
| RESEARCH ARTICLE

A Short Review on the Mechanical, Tribological and Corrosion Behavior of the Aluminum Matrix Composites Reinforced with High-Entropy Alloys Fabricated by Friction Stir Processing

Hussein Mousa Habeeb¹ ✉ and Ahmed. A. Taher²

^{1,2}Department of Mechanical Engineering, College of Engineering, University of Kufa, Iraq

Corresponding Author: Hussein Mousa Habeeb, **E-mail:** Ahmed.abosabeeh@uokufa.edu.iq

| ABSTRACT

Aluminum alloys have found widespread applications in many industries, including transportation, aerospace, and marine industries, owing to their low density and excellent corrosion resistance. However, their relatively low hardness and poor tribological performance limited their durability under severe service conditions. Over the past decades, the improvement of their mechanical, tribological, and corrosion properties via the formation of composites has received great attention from researchers. Recently, high entropy alloys (HEAs) have been introduced as promising reinforcements for the aluminum matrix composites (AMCs) owing to their superior hardness, metal-metal compatibility, low coefficient of thermal expansion, and low tendency to form brittle intermetallic compounds through processing. Among the fabrication methods of AMCs, friction stir processing (FSP), as a solid-state severe plastic deformation (SPD) method, offers many advantages for the incorporation of the HEAs on the surfaces of the AMCs with microstructural refinements. In this short review study, first, microstructural evolution of the aluminum alloys through FSP is discussed, and then, the effects of the HEAs addition on the mechanical, tribological, and corrosion properties of the AMCs fabricated by FSP are discussed. In this work, the effects of the various parameters such as HEA contents, FSP pass number, rotation speed of the tool, and tool pin geometry on the properties of the AMCs reinforced with HEAs are discussed.

| KEYWORDS

High-entropy alloys; Aluminum alloys; Friction stir processing; Mechanical properties; Tribological performance; Corrosion resistance; Microstructure.

| ARTICLE INFORMATION

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1. Introduction

Because of their unique properties, including low density, high ductility, and high corrosion resistance, aluminum and its alloys have attracted great application in different industries. However, their low hardness and poor tribological resistance have been identified as the major problems. The mechanical and tribological performance of the aluminum alloys can be enhanced through the formation of aluminum matrix composites (AMCs) with various reinforcements. Fabrication of AMCs is generally performed via casting and powder metallurgy methods. Despite the various advantages of these methods, they generally have several problems such as matrix porosity, debonding, and poor wettability [Anvari, 2013; Bauri, 2011; Khayyamin, 2013; Rana, 2016].

As a well-known fact, for improving the tribological and corrosion resistance of aluminum alloys, surface modification is adequate. Friction stir processing (FSP) is an effective method for the fabrication of surface composites, where the reinforcements are squeezed into the machined grooves on the surface of a bulk material. During FSP, rotation of the tool and friction between tool and workpiece lead to high plastic deformation and increased heat, resulting in grain refinement in the microstructure. Generally, three distinct zones, including stir zone (SZ), thermo-mechanically affected zone (TMAZ) and heat-affected zone (HAZ), can be identified through this process [Anvari, 2013, Akbari, 2017; Basavarajappa, 2007; Dinaharan, 2017; Mahmoud, 2010; Sarmadi, 2013; Zmitrowicz, 2006].

In the literature, there are many works on the effectiveness of ceramic reinforcements such as SiC, Al₂O₃ and SiO₂ on the mechanical, tribological and corrosion resistance of the aluminum alloys [Yang, 2010; Rong, 2024; Cai, 2025]. Apart from ceramic reinforcements, recent studies have introduced high-entropy alloys (HEAs) as promising reinforcements for aluminum alloys. HEAs are defined as alloys with five or more major elements, where each major element must have a concentration between 5 and 35%. In addition to the major elements, high-entropy alloys can contain minor elements, each of which is less than 5% [George, 2006; Jien-Wei, 2006; Ye, 2016]. Compared to traditional ceramic particles, as reinforcements for aluminum alloys, high-entropy alloys (HEAs) have significant advantages, including proper metallurgical bonding due to their metal-metal compatibility, limited formation of brittle intermetallic compounds through processing, low propensity to micro-crack nucleation, lower coefficient of thermal expansion (CTE) mismatch, and combination of strength and ductility [Yuan, 2019; Yuan, 2020; Zhang, 2023]. Although there are some review studies on the development of the AMCs reinforced with HEAs [Ren, 2024; Chen, 2026; Asadikiya, 2021], as far as we know, there is no review paper on evaluation AMCs fabricated with FSP. Therefore, in this short review, for the first time, an attempt is made to provide a summary of the limited works on the mechanical, tribological, and corrosion resistance of the aluminum alloys/HEA composites fabricated by FSP and the influencing parameters.

2. Microstructural evolution of aluminum alloys through FSP

Fig. 1 shows the schematic image of FSP. During FSP, severe plastic deformation (SPD) is carried out on the surface of the metals. In addition, rotation of the tool and friction between the tool and workpiece lead to heat generation (450 to 550°C). Despite the fact that increasing the dislocation density is caused by SPD, dislocation density of materials can be reduced through dynamic recovery (DRV) and subsequent recrystallization due to the increase during FSP. In addition, the increase during FSP can result in dissolving/coarsening of hardening phases in aluminum alloy (e.g., Mg₂Si in Al6061). Therefore, it can be said that high-temperature buildup in SZ leads to the dissolving/ coarsening of hardening phases in the aluminum matrix. This phenomenon leads to the occurrence of overall softening in SZ. Although increasing the pass number leads to significant grain refinement, higher heat input is produced with a higher pass number. In other words, high heat input causes to dissolving/coarsening of hardening phases, resulting in general softening [Mishra, 2005].

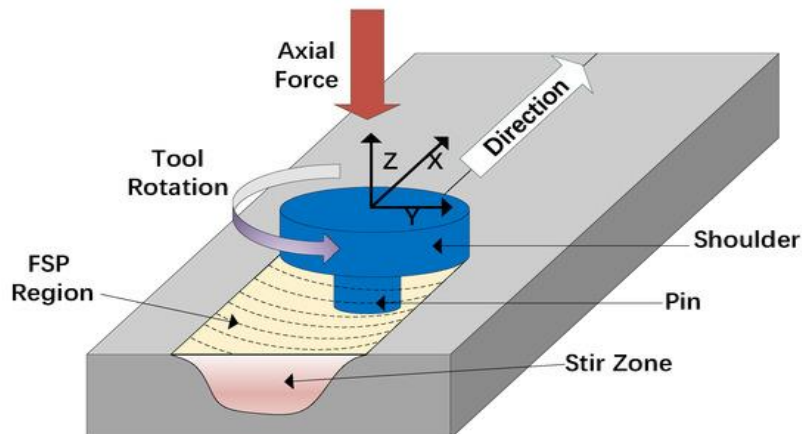


Fig. 1. Schematic image of FSP [Li, 2019].

Rotation of the tool and friction between the tool and workpiece lead to heat generation (450 to 550°C). During FSP, because of the high stacking fault energy of aluminum alloys, dislocations can easily glide/ climb through dynamic recovery (DRV). It is important to note that the dynamic recrystallization can be continuous or discontinuous. In addition, for the initiation of discontinuous dynamic recrystallization (DDRX) in any metal, there should be the following condition:

$$\frac{\rho_m^3}{\dot{\epsilon}} > \frac{2\gamma_b}{KLMGb^5} \quad (1)$$

Where ρ_m is the density of mobile dislocations, $\dot{\epsilon}$ is the grain boundary energy, K is a constant fraction of the dislocation line energy that is stored in the newly formed grains, L is the mean slip distance of dislocations in these grains, M is the boundary mobility, G is the shear modulus, and b is the Burger's vector. These conditions suggest that aluminum, because of its high rate of DRV, does not experience DDRX. Therefore, it can be concluded that CDRX is a possible recrystallization mechanism for aluminum alloys during FSP [Mishra, 2005, McNelley, 2008].

3. Effects of HEA on the mechanical, tribological and corrosion resistance

The HEA, through different mechanisms such as DRX and Zener pinning mechanisms, can refine the microstructure. For example, in Zener mechanisms, the presence of the fine HEA particles at grain boundaries restricts grain growth. In the case of mechanical properties, Hall-Petch and Orowan mechanisms are dominant in improving the mechanical properties of FSPed samples by the addition of HEA. For example, Li et al. [2020] investigated the effects of Al_{0.8}CoCrFeNi HEA particles (with a particle size of 6.5 µm) on the mechanical properties of the Al5083 alloys using FSP. The composites were fabricated using 4 passes of the FSP process with a threaded cylinder pin with a diameter of 6 mm, with a rotational speed of 800 rpm and a processing speed of 50 mm/min. It is worth noting that the volume fraction of the Al_{0.8}CoCrFeNi HEA particles in this work was 3.8%. As can be seen in Fig. 2a and 2b, the microstructural analyses revealed that the addition of the HEAs caused the refinement of the FSPed sample, where the grain size of the FSPed composites was 2.8 µm, which was lower than that of FSPed aluminum (4.6 µm). The morphological analyses revealed the inter-diffusion of the aluminum alloys and HEAs without any discontinuity. The mechanical evaluation of the samples proved the improvement of the hardness and tensile strength of the FSPed aluminum alloys using HEAs, compared to neat samples. For example, the hardness value of the stir zone of the FSPed composite was 125.7 HV, which was about 56% higher than that of the FSPed sample (Fig. 2c). Similarly, as can be observed in Fig. 2d, the tensile properties improved significantly; the ultimate tensile strength increased from 304.7 MPa to 371.2 MPa (22% improvement). Furthermore, the elongation of the samples did not reduce a lot by increasing the tensile strength. The fracture analyses proved the reduction in the size of the dimples in the aluminum matrix by the addition of HEAs. HEAs, by providing high-density dislocations due to the thermal mismatches, improved dynamic recrystallization, improving the equiaxed grains. Moreover, the distribution of the HEAs at grain boundaries restricted the grain growth (Zener pinning mechanism). Consequently, the refined structure and distributed HEA particles through Hall-Petch and Orowan mechanisms improved the mechanical properties of samples.

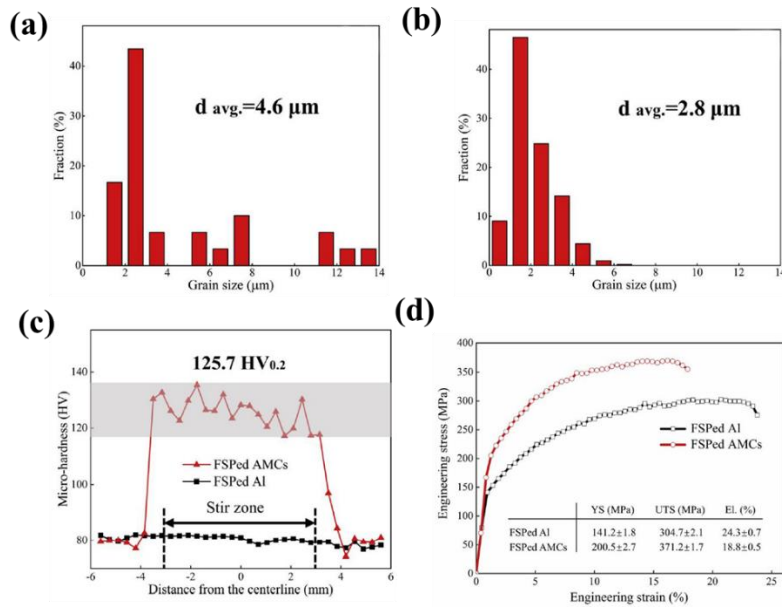


Fig. 1. Microstructural and mechanical properties of FSPed Al5083/ Al0.8CoCrFeNi HEA, (a) grain size distribution of the FSPed Al5083, (b) grain size distribution of the FSPed Al5083/ Al0.8CoCrFeNi HEA, (c) microhardness variation across the stir zone, (d) engineering stress-strain curves of samples, reproduced from [Li, 2020].

In another study conducted by Yang et al. [2020], they investigated the mechanical and tribological performance of the Al5083/AlCoCrFeNi composites subjected to FSP. The FSP with 5 passes was conducted with a constant rotational speed of 1400 rpm and a travel speed of 40 mm/min. Their results showed that the grain size of base metal was 2-15 μm, while FSPed Al5083 and FSPed Al5083/HEA had grain sizes of 2.1 μm and 1.2 μm, showing the positive role of the FSP and HEA addition in microstructure refinement. Analysis of mechanical properties of samples revealed that the FSP caused slight improvement of the UTS, YS, and elongation, compared to the base material. On the other hand, the HEA addition significantly improved the UTS and YS but slightly reduced elongation; a high UTS of 401 MPa (31.9% improvement) and YS of 219 MPa (25.1% improvement) were obtained for the FSPed Al5083/HEA composites.

3.1 Effective Parameters

Although the HEAs have a positive role in the properties of the AMCs fabricated by FSP, there are many parameters such as HEA content, FSP rotational speed, and FSP pin geometry that should be discussed. In the following subsections, the effects of the most important parameters on the mechanical, tribological, and corrosion performance of the AMCs with HEAs are briefly discussed. Fig. 3 present the main parameter affecting the properties of the Al/HEA composites fabricated by FSP.

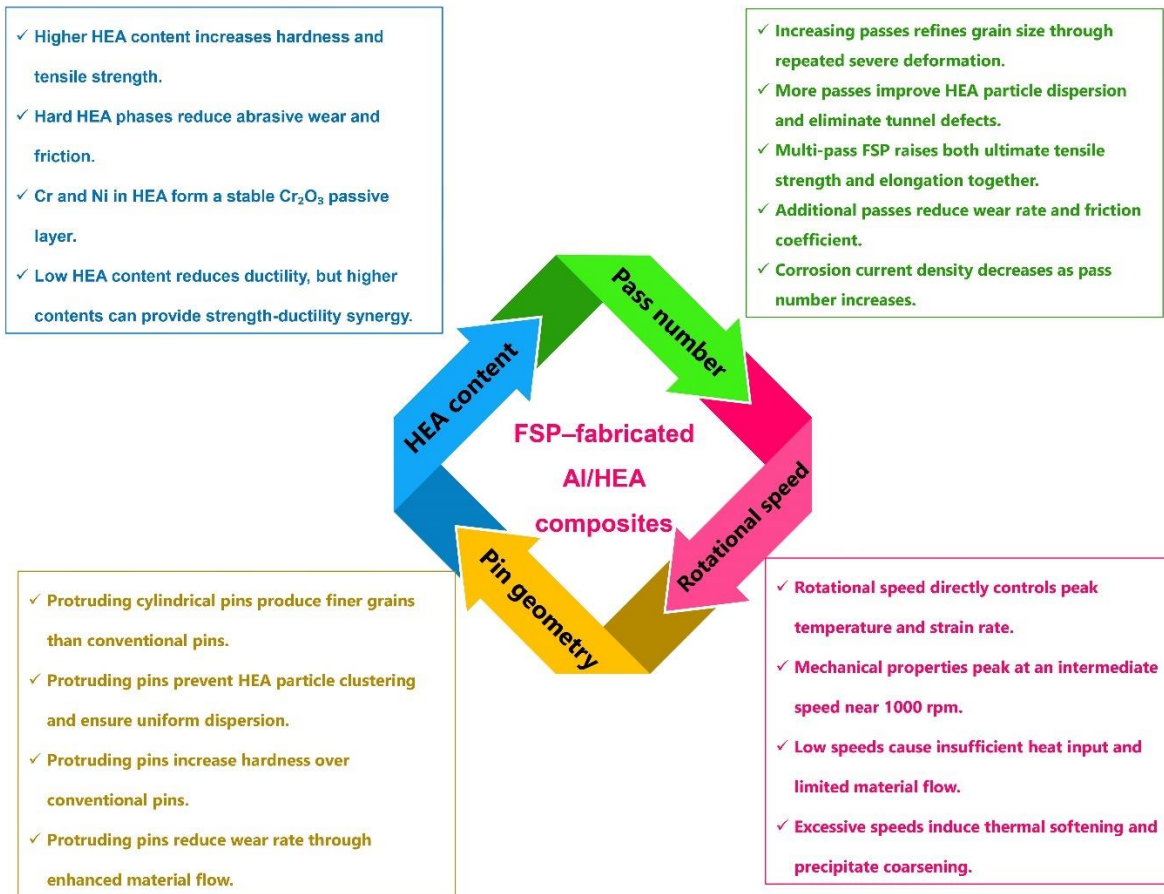


Fig. 3. The main parameters affecting the properties of the Al/Hea composites fabricated by FSP.

3.1.1 Effects of HEA content

The content of HEA is a dominant factor on the mechanical, tribological and corrosion properties of the Al/HEA composites fabricated by FSP. The results of the performed studies have shown that the hardness and strength values of the Al/HEA composites are increased as a function of the volume content of HEAs, while elongation values are dependent on the matrix and post-FSP heat treatment. In the study of Sekban et al. [2025], they investigated the effects of mechanical, tribological, and corrosion resistance of the Al7075/FeNiAlCuCr HEA composites fabricated using FSP. The FSP was done using a rotational speed of 1000 rpm and a traverse speed of 40 mm/mi. As can be seen in Fig. 4a, the hardness of the base sample (Al7075) increased by applying FSP and HEA addition. The application of FSP, due to the grain refinement, caused an increase in the hardness from 107 HBN to 182 HBN (72% improvement). Moreover, the presence of the 5 wt.% and 10 wt.% HEA also caused further increment of the hardness to 219 and 245 HBN, respectively. Similar observations were also found for the tensile strength and yield strength of samples by applying the FSP and HEA addition. In other words, the highest tensile strength of 252 MPa was achieved for the FSPed sample with 10 wt.% HEA. However, the elongation of samples decreased by applying FSP and HEA addition. As an interesting result, the FSPed samples had negative effects on the tribological performance of the Al7075 sample. In other words, the application of FSP increased the friction coefficient and wear rate values. However, the presence of HEA partially recovered the wear resistance of the samples. The worn surface of the samples indicated the occurrence of severe abrasive wear for the FSPed samples and moderate abrasive wear for the base samples and HEA-reinforced FSPed samples (Fig. 4b). The FSP worsened the wear resistance of samples due to the limited strain hardening, while the HEA addition provided hard and wear-resistant phases. In contrast to the wear resistance of samples, the FSP and HEA improved the corrosion resistance of the samples owing to the refined microstructure and passive layers comprising Cr and Ni (from HEA). In other words, the Cr content in the

HEA caused the formation of a stable Cr_2O_3 passive oxide later while the Ni content slowed the electrochemical reactions. All of this caused an 82% improvement in the corrosion resistance of FSPed samples with 10 wt.% HEA, compared to the base sample (Fig. 4c).

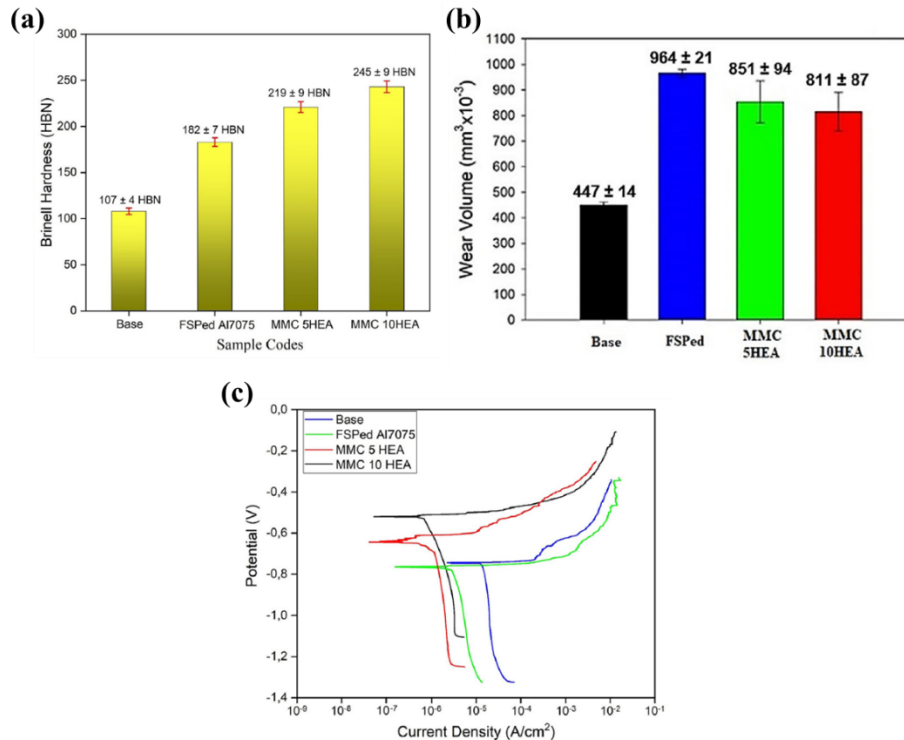


Fig. 4. Effects of the FSP and FeNiAlCuCr HEA volume fraction on the (a) hardness, (b) wear resistance, and (c) corrosion resistance of the Al7075, reproduced from [Sekban, 2025].

In another study, Li et al. [29] investigated the effects of different contents of the $\text{AlCoCrFeNi}_{2.1}$ HEA (5, 10, and 15 vol%) on the mechanical properties of the Al6061 matrix composites fabricated using FSP. The FSP was done using a rotational speed of 1200 rpm, a travel speed of 80 mm/min, and for 6 passes. Their results showed that the grain size of the FSPed samples decreased as a function of the volume contents of HEA (Fig. 5a to 5d). In other words, the grain sizes of 5.16, 4.80, and 3.63 μm were achieved for the 5, 10, and 15 vol.% reinforced samples, which were lower than that of the FSPed sample without HEA (8.12 μm). The hardness evaluation of the stir zone of samples indicated the increment of hardness value with the addition of higher contents of the HEA (Fig. 5e). The highest hardness value of 72 HV was achieved for the FSPed sample with 15 vol% HEA, which was about 28.6% higher than that of FSPed-Al6061 (56 HV). The tensile properties of FSPed samples showed that the lower contents of HEA, although they increased the strength values, decreased the elongation values. However, the addition of 15 vol% HEA increased strength with minor negative effects on the elongation (Fig. 5f).

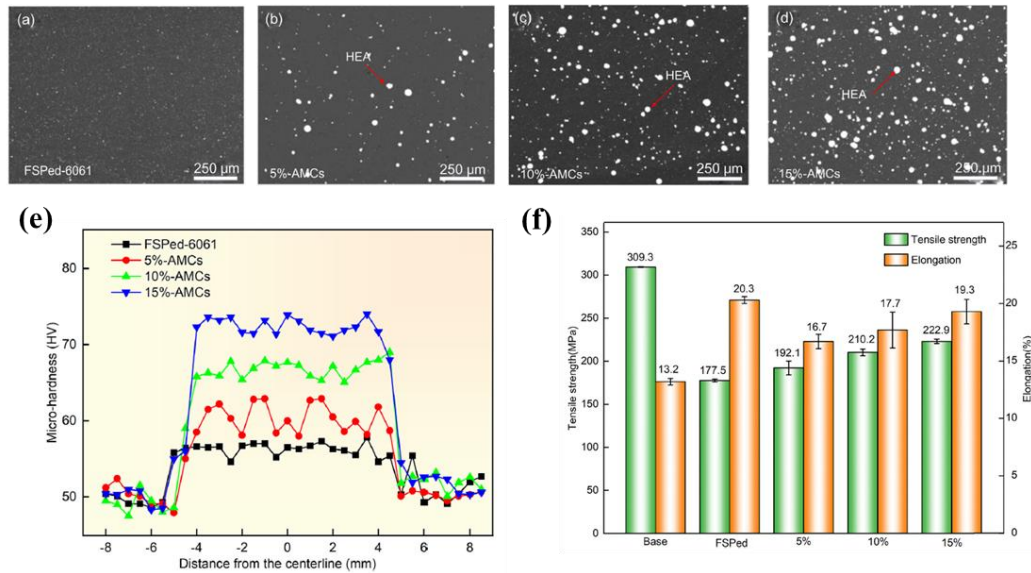


Fig. 5. Influence of AlCoCrFeNi_{2.1} HEA volume fraction on the microhardness and mechanical properties of the Al6061 matrix composites, (a-d) SEM images showing distribution of the AlCoCrFeNi_{2.1} HEA in samples with 0, 5, 10 and 15 vol.%, (e) microhardness variation across the processed zone, (f) tensile strength and elongation of the samples, reproduced from [Li, 2023].

3.1.2 Effects of FSP pass number

The number of FSP passes has a direct influence on the particle dispersion and distribution. Gao et al. [2020] investigated the effects of pass number on the tribological performance of the Al5083/FeCoNiCrAl composites fabricated by FSP. The FSP was performed at a rotational speed of 1200 rpm and a travel speed of 45 mm/min. Their results showed that by increasing the pass number, the dispersion of the HEA particles in the matrix improved. The microhardness of the samples increased as a function of pass number, where the highest hardness value of 158 HV was achieved for the 5-pass samples, which was about two times higher than that of the base metal (78 HV). The wear resistance of the samples improved significantly by increasing the FSP pass number. For example, the friction coefficient decreased from 0.58 in base metal to 0.42 for the 5-pass FSPed sample. The increment in pass number caused to the increased heat input, enhanced plastic flow, and eliminated tunnel effects.

In another study conducted by Ravi et al. [2025], the effects of pass number on the microstructure, mechanical and tribological properties of the Al5083/AlCoFeNiMn composites were investigated. In this work, the single pass (SFSP) and multi-pass (MFSP with 5 passes) were conducted with a constant rotational speed of 800 rpm and travel speed of 30 mm/min using an H13 tool. Their results showed that the increased pass number from 1 to 5 caused a reduction of grain size from 1.32 μm to 0.8 μm. Moreover, the hardness of the MFSP samples was 105 HV, which was about 36% higher than that of the SFSP sample (77HV). The UTS and elongation of the MFSP were much higher than those of the SFSP sample. In other words, the MFSP sample had a UTS value of 297 MPa and an elongation of 12%. The wear rate of both FSPed AMCs was much lower than that of FSPed Al5083, but the wear rate of the MFSP sample was slightly lower than that of the SFSP sample.

In a recent experimental study by Ra and Ga [2026], the effects of FSP pass number (1, 2, and 3) on the mechanical, tribological, and corrosion properties of the Al6061/10 vol% AlFeCrCuMnNi composites fabricated by FSP. The processing was done using a rotational speed of 1000 rpm and a travel speed of 30 mm/min using a square shoulder pin. The grain size of the samples decreased as a function of pass number; the grain sizes of 7.23, 4.65, and 2.43 μm were achieved for the FSPed samples with 1, 2, and 3 passes. Similarly, both strength and elongation improved significantly by increasing the pass number. In other words, the UTS of the base metal increased from 274.7 MPa to 332.9 MPa (21.1%) and elongation from 10.7% to 32.7% using 3-pass FSP. The tribological test results under different loads indicated that the 3-pass FSPed samples had the least wear rate and friction coefficient, owing to the

homogeneous distribution of the HEA and refined microstructure. The electrochemical test in 3.5 w% NaCl electrolyte showed that the corrosion current density decreased from $7.6 \times 10^{-3} \text{ A/cm}^2$ to $3.2 \times 10^{-3} \text{ A/cm}^2$ by increasing the pass number from 1 to 3.

3.1.3 Effects of tool rotational speed

The peak temperature and strain rate in the SZ are generally affected by rotational speed. Bai et al. [2026] investigated the effects of different rotational speeds of FSP on the mechanical properties of the Al-Cu-Mg/FeCoCrNiAl_{0.5}Ti_{0.5} composites. The FSP was conducted at different rotational speeds of 600, 800, 1000, 1200, and 1400 rpm with a constant travel speed of 80 mm/min. Their results showed that the grain size of the FSPed sample (2.11 μm) was much smaller than that of the unprocessed composite (UC, 16 μm). Evaluation of the mechanical properties of the samples showed that the optimal rotational speed was 1000 rpm, where the highest UTS (756 MPa), Yield strength (538 MPa), and elongation (12.1%) were obtained. Increasing the rotation speed up to 1000 rpm caused mechanical properties, but beyond that an adverse trend was observed. Applying low speeds of 600 and 800 rpm was not effective for heat input and caused limited material flow. On the other hand, the higher speeds of 1200 and 1400 rpm caused excessive heat input and thermal softening, as well as precipitation coarsening and grain growth.

3.1.4 Effects of tool pin geometry

Zhang et al. [2025] investigated the effects of Pin type on the mechanical and tribological performance of the Al5083/NbMoTaTiNi composites fabricated by FSP. The FSP was performed using a rotational speed of 1000 rpm and travel speed of 80 mm/min using a protruding cylindrical pin (PCP) Tool and a conventional cylindrical pin (CCP). Their results showed that the grain size of the samples fabricated by the PCP tool was 3.41 μm , which was lower than that of samples fabricated by the CCP tool (5.38 μm). As can be seen in Fig. 6a and 6b, dispersion of HEA particles was uniform in samples with PCP, while clustering was observed for the CCP tool. The worn surface of the samples with the PCP tool was much smoother than that of the CCP tool, and the width of the wear track was smaller. The results showed that the addition of HEA significantly improved the mechanical properties and wear resistance of the samples. However, the effectiveness of the HEA was dependent on the pin type. According to Fig. 6c, the hardness of 130 HV was achieved for the PCP, which was about 17 % higher than that of the CCP sample (111 HV). Based on Fig. 6d, the wear rate of samples with PCP was 0.36 mm^3/N , which was about 18 % lower than that of the CCP sample (0.44 mm^3/N). Similar results were also observed for the friction coefficient. The PCP tool, by enhancing material flow, better particle dispersion and distribution, higher peak temperature, and finer grain size, improved the mechanical and tribological properties of samples, compared to the CCP one.

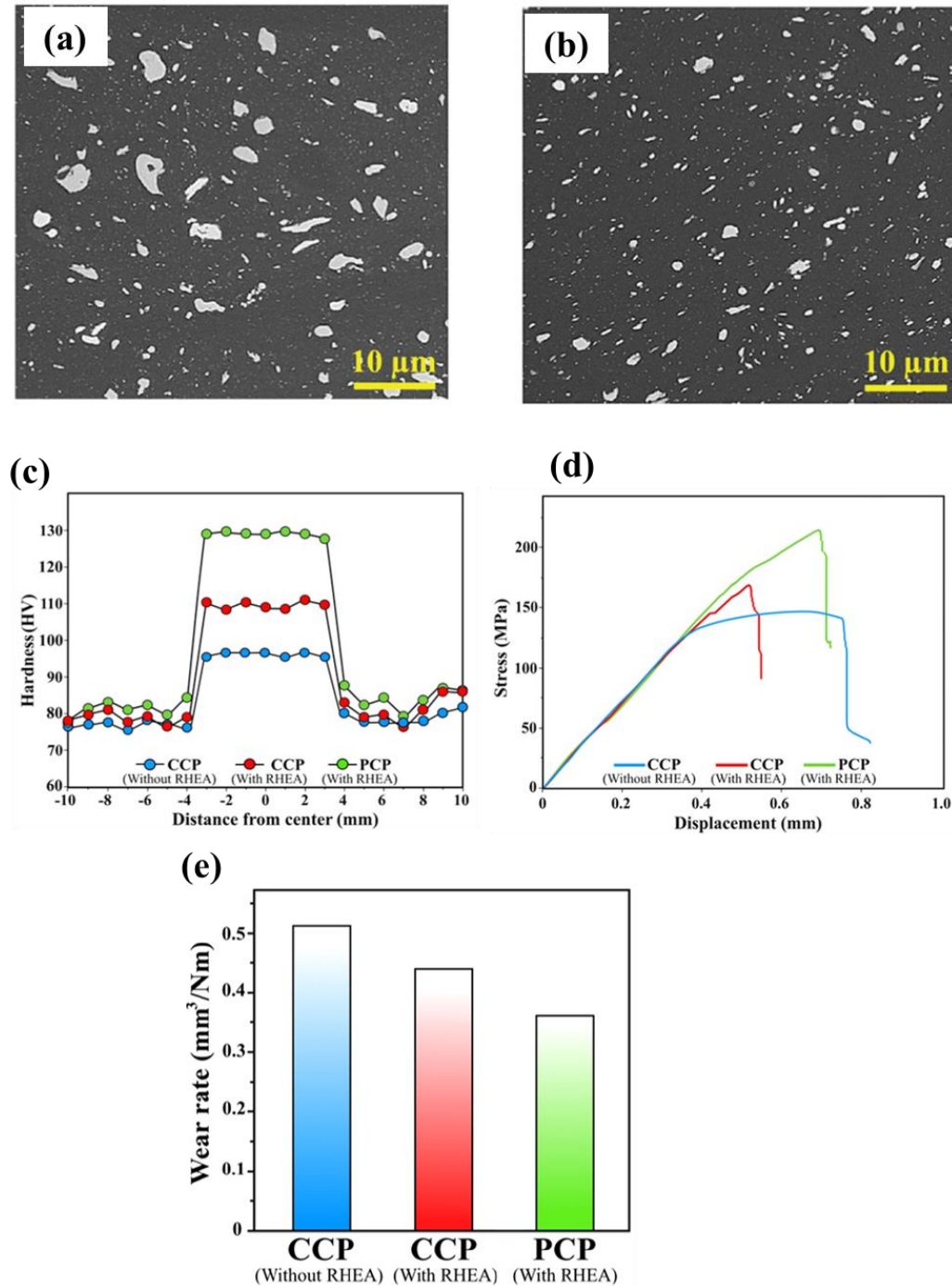


Fig. 6. Effects of tool pin geometry on the Al5083/NbMoTaTiNi composites fabricated by FSP, SEM micrographs showing HEA particle dispersion for (a) CCP and (b) PCP, (c) microhardness, (d) tensile stress strain and (e) wear rate of samples fabricated with two types of pin, reproduced from [Zhang, 2025].

3.1.5 Summary of reviewed studies

Table 1 provide a summary of the FSP parameters and resulting mechanical properties of the reviewed Al/HEA composites.

Table 1. Summary of reviewed studies in this study.

Composite	HEA content (vol%) / size (μm)	FSP parameters			Mechanical properties			Reference
		Rotational speed (rpm)	Travel speed (mm/min)	Pass number	Hardness	Ultimate tensile strength (MPa)	Elongation (%)	
Al5083/Al _{0.8} CoCrFeNi	3.8 vol% / 6.5 μm	800	50	4	125.7 HV	371.2	18.8	[26]
Al5083/AlCoCrFeNi	10 vol.% / 10.5 μm	1400	40	5	-	401	18.9	[27]
Al7075/FeNiAlCuCr	10 vol% / 11.8 μm	1000	40	-	245 HBN	252	-	[28]
Al6061/AlCoCrFeNi _{2.1}	15 vol.% / 20.1 μm	1200	80	6	72 HV	222.9	19.3	[29]
Al5083/FeCoNiCrAl	16 μm	1200	45	5	157 HV	-	-	[30]
Al5083/AlCoFeNiMn	-	800	30	5	105 HV	297	12	[31]
Al6061/AlFeCrCuMnNi	10 vol.%	1000	30	3	-	332.9	32.7	[32]
Al6061/AlFeCrCuMnNi	2 wt.% / 11.7%	1000	80	-	-	756	12.1	[33]
Al5083/NbMoTaTiNi	1-5 μm	1000	80	-	130 HV	221	71	[34]

4. Summary, and future perspectives

In this short review study, the recent studies on the development of aluminum alloy matrix composites reinforced with different types of high-entropy alloys (HEAs) fabricated with friction stir processing (FSP) were collected. In this work, the effects of the main variable on the mechanical, tribological, and corrosion resistance of these composites were discussed. The main findings of this study are as follows:

- 1- In the case of microstructural evaluation, the incorporation of HEA particles in the aluminum matrices using FSP caused considerable grain refinement in the stir zone. The enhanced continuous dynamic recrystallization (CDRX) and Zener pinning mechanisms are two main mechanisms for the grain refinement. The enhanced CDRX is caused by high-density dislocations generated from thermal mismatch between the HEA and aluminum matrix. In the Zener mechanism, the dispersion of the fine HEA particles at grain boundaries restricts grain growth.
- 2- The mechanical evaluation of the Al/HEA composites indicated an improvement in the hardness (up to 130%) and ultimate tensile strength (up to 32%) primarily through Hall-Petch and Orowan strengthening mechanisms. Some studies have also shown that the simultaneous increment of the strength and ductility by addition of HEAs, showing the achievable strength -ductility synergy by proper control of parameters.

- 3- In the case of tribological performance, the addition of HEAs through providing g hard and wear-resistant phases can decrease abrasive wear. In the case of corrosion resistance, the presence of Cr and Ni in HEAs facilitates the formation of a stable passive oxide layer (such as Cr_2O_3) on the surface of composites.
- 4- In the case of parameters affecting the properties, the higher HEA contents improve the hardness and strength values but may reduce the ductility. Increasing the pass number can improve particle dispersion and grain refinement, and 3-5 passes are generally optimal. Intermediate rotational speed is often optimal, where the low speeds cause insufficient material flow, while higher speeds produce thermal softening and precipitate coarsening.

For future work, the following topics are suggested:

- 1- FSP fabrication and characterization of AMCs reinforced with novel HEAs
- 2- FSP fabrication and characterization of AMCs reinforced with a hybrid of HEAs and common ceramic reinforcements

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