a significant reduction in microhardness profile across the NZ. When compared to BM, the NZs has coarser grain size. This is due to the thermal effect, which caused grain growth in the deformed UFG microstructure. The formation of different grain sizes causes the variation in hardness readings in welded UFG AA 5083 alloy [4]. The FSW technique has the advantage of improving the mechanical properties of the UFG welded joint. However, due to the unstable nature of the UFG structure which more sensitive to thermal effects [9] is resulting in difficulties of UFG materials welding.

Sample welded at low rotational speed of 410 and 600 rpm recorded low average micro-hardness value within the NZ. From the microstructural observations, the grain structure within the NZ for 410 and 600 rpm experienced increased in size after welding with an average grain size of 32.2 µm and 27.4 µm, respectively, thus it decreased in microhardness value. Low rpm resulted in a low amount of heat generated during welding. The UFG structures were unstable, and the grain structures were expected to undergo recovery at low temperatures and the defect density within the grains were reduced. As welding process continues, the grain growth occurred, increasing the average grain size at NZ [11]. The sample welded at 865 rpm has the highest average hardness value in NZ. The NZ has a finer and more homogeneous grain size distribution, with an average of 13.3 µm. A sufficient heat source during welding allowed the grain in NZ to recrystallize. Despite the ability of the grain to recrystallize, however the grain size produced was larger than the grain size of UFG base metal due to the thermal effect during welding process.

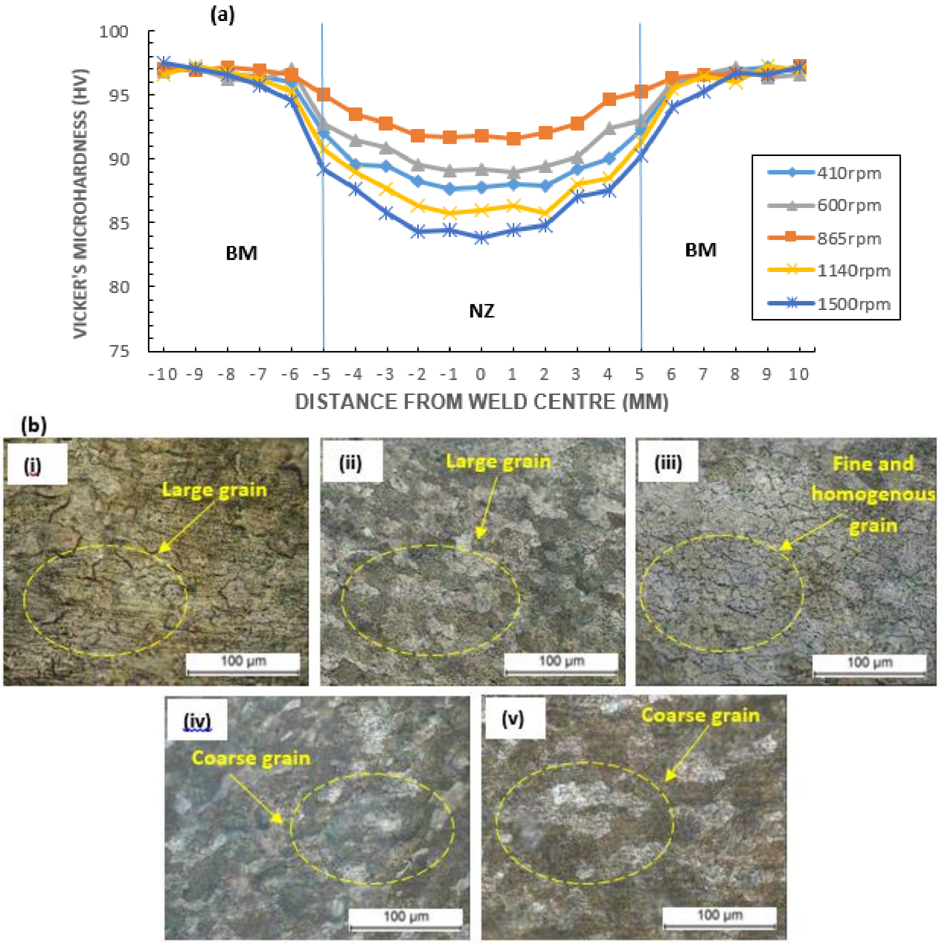

Figure 5. (a) Micro-hardness profile of the welded zone at different rotational speed, (b) microstructure of nugget zone (NZ) at rotational speed of (i) 410, (ii) 600, (iii) 865, (iv) 1140, and (v) 1500 rpm

The Vickers microhardness profile of a weld joint welded at 1140 and 1500 rpm, on the other hand, recorded the lowest hardness in NZ. The grain in NZ was larger and coarser at 1140 and 1500 rpm with an average size of 44.6 µm and 50.2 µm, respectively, resulting in a significant reduction in micro-hardness profile. This could be due to the excess welding heat generated during the welding process, which aided in faster grain growth during slow cooling [18]. Cryorolling has shown to be an efficient method for microstructural refining and the UFG microstructure can be preserved within the NZ following the FSW process. Although all welded samples have a reduction in hardness value in the nugget zone, the reported average hardness for NZ welded at 865 rpm was comparable to the UFG counterparts and was not considered a technical limitation [8].

Tensile Properties. Figure 6 shows the tensile strength of welded joints for samples welded at various rotating speeds. The tensile strength of welded joints was low in samples welded at low rotational speeds of 410 and 600 rpm. As previously stated, the as-received sample has less welding heat during welding, resulting in the formation of defects and an increased in grain size within the NZ. As a result, the microhardness decreased, causing a welded joint with low tensile strength. The sample welded at 865 rpm joint has the highest tensile strength. The formation of defect-free welds and recrystallized grain structure in NZ increased microhardness leading to high tensile strength. According to [15], a joint fabricated at the optimum welding rotational speed has a higher tensile strength due to balanced material flow and defect-free weld joint. The tensile strength of welded joints was reduced in samples welded at high rotational speeds of 1140 and 1500 rpm. Excess welding heat caused the formation of welding defects and the coarsening of grain size within NZs, which decreased the microhardness value of the welded joints.

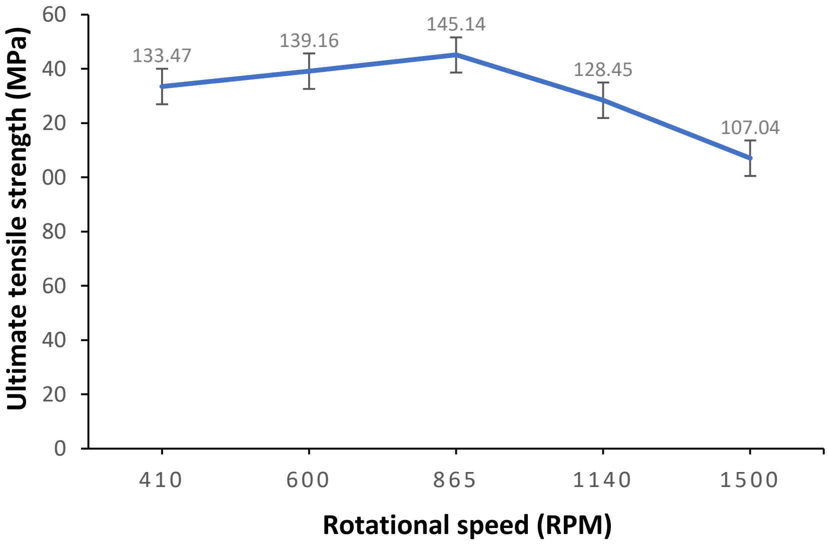

Figure 6. Ultimate tensile strength of FSW joints at different rotational speed

Fracture morphology. The fracture surface of a welded sample at various rotational speeds is depicted in Figure 7. In general, all welded samples displayed well-developed cup and cone dimples and cleavage facets across the entire surface indicating that they were failing under both ductile and brittle conditions. Despite this, the samples have more cup and cone dimple surface than cleavage surface. Sample welded at 400 rpm has a large dimple size and a medium area of cleavage facets. This accounted for the fractured sample of low ductility [19].

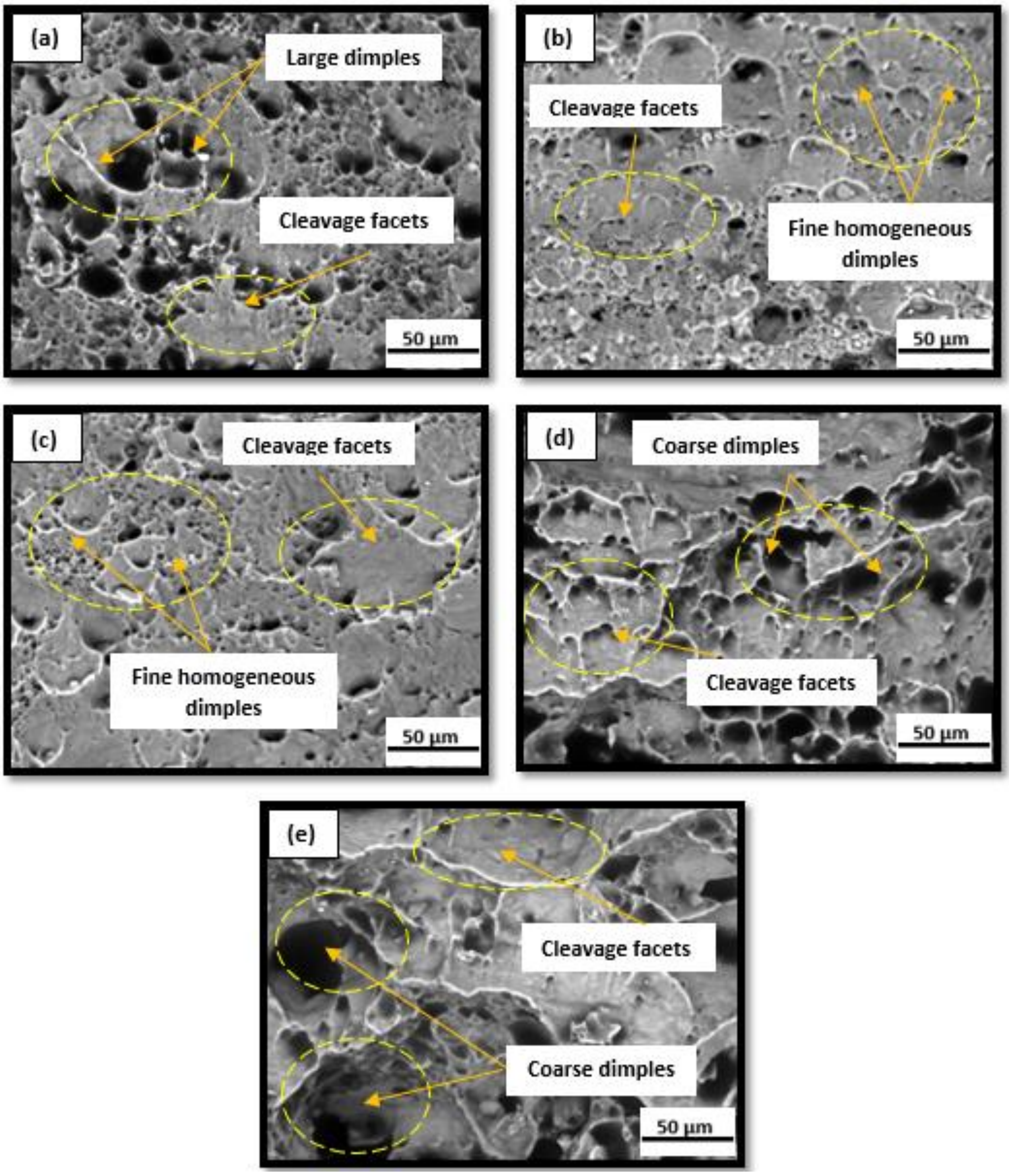

Figure 7. Fracture surface of tested tensile sample welded at different rotational speed (a) 410 rpm (b) 600 rpm (c) 865 rpm (c) 1140 rpm, and (e) 1500 rpm

As the rotational speed increased to 600 and 865 rpm, the fracture surface of the welded sample had finer and more homogeneous dimples as shown in Figure 7 (b, c). Apart from that, less cleavage facet surface area was observed. This proved that the welded sample have good ductile property. According to [20], he claimed that ductilite property of the sample may be determined by detecting a tiny and deep dimple on the fracture surface of the sample. The effect of grain refinement from recrystallization and formation of defect free weld led to the production of welded joint with high in ductility [21]. On the other hand, fracture surface for the sample welded with 1140 and 1500 rpm exhibited relatively coarser dimples with large cleavage facets area. This proved that tested samples failed by brittle manner. Extreme welding heat generation lead to the formation of welding defect and reduction in micro-hardness within the NZ and consequently produced brittle welded joints [22].

Conclusion

UFG plates of AA 5083 alloy have been successfully joined using FSW at various rotational speeds (400, 600, 865, 1140, 1500) rpm and good quality welds was obtained. The rotational speed has great effect on microstructure and mechanical properties of welded UFG joint due to heat generation and material flow. The insufficient heat resulted in weak joint while excessive heat attribute to ejection of material (excessive flash defect). Hence optimum heat generation was obtained at the rotational speed of 865 rpm. An optimal rotational speed of 850 rpm produced a smooth welded surface, defect-free and refined grain with NZ that attributed to the highest value of microhardness (91.78 HV) and ultimate tensile strength (145.14 MPa).

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Author Contribution

All authors contributed to the data analysis, drafting, and critical revision of the paper, and they all agree to accept responsibility for all aspects of the work.

Disclosure of Conflict of Interest

The authors have no disclosures to declare.

Compliance with Ethical Standards

The work is compliant with ethical standards.

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