Fabrication of Metal Matrix Composites using the Submerged Friction Stir Processing Technique: A Recent Progress Review

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Received: 28 June 2024 | Revised: 18 July 2024 | Accepted: 20 July 2024

 DOI: https://doi.org/10.48084/etasr.8255

ABSTRACT

The design of structures and their components requires versatility due to the complexity of the loads that these structures and components are exposed to. Traditional materials generally do not have this feature of versatility and therefore, new materials are needed. Metal matrix composites are metallic materials that are promising to possess the versatility feature. However, the fabrication of these types of materials requires special attention. This paper reviews specifically the fabrication of metal matrix composites through the use of the friction stir processing technique coupled with water. The discussion deals with the fabrication of composites using single-pass and multipass submerged friction stir processing techniques. These fabrication methods still do not receive much attention even though they possess a significant microstructural influence.

Keywords-submerged friction stir processing; metal matrix composites; mechanical properties; microstructural analysis

I. INTRODUCTION

Metal matrix composites consist one of the most promising class of metals that can be employed to deal with dynamic loads due to their properties achieved by controlled microstructure [1]. These composites can be produced using various techniques, including solid-state, liquid-state, semi-solid-state, etc. Ball milling [2], high energy ball milling and molecular level mixing coupled with spark plasma sintering [3], short time intermittent ball milling [4], selective laser melting [5], are some of the techniques that have utilized to produce metal matrix composites. However, the solid-state technique is the main focus of this work because it presents fewer challenges than the other techniques and has the potential to receive full commercial implementation. The solid-state technique can be classified into various groups including powder metallurgy, foil diffusion bonding, and Friction Stir Processing (FSP). It should be noted that the mentioned classes, with the exception of FSP, involve elevated temperature. FSP operates at a temperature below the melting temperature of the material. FSP is a solid-state technique that was derived from the principle of Friction Stir Welding (FSW) [6, 7]. FSP has attracted the attention of researchers due to its versatility and its capability to modify the properties of a metal through microstructural modification [8-10]. FSP technique is often utilized to modify the microstructure through the reinforcement of foreign particles to a metal [11-13].

Authors in [7] reinforced tungsten carbide into AA5083 with the use of the FSP technique. Rotational speed of 1600 rpm, traverse speed of 60 mm/min, tilt angle of 2^o, and plunge force of 10 kN were the parameters used. These parameters were constantly utilized while the FSP passes were repeated four times per sample. The volume of the reinforcement increased from 0 to 11.6 vol%. The microstructural analysis showed good particle distribution with refined grains, and this was accredited to the repetition of FSP passes. Linear increase in microhardness and tensile strength with the increase in volume fraction of WC was observed. However, the increase in tensile strength was achieved at a cost of tensile elongation. Mono and hybrid composite layers were fabricated in [14] using a varying fraction of B_4C and TiB_2 on AA6063. The traverse speed and tilt angle were kept constant at 40 mm/min and 2^o while the rotational speed was kept constant at 1000 rpm for the first three passes and reduced to 710 rpm for the fourth pass. The increase in TiB_2 volume fraction showed a linear increase in microhardness with 100 vol% exhibiting highest microhardness and wear resistance. There many other works that have been reported in which FSP technique was employed to modify the microstructure of pure metal or composite material fabricated by other non-solid-state techniques [15-27]. The focus of this paper is to track the status of fabricating metal matrix composites using submerged FSP. This brief analysis will pave a way to understand the impact of the FSP medium towards various properties of the fabricated MMC. This review can be used to properly produce a metal matrix composite that can be suitable for a specific industrial engineering application.

II. GENERIC SETUP OF SUBMERGED FRICTION STIR PROCESSING

The schematic diagram of the Submerged FSP (SFSP) is shown in Figure 1. The setup consists of a tool with the pin, a tank filled with water, the plate (substrate) with enclosed reinforcement, and the backing plate (fixture) to hold the plate during processing. It should be noted that the reinforcement holes close before the water fills the tank through the inlet channel. The enclosing of the reinforcement holes is conducted through the pin-less tool (not shown in the Figure). The SFSP is conducted as follows: before inserting the rotating tool into the plate, cold water will be flown into the tank using the inlet channel and will be allowed to leave the tank using the outlet channel. The continuous flow of water is necessary so as to keep the temperature of water at room temperature. Once the continuous flow of water is achieved, the rotating tool will then be inserted into the plate for the commencement of the FSP [28-31].

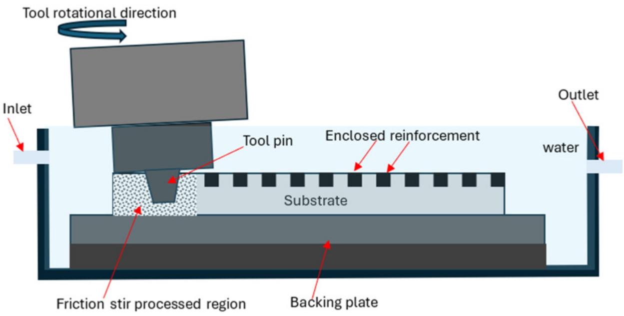

Fig. 1. Schematic diagram for SFSP.

III. FABRICATION OF METAL MATRIX COMPOSITES VIA SUBMERGED FRICTION STIR PROCESSING

A. Fabrication via Single-Pass SFSP

The enhancement of mechanical properties of various metals is an ongoing process and some of the techniques being used is reinforcing the substrate with reinforcement in different media. Authors in [31] fabricated metal matrix composites using Al-Mg as substrate and High Entropy Alloy (HEA) powder as reinforcement. The single-pass FSP technique was employed to produce the composite and the whole procedure was conducted underwater. The initial step towards the fabrication of the HEA/Al-Mg composite involved the inclusion of HEA powder in 4 mm deep drilled holes of 1.5 mm diameter which were 2 mm transversally spaced (Figure 2(a)). The holes with HEA powder were then enclosed with pinless FSP tool to avoid reinforcement from escaping during the underwater FSP. The enclosed surface was then immersed under water during the FSP procedure (Figure 2(b)). The processed surface was then analyzed using different techniques. The most appalling result was the formation of dual interface of FCC phase nanotwin structure which macroscopically resulted in the enhancement of the mechanical and tribological properties of the composite.

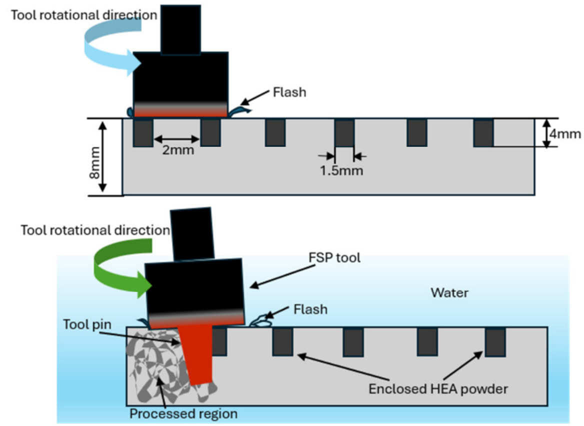

Fig. 2. (a) Schematic diagram for inclusion and enclosure of HEA powder into the substrate. (b) The performance of SFSP.

Authors in [32] used the SFSP technique to modify the AA5083 matrix through the incorporation of AlCoCrFeNi particles. The procedure used in reinforcing these particles to the aluminum matrix is similar to the one indicated in Figure 2. The microstructural analysis revealed the uniformity in the distribution of particles with refined grains which was attributed to the heat control that was facilitated by the water. The uniform distribution of particles and grain refinement contributed to the enhancement of mechanical and tribological properties. To demonstrate the impact of the fabricating environment towards the quality of the composite material, authors in [33] fabricated AA5083/Al_2O_3 nanocomposite using FSP that was submerged under water. The preparation procedure used is similar to the one shown in Figure 2. However, it is good to note that there were prior preparations that were performed before the fabrication procedure. These included the reduction of thickness from 10 mm to 8 mm prior to the introduction of nanoparticles. To effectively study the influence of fabrication media, the fabrication of nanocomposites was fabricated under normal room temperature and underwater. The microstructural analysis showed uniform distribution of particles for the samples that were fabricated using water as the cooling medium (submerged). Significant grain refinement was also observed from the samples fabricated underwater (reduced from 100 microns to 13.3 microns). The microhardness of the sample fabricated using submerged FSP was higher (129 HV) compared to the base metal (96 HV). The microhardness results were also found to be in agreement with the tensile strength results whereas the samples produced underwater possessed higher tensile properties. The mechanical performance of underwater fabricated nanocomposites was higher than the one of those that were fabricated under normal conditions (room temperature) and this is attributed to the faster cooling rate brought by water.

Authors in [34] fabricated metal matrix composites using AA5083 reinforced with titanium particles. The Ti/AA5083 composites were fabricated using submerged FSP technique and the procedure was similar to the one in Figure 2. For comparison purposes, the fabrication of Ti/AA5083 composites was conducted under normal conditions (air or room temperature). The increased cooling rate from the water resulted in a refined grained size and uniform distribution of titanium particles. The increased cooling rate inhibited the material flow thereby enforcing dynamic recrystallization hence the refined grains were observed in the samples that were produced underwater. The refined grains contributed to increased tensile property. However, it was also observed that the increase in Ultimate Tensile trength (UTS) resulted in a slight decrease in elongation. Authors in [35] fabricated hybrid metal matrix composites using magnesium plate and two different reinforcements (zirconium oxide and copper oxide). These hybrid composites were fabricated using different media, i.e. air (room temperature) and water. It was discovered that the samples produced using SFSP were dominated by refined grains and uniform distribution of reinforcement particles microstructurally which was attributed to the enhanced cooling rate due to the presence of water. The samples fabricated using SFSP had higher microhardness and exhibited better resistance to wear compared to those produced under room temperature. Also, higher UTS was recorded for samples produced using SFSP. The interesting phenomenon observed in tensile analysis is that the increase in UTS did not come at the expense of elongation like it was reported in the other studies. Authors in [36] conducted an analysis similar to the one in [35] with the difference that they used CeO_2 and ZrO_2 as reinforcements. The mechanical properties of the samples produced via SFSP were superior than those of the samples produced under room temperature.

The works reported in this section shows that the properties and the behavior of the fabricated composites can be influenced by the fabricating environment.

B. Fabrication via Multi-Pass SFSP

Fabrication of metal matrix composites via multipass SFSP has received attention due its microstructural impact. Generally, multipass FSP is performed through applying the FSP procedure on top of the previously performed FSP run. To distinctly indicate or show different runs, the different runs are concluded at different locations as shown in Figure 3.

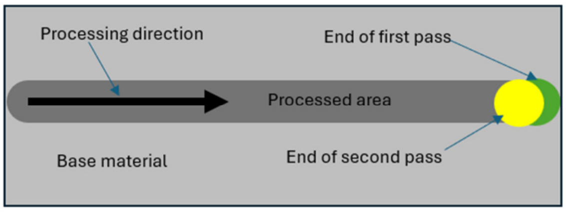

Fig. 3. Schematic diagram of multipass SFSP.

Authors in [37] used 3-pass SFSP to fabricate AA5053/Ti composites. The microstructural analysis showed very refined grains (1 microns) and the uniform distribution of titanium particles. There was no particle clustering and no intermetallic phases detected in X-Ray Diffraction (XRD) analysis. The absence of intermetallic phases was facilitated by the short thermal cycle that was facilitated by cold water. Moreover, Al-Ti-based intermetallic compounds generally form at temperatures above 600 ^oC [38-41]. However, the presence of water kept the maximum temperature below 460 ^oC, hence no intermetallic compounds were detected on the XRD results. The reduced grain size of the SFSP based composites showed improved tensile properties. The fractured surface of SFSP-produced composites exhibited finer dimples which exhibit the nucleation of crack propagation and thereby improve mechanical properties. Moreover, it was observed that there were no microstructural defects in the fabricated composites hence the improved mechanical properties. Authors in [42] utilized 2-pass SFSP to develop the AA2219/Y2O3 composite. The 2-pass SFSP was employed in such a way that the rotational direction of the first pass was in opposite direction with the second pass. This approach did not yield positive results given the fact that microstructural defects were observed. Clear particle clustering was also noticed, which was an indication of insufficient dispersion of the reinforcement particles. This non-uniform distribution of particles compromised the microhardness at the stir zone.

IV. FUTURE DIRECTION OF METAL MATRIX COMPOSITES PRODUCED VIA FRICTION STIR PROCESSING

Metal matrix composites are promising materials that can be used to solve weight related problems of various structures especially mobile structures. However, the fabrication of MMCs requires further understanding and analysis. It has become obvious that a careful consideration is needed when the fabrication parameters are chosen and also that the environmental conditions play a significant role regarding the resulting properties of the fabricated product. The reviewed literature reveals that the incorporation of cooling media during the fabrication of MMCs is very crucial since it accelerates the cooling rate which inhibits the grain growth and the formation of unwanted phases. The shortened thermal cycle also assists in limiting the material flow and thereby enhancing the grain refinement. However, it was observed that this area of research has not gained too much attention hence a limited literature was discussed in the present study.

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