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MODIFICATION OF MICROSTRUCTURE, MECHANICAL PROPERTIES AND WEAR PERFORMANCE OF 5083 ALUMINUM ALLOY USING FRICTION STIR PROCESSING

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ABSTRACT
Friction Stir Processing (FSP) was applied to as-rolled AA5083 aluminium alloy to enhance its wear resistance through microstructural refinement. Processing was conducted at a tool rotation speed of 1120 rpm and a traverse speed of 40 mm/min. The Peak processing temperature increased with the number of passes, reaching ~492°C after three passes, which, combined with severe plastic deformation, promoted dynamic recrystallization and grain refinement. Orientation maps confirmed progressive refinement in the nugget zone, with average grain size reduced from ~10 µm (one pass) to 4 µm (three passes). This refinement enhanced hardness in line with the Hall–Petch effect. Tribological testing showed that the as-rolled alloy had a wear rate of 6×10^{-3} g/min, which rose to 7×10^{-3} g/min after one FSP pass due to abrasive particle generation. With additional passes, the wear rate decreased to 5.5×10^{-3} g/min and 4.5×10^{-3} g/min, demonstrating improved resistance beyond the as-rolled condition. The enhancement is attributed to grain refinement, and higher hardness.

KEYWORDS
Friction Stir Processing (FSP), AA5083, grain refinement, hardness, wear resistance.

INTRODUCTION
Aluminum and its alloys are extensively utilized across various engineering sectors, including aerospace, transportation, and marine fabrications, owing to their low density, high strength-to-weight ratio, excellent corrosion resistance, and good formability, [1 - 4]. Among these, the AA5083 (Al-Mg alloy), stands out for its outstanding corrosion resistance, especially in marine environments, [1, 5 - 8], making it a material of choice for naval welded structures, automotive, and aerospace panels where weight savings are critical, [1, 6, 7]. However, the useful life of components often depends on their surface properties, such as wear resistance, [1, 9 - 12]. The

inherent soft nature of aluminum alloys can lead to higher wear, even under low loads, necessitating surface modification techniques to enhance their performance.

Friction Stir Processing (FSP) is an emerging solid-state surface modification technique, [1, 6, 7, 9] derived from Friction Stir Welding (FSW), invented by The Welding Institute (TWI) in 1991, [1, 5 - 7, 9, 13, 14]. FSP is a local thermo-mechanical metalworking process that modifies the microstructure and mechanical properties of sheet metals and as-cast materials without reaching the melting temperature [1, 6, 7]. In this process, a rotating tool with a shoulder and a pin plunges into the workpiece and traverses along a desired path, [1, 5] .The frictional heat generated by the rubbing shoulder and the mechanical stirring action of the pin induce intense plastic deformation, leading to dynamic recrystallization (DRX) within the processed zone, [1, 5 - 7, 9, 14 - 17]. This fundamental mechanism results in a refined and homogenized grain structure, typically referred to as the stir zone (SZ) or nugget zone (NZ), [1, 5 - 7, 9, 13 - 19].

The microstructural modifications induced by FSP are profound, [1]. The original coarse, elongated, or dendritic grains are transformed into fine, equiaxed, and recrystallized grains, [1, 5 - 7, 9, 13 - 17, 20, 21], with an average grain size often decreased significantly from ~10 µm to ~3 µm for AA5083, [1], or from ~32 µm to ~7 µm in a first pass, [1, 14]. This grain refinement is largely attributed to continuous dynamic recrystallization (CDRX), a dominant restoration mechanism, [7, 14]. Process parameters such as tool rotational speed, traverse speed, and shoulder diameter significantly influence the extent of grain refinement and the heat input [9, 13, 16, 17, 20]. While lower heat input generally leads to finer grains, [13, 17], excessive heat can cause grain coarsening, [5, 9]. FSP also impacts the distribution and morphology of second-phase particles, often causing their fragmentation and uniform dispersion, [5, 14, 15, 21], though some particles, like Mn-rich ones, are stable and their size/morphology may not change significantly with external cooling, [5, 20]. The dislocation density dramatically decreases after FSP due to annealing and dynamic recrystallization, [5].

These microstructural changes translate into significant enhancements in mechanical properties, [1, 7]. FSP has been shown to improve hardness, ductility, formability, and mechanical strength, [1, 7]. Hardness values typically increase in the processed zone compared to the base material, following the Hall-Petch relationship due to grain refinement, [1, 7, 9, 13]. While FSP can sometimes lead to a reduction in yield strength (YS) and ultimate tensile strength (UTS) due to annealing softening and recrystallization [5],the total elongation (TE) is often elevated, significantly enhancing the product of UTS and TE, [5]. For instance, cryocooling during FSP of AA5083 can achieve superior strength and ductility, [20]. Superplasticity, characterized by very large elongations at elevated temperatures and slow strain rates, is also a notable outcome, especially in ultrafine-grained FSPed materials, [6, 15]. However, factors like abnormal grain growth (AGG) at elevated temperatures can restrict superplastic elongations. [5, 15], and the stability of the microstructure against AGG depends on

processing parameters, with higher rotational speeds and multiple passes sometimes inhibiting its expansion, [5].

Beyond bulk mechanical properties, FSP also positively affects surface properties like wear resistance, [1]. The wear resistance of most FSPed AA5083 specimens is notably higher than that of the base material, [1, 7, 9]. This improvement is attributed to the fine-grained microstructure, optimal dispersion of secondary phases, lower coefficient of friction, and strain hardening effects, [1, 9] in the processed zone. While increased wear can occur due to fragmentation of work-hardened layers leading to abrasive wear, appropriate process parameters can mitigate this, [9].

Furthermore, FSP influences corrosion behavior, a critical aspect for AA5083 in marine applications, [1, 7]. Studies indicate that FSP can reduce susceptibility to localized corrosion and pitting corrosion due to grain refinement and the refinement/re-dissolution of Mn-rich secondary phase particles, [1, 7]. FSP is also believed to prevent the detrimental precipitation of anodic β-phase (Al3Mg2) along grain boundaries, which typically increases intergranular corrosion (IGC) susceptibility in sensitized AA5083 alloys, [7]. Despite the extensive research on FSP of aluminum alloys, and some initial studies on AA5083, there remains a need for a comprehensive understanding of how various FSP parameters synergistically influence the microstructure, and consequently the mechanical and wear performance of AA5083. Existing literature sometimes presents contradictory results or focuses on specific aspects, leaving gaps in optimizing FSP for a balanced enhancement of properties in this crucial alloy.

The current study aims to investigate the modification of microstructure, mechanical properties, and performance of 5083 aluminum alloy using Friction Stir Processing. The study will focus on understanding the relationships between the number of FSP passes, the resulting microstructural evolution, and the consequent changes in hardness, and dry sliding wear resistance, with the objective of identifying optimal processing conditions.

EXPERIMENTAL

Materials and chemical composition

Hot rolled sheets of AA 5083 Al-alloys were used to investigate the effect of the FSP processing on its microstructure, mechanical properties and wear rate. Table 1 illustrates the chemical composition of the investigated alloy.

Table 1: Chemical Composition of the 5083 Alloy (wt. %).

Element	Si	Mg	Mn	Fe	All other elements	Al
wt. %	0.15	4.2	0.7	0.3	<0.1	Bal.

Friction Stir Processing

The surface of the rolled sheets was treated to Friction Stir Processing (FSP) utilizing an automated milling machine at a rotational speed of 1120 rpm and a traverse speed

of 40 mm/min. Fig. 1 illustrates the FSP and the tool geometry employed, featuring a triangle taper tip pin configuration (top view in Fig. 1,a). The surface was processed with three different routes: 1) single pass route, 2) double passes route, and 3) triple passes route as shown in Fig. 1,b. During the FSP, the temperature distribution maps were captured using an infrared thermal imaging camera (Fluke-Ti32).

Microstructure Investigations

Following the FSP, the processed sheets were cut perpendicular to the FS-processing direction to study the microstructure across the processing direction. The samples were mechanically ground using SiC paper ranged from 180-to-4000-grit prior to polishing in a colloidal silica (0.04 µm) suspension containing 20% water. After polishing, all samples were subjected to etching using Keller's etchant, comprising 2.5mL (HNO_3), 1.5mL (HCl), 1mL (HF), and 95mL (H_2O). The microstructure was examined using an optical microscope (OM, Olympus BX51) with polarized light. The average grains sizes in the stirred zone of the processed samples were determined using by the liner intercept standard method according to ASTM E1382.

Hardness Measurements

Vickers microhardness tests were conducted with an HVD-1000AP hardness tester with a load of 20 N and a dwell duration of 10 seconds, in accordance with the ASTM E-384-17 standard. Before performing the hardness tests, all samples were prepared as described in the microstructure section. Hardness maps were recorded and illustrated along the sample surface perpendicular to the FSP processing direction (as shown in Fig. 1,c).

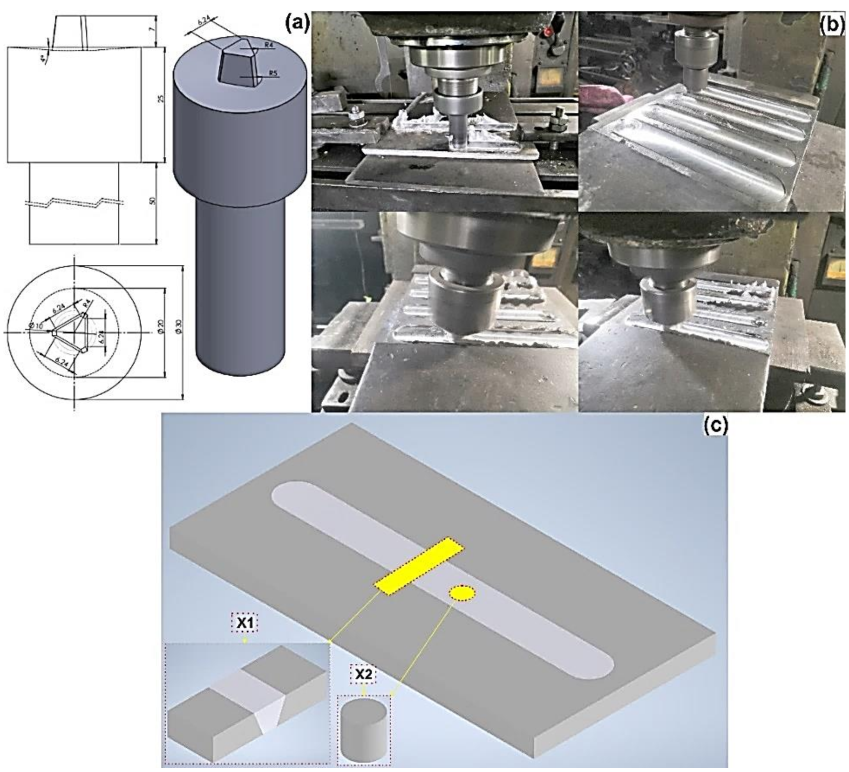


Fig. 1 (a) The friction stir processing (FSP) tool. (b) A photograph of the FSP operation in progress. (c) Schematic diagram illustrates the extraction locations of test samples: (×1) sample for microhardness test and (×2) Pin sample for wear test.

Wear test

The wear test using weight loss technique was performed with pin on ring apparatus on samples located as shown in Fig. 1,c . All samples for wear testing were carefully polished using a series of grinding papers ranging from 600 to 4000 grit to provide a superior surface finish and standardize the initial surface roughness across all samples. The weight loss was quantified and recorded using a digital balance with an accuracy of ± 0.0001 g. The testing parameters were 0.3 bar and a rotational speed of 265 rpm for a duration of 10 minutes.

RESULTS AND DISCUSSION

Thermal map

Fig. 2, presents the results obtained from the thermal camera during FSP with different passes conditions, as shown in Fig. 2 shows that the peak temperatures recorded for 3 passes samples is higher than those recorded for one and two passes. The peak temperature ranges from 40 to 446 °C and from 37 to 463 °C, for one and two passes conditions, respectively. The maximum recorded peak temperature was about 492 °C during the three passes conditions, [7].

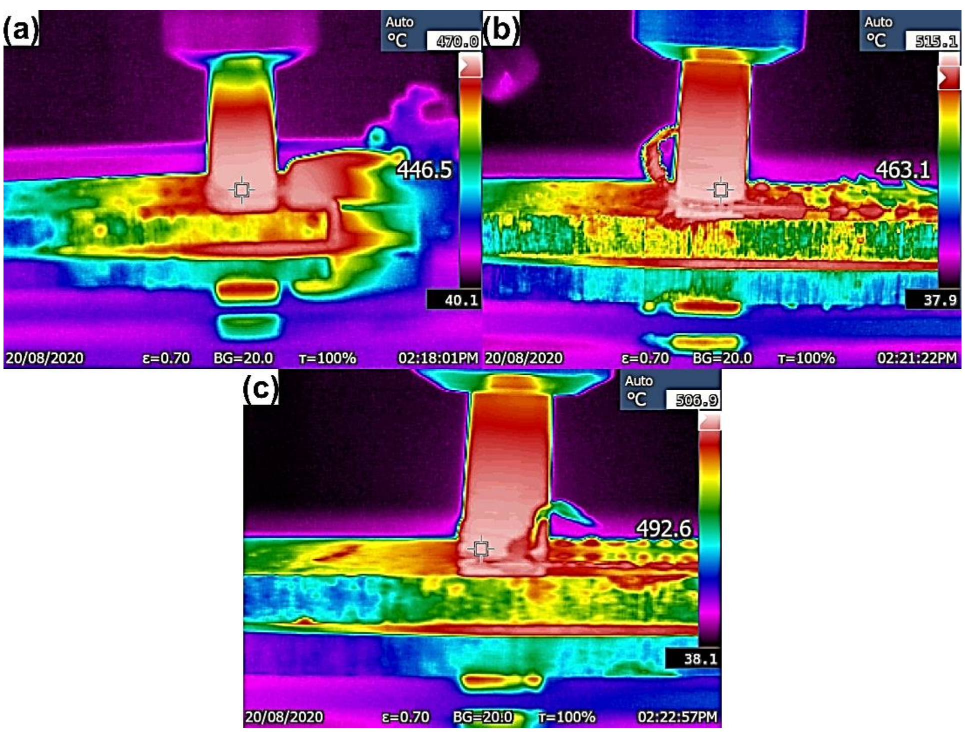


Fig. 2 Thermal camera imagery showing the temperature distribution during friction stir processing (FSP) for (a) a single pass, (b) two passes, and (c) three passes.

Microstructural Investigations

Fig. 3 and Fig. 4 present color-coded orientation maps of AA5083 alloys subjected to friction stir processing (FSP) at low and high magnification, respectively. As shown in
Fig. 3 (d), very fine equiaxed grains were observed in the nugget zone (NZ) of the samples processed with three FSP passes, compared to the larger and elongated grains found in elongated grains found in the as received alloy.
Fig. 3 (a). Furthermore,
Fig. 3 (b - d) and Fig. 4 demonstrates that increasing the number of FSP passes results in the formation of more homogeneous and finer grains in the nugget zone. This grain refinement is attributed to dynamic recrystallization induced during FSP. The combined effect of increased temperature and severe plastic deformation during processing promotes recrystallization and consequently reduces grain size, consistent with previous studies, [7].

Fig. 5 presents the statistical distribution of cell sizes for the three FSP conditions. For the one-pass and two-pass conditions, the average grain sizes were approximately 10 µm (standard deviation: 11 µm) and 8 µm (standard deviation: 5 µm), respectively. In the case of three passes, the average cell size was further reduced to 4 µm with a standard deviation of 1 µm, representing nearly a 50 % reduction compared to the grain size obtained after a single pass. This observation is consistent with a previous study, [1], which reported a 70 % reduction in average grain size in the nugget zone (from 10 µm to 3 µm) based on optical microscopy analysis of grain size and particle distribution, [1].

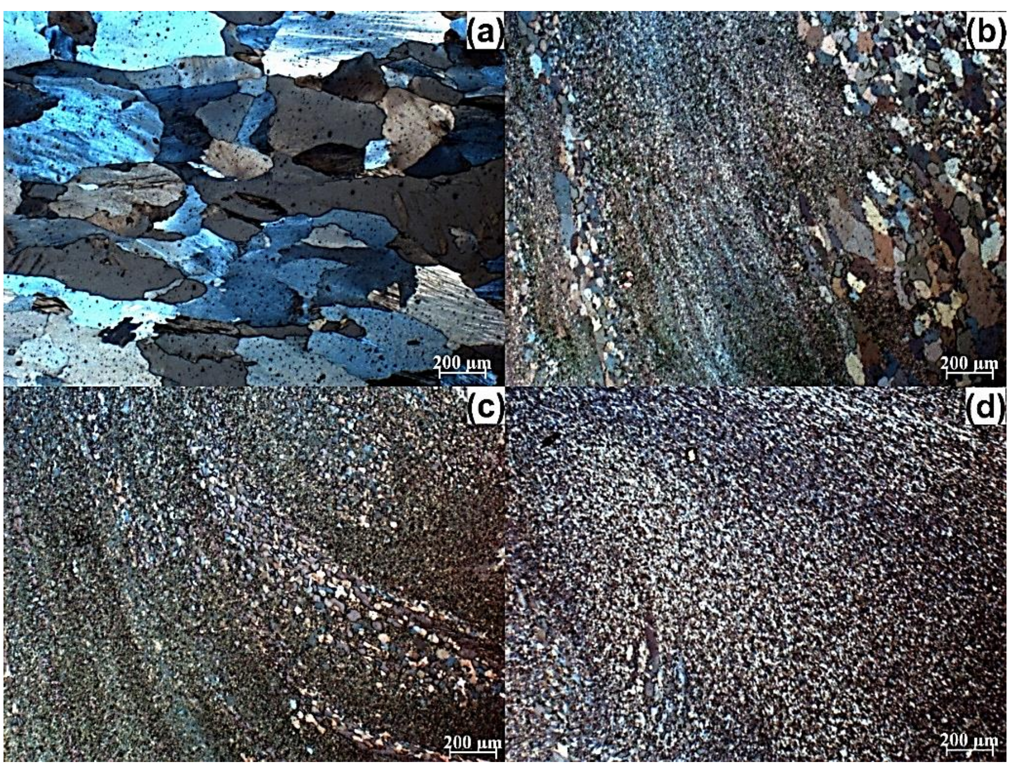


Fig. 3 Low-magnification optical micrographs (polarized light) showing the transverse cross-section of 5083 alloy under different processing conditions: (a) as-rolled base material, (b) after one FSP pass, (c) after two FSP passes, (d) after three FSP passes.

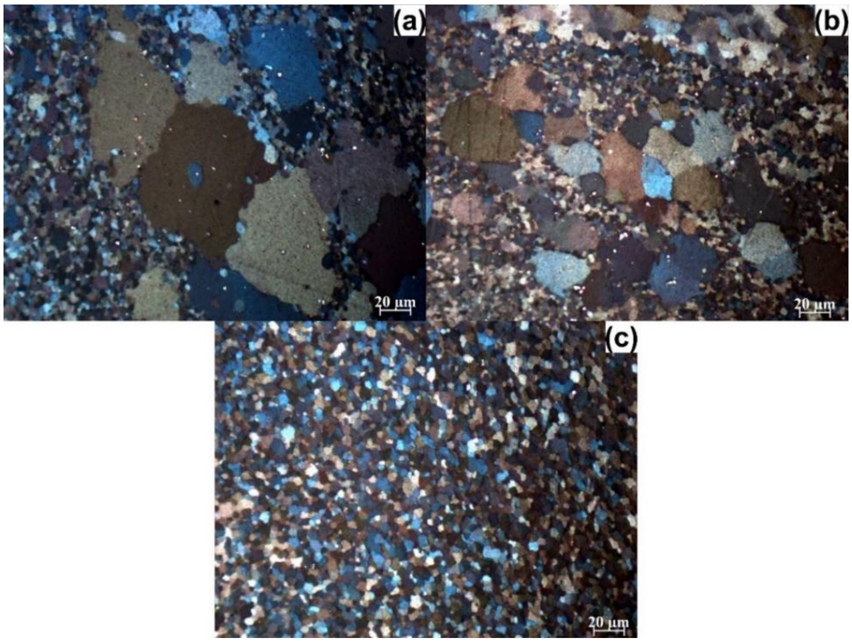
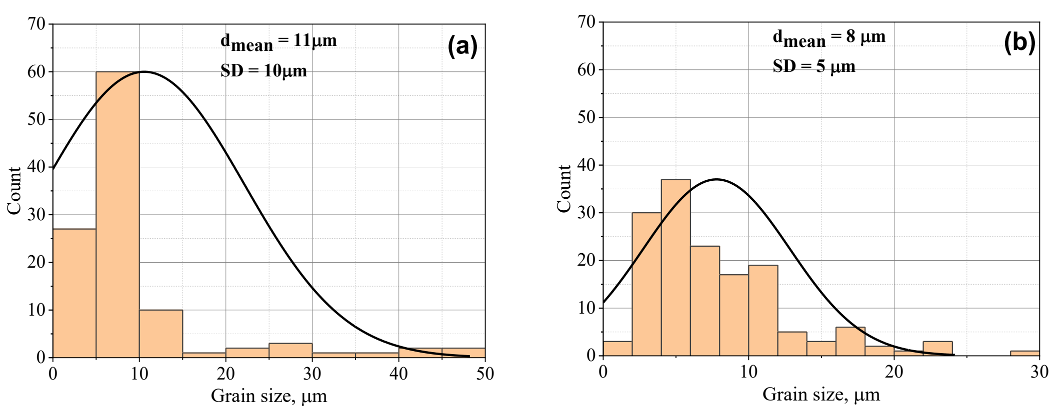


Fig. 4 High-magnification optical micrographs (polarized light) showing the transverse cross-section of 5083 alloy under different processing conditions: (a) after one FSP pass, (b) after two FSP passes, (c) after three FSP passes.



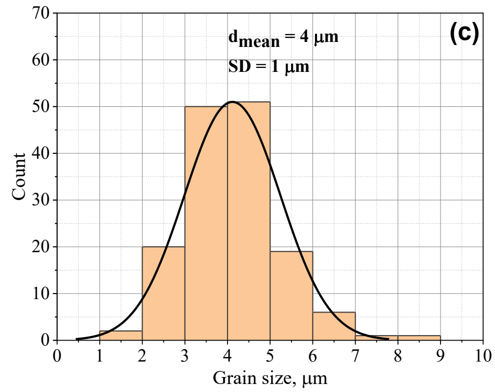


Fig. 5 Grain size distribution measured from polarized light optical micrographs of the friction stir processed (FSP) region after (a) one pass, (b) two passes, and (c) three passes.

Hardness of the FS Processed Zones

The microhardness distribution maps of FSP specimens are depicted in Fig. 7 with different number of passes from single pass to their passes. They observed that increasing the number of passes, from single-pass to three-pass, led to increase in average hardness value in the FSPed regions. This enhancement in hardness is primarily attributed to the significant grain refinement strengthening that occurs during the FSP process, as fine grains produced in the FSPed specimens have a positive effect on hardness according to the Hall-Petch relationship, [7]. This indicates that the number of passes is a critical process parameter influencing various material properties, including microstructural characteristics and mechanical properties.

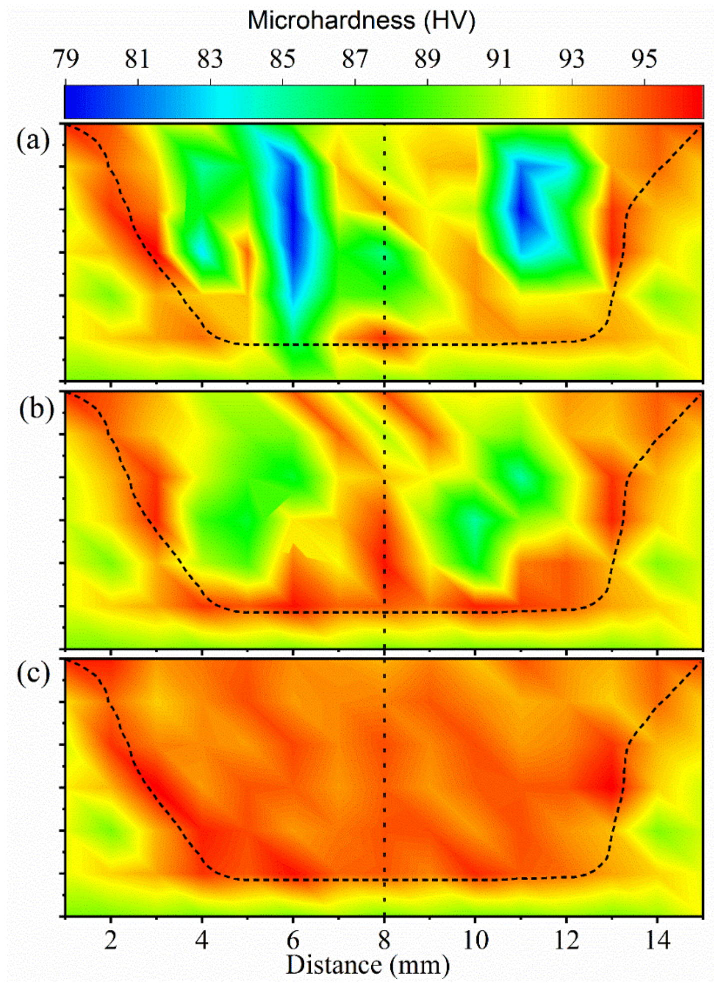


Fig. 6 Microhardness distribution maps of the transverse cross-section for friction stir processed (FSP) samples: (a) one pass, (b) two passes, (c) three passes.

Wear of the FS Processed Zones

As shown in Fig 7, as-rolled AA5083 material exhibits a wear rate of 6 (× 10^{-3} g/min). Following one pass of friction stir processing (FSP), wear rate increases to 7×10^{-3} g/min, which initially suggests a reduction in wear resistance compared to the as-rolled condition. This seemingly counter-intuitive observation, where FSP generally aims to enhance wear resistance, [1, 9], can be understood through literature that suggests that poor wear resistance in some FSP conditions may be attributed to the fragmentation of a work-hardened layer, leading to the formation of loose, hard particles that cause abrasive wear on the surface, [9]. These particles, being harder than the base material, can actively erode the surface, thereby increasing the wear rate, [9]. However, subsequent processing leads to a notable improvement: wear rate significantly decreases to 5.5 ×10^{-3} g/min after two passes and further to 4.5 ×10^{-3} g/min after three passes, demonstrating an enhanced wear resistance that is superior to the as-rolled state. This positive trend aligns with the widely reported benefits of FSP for AA5083, primarily due to microstructural refinement achieved through intense plastic deformation and dynamic recrystallization in the stir zone (SZ), [1, 6,

7, 15]. This process typically results in a finer, more homogenized, and equiaxed grain structure, which consequently increases the material's hardness in the processed zone, [1, 7, 9]. According to the Hall-Petch relationship, this grain refinement positively impacts hardness and, therefore, wear resistance, [7, 9]. While some studies on multi-pass FSP indicate that the number of passes does not significantly alter grain size or hardness under certain conditions, [5], other literature supports that increasing the number of passes can lead to ultrafine grains, [7] and improved surface integrity, as seen in corrosion resistance studies where weight loss decreased with more passes, [1, 7]. The observed reduction in wear rate with increasing passes (two and three) therefore reflects the establishment of a more stable and refined microstructure that effectively resists wear through optimized processing conditions, [9].

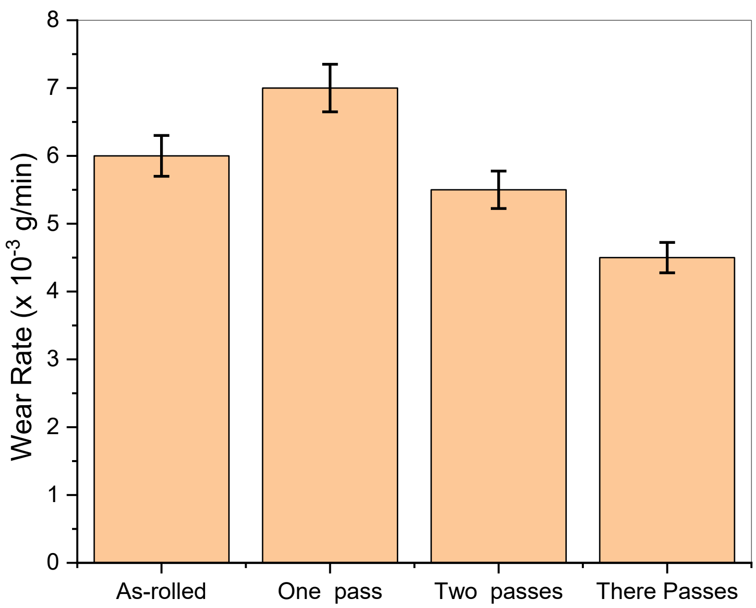


Fig 7 Relationship between weight rate and the number of frictions stir processing (FSP) passes.

CONCLUSIONS

This study investigated the effect of friction stir processing (FSP) passes on microstructure, mechanical properties and wear resistance of 5083 Al alloy.

1. Peak processing temperature rose with the number of passes, reaching ~492 °C after three passes. Elevated temperature combined with severe plastic deformation promoted dynamic recrystallization (DRX), producing finer, equiaxed grains in the stir zone.

2. Orientation maps confirmed that multi-pass FSP progressively refined grains in the nugget zone, with three passes producing uniformly distributed fine equiaxed grains compared to the elongated grains in the as-received alloy.

3. Statistical analysis showed grain size decreased from ~10 µm (one pass) to 8 µm (two passes) and 4 µm (three passes), representing nearly a 50% reduction relative to a single pass.

4. Hardness Enhancement via Hall–Petch Effect: Grain refinement increased hardness in the processed zone, consistent with the Hall–Petch relationship, thereby strengthening wear resistance.
5. The as-rolled alloy exhibited a wear rate of 6 × 10^{-3} g/min, which increased to 7 × 10^{-3} g/min after a single FSP pass due to fragmentation of the work-hardened layer and abrasive particle generation.
6. Additional passes reduced the wear rate to 5.5 × 10^{-3} g/min (two passes) and 4.5 × 10^{-3} g/min (three passes), indicating that multi-pass FSP enhances wear resistance beyond the as-rolled condition.

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