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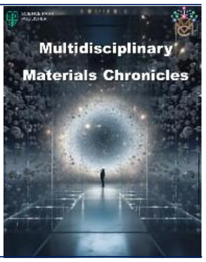

The Impact of Friction Stir Process on Mechanical Properties of AA6082 Enhanced by Titanium Aluminum Carbide Ti_3AlC_2

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Abstract

This study investigates the effects of Friction Stir Processing (FSP) on the mechanical properties and microstructural refinement of aluminum alloy AA6082 and its composite reinforced with Titanium Aluminum Carbide (Ti_3AlC_2). The primary aim was to determine the extent to which FSP can enhance the compression strength and modify the microstructure of the base AA6082 and the AA6082/Ti_3AlC_2 metal matrix composite. Through a series of FSP treatments, we observed a microstructural refinement of 26% in the composite material. Concurrently, the compression strength of the materials processed by FSP demonstrated a significant increase of 16.3%. These results suggest that FSP is an effective method for enhancing the mechanical properties of AA6082, with implications for the material's application in industries where the strength-to-weight ratio is critical. This paper provides a detailed analysis of the microstructural transformation mechanisms and the corresponding enhancement in mechanical properties, offering insights into the potential of FSP in developing high-performance metal matrix composites.

Keywords: Aluminum Metal Matrix Composite, Titanium Aluminum Carbide, Mechanical Properties, Microstructure Refinement, Compression Test

1. Introduction

Aluminum 6082 is a highly adaptable material employed across numerous sectors, including the defense industry. This material is crucial in creating superior alumina thin films that serve integral roles in electronic devices by providing insulation, protection, and acting as barriers [1]. Owing to its robustness and resistance to corrosion, aluminum 6082 is particularly suited for these uses, securing the reliability and efficiency of electronics in defense applications [2]. These materials offer notable enhancements in weight, strength, and rigidity, contributing to improved performance of military vehicles [3]. The integration of aluminum 6082 in such contexts is vital to elevate the reliability and functionality of defense electronics, where superior quality and durability are of the utmost importance.

Aluminum 6082, a versatile material, is widely used in various industries, including defense, due to its strength and corrosion resistance [4]. In the defense industry, producing high-quality alumina thin films is vital, which are essential for improving the dependability and performance of defense-related electronics. The forging performance of aluminum 6082 has been studied, revealing its potential as a replacement for forged steel parts in applications with shock and vibration loads [5]. The fatigue behavior of aluminum 6082 has also been investigated, with the alloy showing cyclic softening and crack initiation [6].

The demand for superior material characteristics has led to the increasing use of aluminum matrix composites in automotive and aerospace applications [7]. These composites, reinforced with nanoparticles like alumina and zirconia, exhibit enhanced tensile strength and hardness, making them ideal for applications requiring exceptional mechanical properties [8]. The use of SiC, Al_2O_3, and graphene as reinforcements in these composites has also been explored, with graphene showing potential for outperforming carbon nanotubes [9]. Various fabrication techniques, such as stir casting and friction stir processing, have been employed to produce these composites, with a focus on enhancing their mechanical properties [10].

Friction stir processing (FSP) is a solid-state technique that has revolutionized the fabrication of aluminum metal matrix composites (AMMCs), enhancing their properties and reducing defects [11]. FSP refines the microstructure and uniformly disperses reinforcing agents throughout the aluminum substrate, resulting in improved mechanical and wear properties [12]. The process is particularly effective in producing in-situ AMMCs, which are thermodynamically more stable and have finer reinforcements [13]. However, the distribution of reinforcement at the nanoscale and the role of single-pass processing in FSP composites require further investigation [14].

The friction stir process (FSP) and Friction Stir Welding (FSW) function on a similar principle, a rotating tool equipped with a shoulder and a pin is driven into the material, Once the pin is fully immersed and the shoulder makes contact with the material's surface, the tool proceeds to move in a specified direction [15].

The hardness of surface composites, particularly in FSP AA6063, is influenced by the refinement of the microstructure [16]. This is further enhanced by the incorporation of ceramic reinforcements, which contribute to the increased hardness [17].

The incorporation of Titanium Aluminum Carbide (Ti_3AlC_2) particles as a reinforcement material has been investigated due to its significant impact on enhancing both mechanical and tribological properties, this enhancement is attributed to the unique microstructural characteristics imparted by these reinforcements, which contribute to the overall strength and wear resistance of the composite material [18].

Therefore, the current work investigates the impact of the reinforcement particles of titanium aluminum carbide (Ti_3AlC_2) on the mechanical properties of the metal matrix composite fabricated by friction stir processing (FSP). The microstructure grain refinement and its influence on the mechanical properties of aluminum alloy AA6082 and such composite were evaluated using an optical microscope. The focus of this paper is on aluminum alloy AA6082, selected for its widespread use in diverse industrial sectors and its balanced properties. The alloy is favored in numerous applications because of its optimal mix of strength, malleability, and resistance to corrosion, positioning it as a prime subject for thorough investigation in our study.

2. Materials and Methods

For this paper, the selected reinforcement particle is the titanium aluminum carbide (Ti_3AlC_2), which has a density of 4.52 g/cm^3. These reinforcement materials were selected due to the relatively scarce research regarding their use as strengthening agents in aluminum alloy AA6082 when applied through the friction stir processing (FSP) technique.

The FSP setup is shown in Figure 1(a). The received aluminum alloy 6082, was sectioned into a plate measuring 150 mm by 150 mm by 10 mm as shown in Figure 1(b). The plate was perforated with holes, each hole being 3 mm in both diameter and depth. After filling the holes with Ti_3AlC_2 particles the friction stir processing was performed on the plates and the plates were cut into specimens of 6 mm by 8 mm.

The selected Ti_3AlC_2 reinforcement particles are in the range of 40 – 50 nanometers (nm). The purity of the particles is 99.5%. The percentage of the volume fraction of the particles is 20%.

The experimental evaluations conducted in this paper involved analyzing the microstructure using an optical microscope model UPT203i with polarized light capabilities and performing compression tests using XB-OTS-600 machine to compare the properties of the aluminum alloy AA6082 with those of the manufactured aluminum metal matrix composites (AMMCs) enhanced by Ti_3AlC_2 created through friction stir processing (FSP). These tests were designed to assess the differences in microstructural features and mechanical behavior between the untreated alloy and the composite material enhanced by FSP.

3. Results and Discussion

3.1. Optical microscopic observation

The addition of Ti_3AlC_2 to AA6082 aluminum alloy led to a significant 26% reduction in grain size, showcasing the effective manipulation of microstructural development to produce nanocomposites with smaller grain sizes. This is critical in microsystems technology, as smaller grains improve hardness, strength, and wear resistance while maintaining sufficient toughness and ductility [19]. Most existing research focuses on how process parameters like rotation and travel speeds, and types of reinforcement particles affect the properties of composites. However, studies on the impact of nanoparticle reinforcements on grain size through friction stir processing are limited.

Figure 1(c1) shows the microstructure of AA6082 as initially received, and processed into a rolled sheet which aligned and deformed the grains. The base metal had an average grain size of 58.75 ± 2 µm and an aspect ratio of 4.27. Friction stir processing (FSP) enhanced the quality of the processed zone (PZ), inducing complete recrystallization and forming equiaxed grains across the composites. Figure 1(c2) reveals that composites with Ti_3AlC_2 had a smaller average grain size of 76.25 ± 2 µm and an aspect ratio of 2.6, demonstrating the reinforcement's effectiveness in refining the grain structure.

The optical micrographs in Figure 1(c) illustrate the grain refinement in AA6082/Ti_3AlC_2 compared to unmodified AA6082. Using the Average Grain Intercept (AGI) method, it was found that the addition of Ti_3AlC_2 during casting refined the grain size by 26%. These finer grains are attributed to Ti_3AlC_2 particles acting as nucleation sites during solidification and obstructing grain growth during recrystallization, leading to a more uniform and compact grain structure. This refinement is crucial as it correlates with enhanced mechanical properties due to the fine-grained structure.

The mechanism behind the grain refinement observed in AA6082 when Ti_3AlC_2 is added involves the particles acting as physical barriers during the recrystallization process. The Ti_3AlC_2 particles disrupt the movement and growth of grain boundaries. By serving as nucleation sites, they facilitate the formation of new grains that are smaller and more uniform in size. This process is particularly effective in friction stir processing (FSP), where the intense localized heating and subsequent cooling create conditions ideal for these particles to exert their influence on the microstructure.

3.2. Compression Strength

A compression test was carried out as shown in Figure 2(a) on both the AA6082 specimen and the A6082 reinforced with Ti_3AlC_2 to evaluate and compare their compressive strengths. These tests are critical or understanding how the addition of Ti_3AlC_2 affects the mechanical properties of the aluminum alloy AA6082. Figure 2(b) in your referenced material likely illustrates the test specimens alongside the compression testing machine that was used for this experiment. The compressive strength for AA6082 and AA6082/Ti_3AlC_2 are 411MPa and 484.2MPa respectively as shown in Figure 2(b). By comparing the compression test results of the untreated AA6082 specimen with those of the AA6082 + Ti_3AlC_2 composite, researchers can quantify the effects of the reinforcement on the alloy's ability to withstand compressive stresses. An increase in compressive strength in the composite specimen would indicate that the FSP technique and the addition of Ti_3AlC_2 particles are effective in enhancing the material's mechanical properties.

The compression test showed that adding Ti_3AlC_2 improved the compression strength of AA6082 by 16.3%. The refined grain structure resulting from the intense plastic deformation and subsequent dynamic recrystallization typically increases mechanical properties, including compression strength. This is due in part to the Hall-Petch effect, where smaller grain sizes lead to increased hardness and strength [20]. This compression test provides insights into the potential of Ti_3AlC_2 to significantly enhance the compressive properties of aluminum alloys, which is crucial for applications where resistance to deformation under compression is critical, such as in automotive and aerospace components.

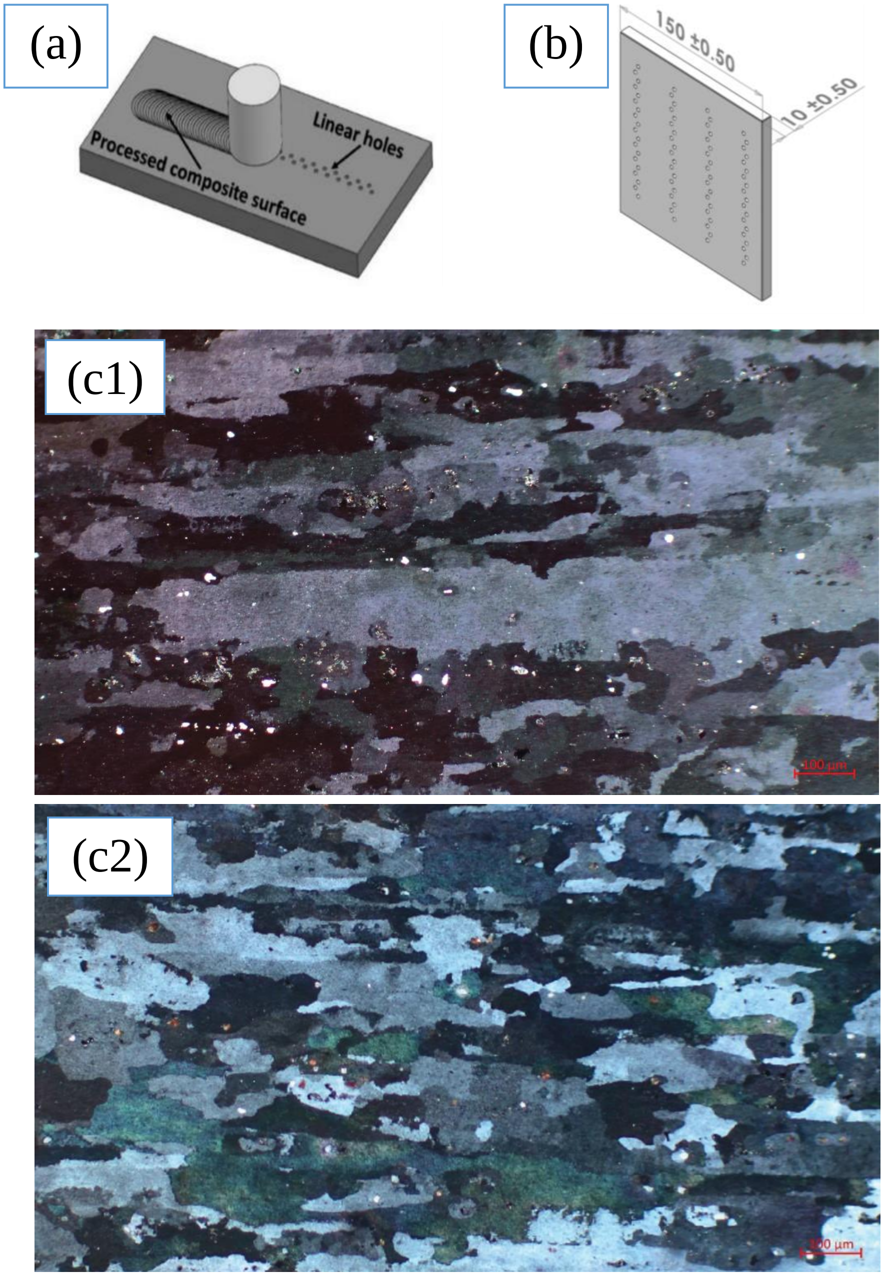

Figure 1. (a) Fabricating process of friction stir process [19], **(b)** Shows the plates used for the friction stir process (FSP), **(c)** Optical microstructure images of the original and FSP samples. (c1) AA6082 as received (c2) AA6082/Ti_3AlC_2.

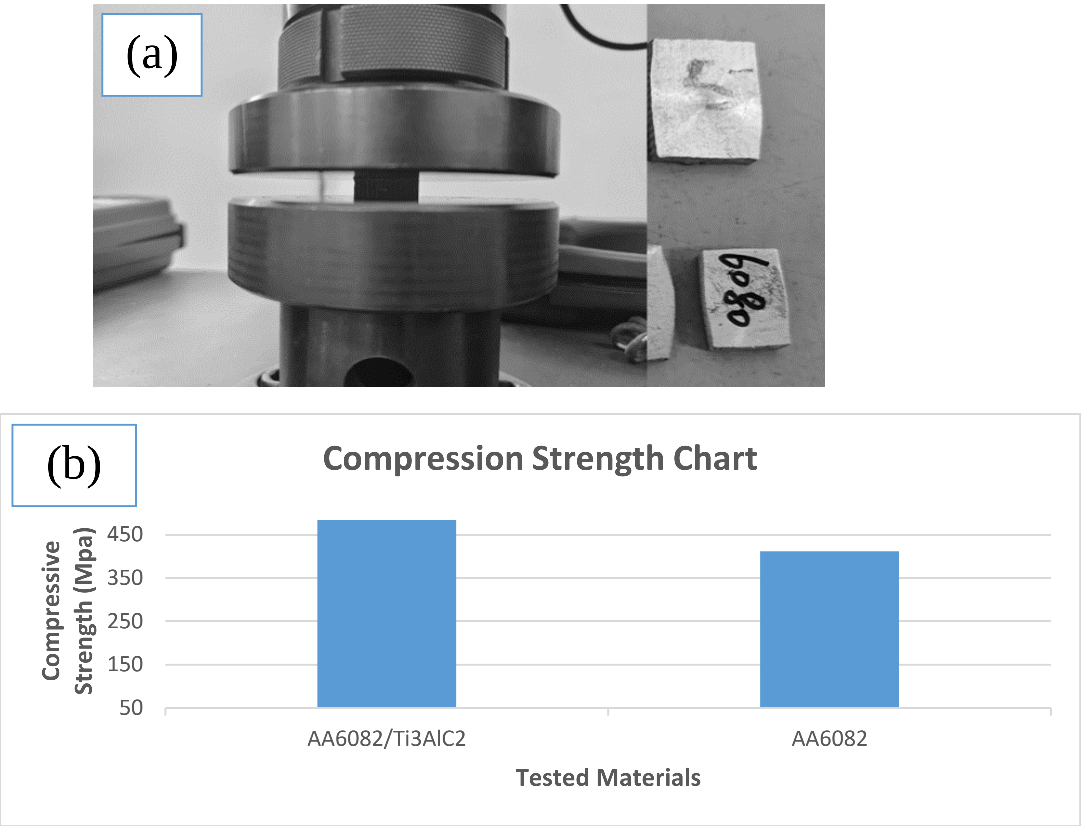

Figure 2. (a) Shows the compressive strength graph of the as-received metal and the metal matrix composite, (b) Shows the compression machine.

4. Conclusion

In the current investigation, AA6082 is reinforced with Ti_3AlC_2 nanoparticles using friction stir processing; the following conclusion is driven:

- The FSP and Ti_3AlC_2 nanoparticles significantly affect the refinement of the microstructure grain size; thus, the refining grains reach 26% less than the as-received alloy. As the grain size decreases, the number of grain boundaries within a given area of the material increases. The presence of grain boundaries hinders the motion of dislocations. Increased barriers impede the movement of dislocations, resulting in greater difficulty for the material to undergo deformation. This results in a more robust material with increased yield strength and tensile strength.
- The ceramic particles Ti_3AlC_2 in the MMC act as hard, dispersed inclusions within the softer metal matrix AA6082. These particles experience minimal deformation under compression and impede the movement of dislocations in the metal matrix. This makes it more difficult for the entire composite material to deform, resulting in a higher compression strength compared to the unreinforced aluminum alloy AA6082.

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