CORPUS PUBLISHERS

Journal of Mineral and Material Science (JMMS)

ISSN: 2833-3616

Volume 5 Issue 1, 2024

Article Information

Received date : March 19, 2024

Published date: March 28, 2024

***Corresponding author**

Essam B Moustafa, Mechanical Engineering Departments, Faculty of Engineering, King Abdulaziz University, Jeddah 21589, Saudi Arabia

DOI: 10.54026/JMMS/1081

Key Words

FSP; Mechanical Properties; Microhardness; Tantalum Carbide (TaC); Chromium Carbide (CrC); Niobium Carbide (NbC)

Research Article

Friction Stir Processing of AA6061 Aluminum Alloy Reinforced with Ceramic Particles for Enhanced Mechanical Properties

Faisal Alajlani, Ammar Maliabari and Essam B Moustafa*

Mechanical Engineering Departments, Faculty of Engineering, King Abdulaziz University, Jeddah 21589, Saudi Arabia

Abstract

This study investigates the effect of incorporating ceramic particles, specifically Chromium Carbide (CrC), Tantalum Carbide (TaC), and Niobium Carbide (NbC), on the mechanical properties of AA6061 aluminum alloy. The investigation uses the Friction Stir Processing (FSP) fabrication technique. The results indicate substantial enhancements in mechanical properties compared to the material without reinforcement. Reinforced composites display elevated longitudinal and shear velocities, which signifies enhanced rigidity and ability to withstand deformation when subjected to different force directions. Using CrC and TaC reinforcements in the AA6061/CrC+TaC composite led to the maximum velocities for both wave types, indicating a notably rigid composite material. Introducing ceramic particles to AA6061 significantly augments Young's and shear modulus, indicating improved strength and stiffness. AA6061/CrC+TaC showed the most notable enhancement of all the reinforcements, underscoring the potential of using combined reinforcements. Incorporating ceramic particles into AA6061 greatly enhances its microhardness and Vickers hardness. The addition of Tantalum Carbide (TaC) as a reinforcement resulted in the most significant enhancement, indicating a robust interaction with the matrix. Notably, composites with a combination of reinforcements (CrC+TaC and CrC+NbC) displayed even greater hardness, possibly due to synergistic effects.

Introduction

In recent years, the new composite metal matrices have become significantly important in emerging technologies because of their improved performance in handling various loads and environmental effects. The unwavering quest for lightweight and high-strength materials fuels ongoing innovation in several engineering disciplines, especially in challenging sectors such as aerospace and automotive [1-4]. Aluminum alloys, particularly AA6061, are notable among possible alternatives because to their exceptional combination of low density, high strength, and formability [5,6]. Nevertheless, their intrinsic limitations, such as limited resistance to wear and mechanical characteristics, limit their application in situations involving high wear and load-bearing levels [7,8]. To address these restrictions, adding ceramic reinforcements has emerged as a revolutionary approach [9-11]. Ceramic particles provide a synergistic method for improving the tribological and mechanical properties of AA6061 due to its excellent hardness, high melting temperatures, and improved wear resistance [12]. Tungsten Carbide (WC), Tantalum Carbide (TaC), Niobium Carbide (NbC), Vanadium (VC), Silicon Carbide (SiC), Aluminum Oxide (Al_2O_3), Boron Carbide (B_4C), Titanium Carbide (TiC), and Zirconium Carbide (ZrC) are notable options due to their strong compatibility with AA6061 [13-23]. These particles are used in metal matrices as either mono-composite or hybrid-composite materials. Studies have shown that incorporating Hexagonal Boron Nitride (HBN) nanoparticles into aluminum alloys enhances their mechanical characteristics, lubrication behavior, and wear resistance [24-26]. Friction Stir Processing (FSP) offers a distinctive and effective method for integrating ceramic reinforcements into AA6061 [27]. Frictional heat produced during Friction Stir Processing (FSP) causes the matrix material to become softer, facilitating the thorough mixing and scattering of ceramic particles, thereby maximizing their combined impact [28].

Consequently, including ceramic reinforcements enhances the mechanical characteristics of the AA6061 matrix, resulting in increased tensile strength, hardness, and fatigue resistance [29]. Friction Stir Processing (FSP) causes the microstructure of the aluminum matrix to become more refined, resulting in smaller grain sizes. This refinement of the microstructure leads to improved mechanical characteristics of the material. Nevertheless, this strategy prioritizes one aspect while disregarding the enhancement of other attributes. The key development is a hybrid Chrome Carbide (CrC) reinforced with tantalum and niobium carbides. TaC has excellent hardness and wear resistance, NbC has high-temperature strength and oxidation resistance, and CrC is a strong matrix material. FSP's low processing temperature and effective particle dispersion increase the composite's microstructure and interfacial bonding, resulting in excellent performance.

Materials and Setup

AA6061 aluminum alloy sheets were the basic matrix. AA6061 was the matrix, and CrC, TaC, and NbC were the reinforcements for the basis mono-composites. CrC is the fundamental reinforcement in the hybrid method, deliberately mixed with TaC or NbC at 50% volume fractions. According to manufacturers' suppliers, the typical particle size of CrC, NbC, and TaC is 1.4 to 2.6 μm. The FSP approach incorporated hybrid reinforcement particles into the aluminum matrix. Figure 1 depicts the experimental techniques prior to FSP. The triangular pin is utilized to machine the liner hole patterns on the AA6061 aluminum sheet. Ensuring consistency was achieved by blending the mono and hybrid reinforcement particles before inserting them into the pre-milled holes. It guaranteed consistent allocation and enhanced reinforcement. Figure 2 depicts using an automatic milling machine for fine parameter control in FSP. The specifications include a tool rotation speed of 1120 rpm, a 60 mm/minute movement speed, and a tilt angle 3°.

How to cite this article: VAlajlani F, Maliabari A and Moustafa EB* (2024) Friction Stir Processing of AA6061 Aluminum Alloy Reinforced with Ceramic Particles for Enhanced Mechanical Properties. J Miner Sci Materials 5: 1081

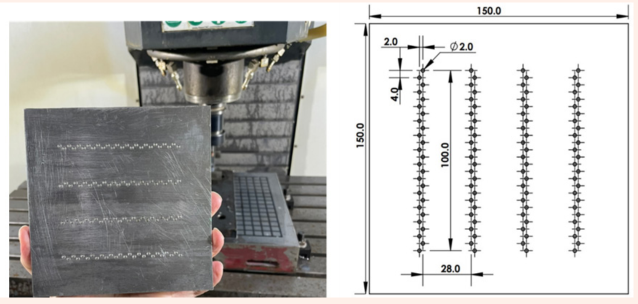

Figure 1: AA6061 sheet preparation and hole creation.

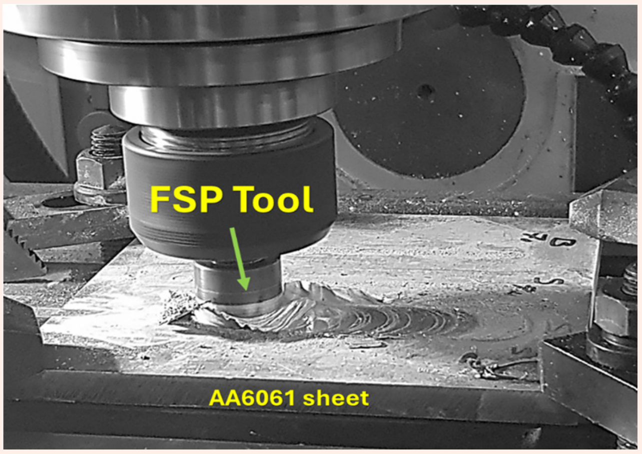

Figure 2: Friction stir processing setup.

Results and Discussion

Microstructure observation

Most metal matrix composites refine their grain by reducing the average grain size of the matrix metal after solidification using FSP [30,31]. In this study, metal matrix nanocomposites based on transition metal carbides were investigated. Transition metal carbides refine the microstructure. Transition metal carbides reduced the grain size by more than 50% compared to the matrix without reinforcement. This indicates that controlling the microstructure leads to nanocomposite materials with tiny grains. In microsystems technology, grain size influences mechanical and physical properties. Finer grains improve toughness, ductility, wear resistance, and hardness. Nanocomposite research is looking for tiny grains. It compares the matrix with dispersed sub-particles to determine how these materials can create new properties. The study investigates how transition metal carbides influence grain size and fineness. Microstructural and grain size-related effects can be examined. The grain size data are compared and analyzed to find the best nanocomposite carbides. This enables material improvements. Figure 3 shows the microstructure of rolled AA6061 and composite material under an optical microscope. The images of the composite material are located in the center of the machining zone. Rolling the base material produced distorted grains aligned with the rolling direction. The base metal AA6061 has a height-to-thickness ratio 2.8 with an average grain size of 167.4 ± 8.5 µ. The agitated area was greatly increased by friction stir machining. Complete recrystallization was achieved using the PZ turning tool and the heat of the base metal. All composite materials have equiaxed grains. Uniform finishing methods should be used for similar base materials and situations. Many reinforcements affect the finishing of composites. During recrystallization, FSP reinforcements inhibit grain formation. Reinforcement limited composites. Simply reinforced composites had an average grain size of 14.7 ± 3.8 µm for AA6061/CrC, 13.84 ± 3.4 for NbC and 12.45 ± 1.6 for the hybrid composites AA6061/CrC+TaC and AA6061/CrC+NbC have tiny grain sizes (11.6 ± 0.7 µm and 12.3 ± 0.2 µm) due to the semi-solid thermomechanical deformation of the FSP.

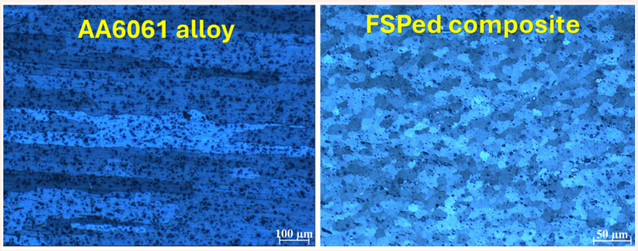

Figure 3: Optical microstructure images of the base alloy and friction stir processed samples.

Ultrasound analysis

Longitudinal velocity: Longitudinal velocity refers to the speed at which sound waves travel through the material in a parallel direction to the application of force. Increase in velocity with ceramic reinforcement: All the AMC composites (AA6061/Cr+TaC) have a higher longitudinal velocity than the unreinforced aluminum alloy (AA6061). This indicates that sound waves travel faster through the composite materials. Among the AMCs with single ceramic reinforcements (CrC, TaC, NbC), AA6061/TaC shows the highest longitudinal velocity (6274.28 m/s). This suggests that the presence of Tantalum Carbide (TaC) particles stiffens the material matrix more compared to Chromium Carbide (CrC) and Niobium Carbide (NbC). Hybrid ceramic reinforcement: Combining two ceramic reinforcements (CrC+TaC and CrC+NbC) resulted in even higher longitudinal velocities than single reinforcements, as shown in Figure 4. AA6061/CrC+TaC has the highest overall velocity (6485.28 m/s), indicating a stiffer material matrix due to the combined effect of chromium carbide and tantalum carbide reinforcements. The data suggest that the presence of ceramic reinforcements (CrC, TaC, NbC) increases the stiffness of the aluminum matrix, leading to higher longitudinal velocity of ultrasound waves. Furthermore, a combination of certain reinforcements (like CrC+TaC) can provide an even stiffer composite material.

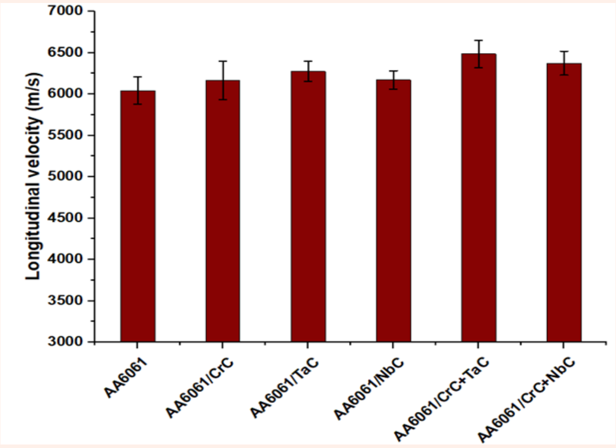

Figure 4: Longitudinal velocity of ultrasound in different aluminum matrix composites (AMCs).

Shear velocity: Shear velocity refers to the speed at which sound waves travel through the material in a direction perpendicular to the applied force. AA6061/CrC+TaC (3193.32 m/s) has the highest shear velocity among all the samples. This indicates that sound waves travel fastest through this composite material when applying a shearing force. All AMC composites (AA6061/X) exhibit higher shear velocity than the unreinforced aluminum alloy (AA6061-3039.88 m/s). This signifies that ceramic reinforcements strengthen the material against shear forces. While all reinforced composites show higher velocity than the unreinforced material, the effect of reinforcement type is evident. Among samples with single reinforcements (CrC, TaC, NbC), AA6061/TaC (3108.2 m/s) has the greatest shear velocity, as shown in Figure 5. This suggests that TaC particles enhance the material's resistance to shear deformation compared to CrC and NbC. Interestingly, both dual-reinforced

Citation: VAlajlani F, Maliabari A and Moustafa EB* (2024) Friction Stir Processing of AA6061 Aluminum Alloy Reinforced with Ceramic Particles for Enhanced Mechanical Properties. J Miner Sci Materials 5: 1081

composites (CrC+TaC and CrC+NbC) have even higher shear velocities than single reinforcements. This indicates a synergistic effect from the combined presence of two ceramic reinforcements. Ce'amic reinforcements (CrC, TaC, NbC) improve the shear strength of the aluminum matrix, leading to higher shear velocity of ultrasound waves. Moreover, combining certain reinforcements (like CrC+TaC) can further improve the material's resistance to shear forces.

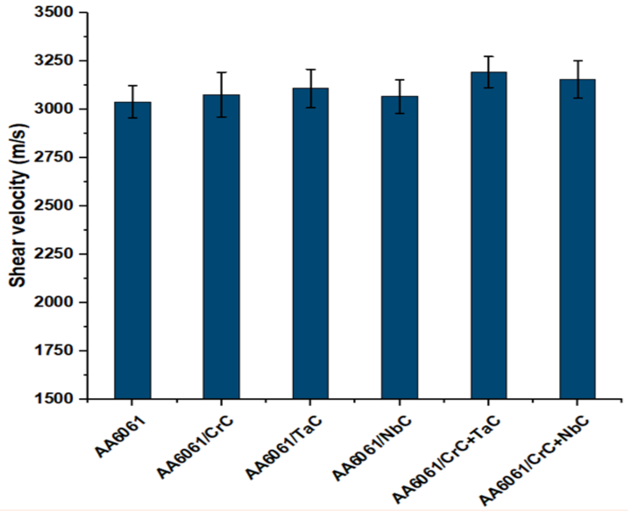

Figure 5: Shear velocity of ultrasound in different aluminum matrix composites (AMCs).

Mechanical properties

Longitudinal and shear velocities obtained from ultrasound tests can be used to estimate certain mechanical properties of a material, but it's not a direct one-to-one conversion. The key connection lies in the relationship between the velocities and the material's elastic moduli. Elastic moduli, like Young's modulus (stiffness) and shear modulus (resistance to shearing), govern how a material deforms under stress. The velocities of sound waves (longitudinal and shear) are related to the material's density (ρ) and the relevant elastic modulus (E or G) through a specific equation. This equation can be rearranged to solve for the elastic modulus based on the measured velocity (v) and density.

$$\lambda = \rho\left(V_L^2 - 2V_S^2\right) \quad (1)$$

$$\mu = \rho V_S^2 \quad (2)$$

The metal matrix composite specimens were analyzed to determine their longitudinal modulus, Young's modulus, shear modulus, bulk modulus, and Poisson's ratio. These properties, denoted as L, E, B, G, and v respectively, were calculated using the appropriate formula [32,33]:

$$L = \lambda + 2\mu \quad (3)$$

$$G = \mu \quad (4)$$

$$E = \mu\frac{3\lambda + 2\mu}{\lambda + \mu} \quad (5)$$

$$B = \lambda + \frac{2}{3}\mu \quad (6)$$

$$\upsilon = \frac{\lambda}{2(\lambda + \mu)} \quad (7)$$

The Young's modulus of all the reinforced composites, consisting of AA6061 with ceramic particles, is higher than that of the unreinforced AA6061. This suggests that including ceramic particles enhances the strength and rigidity of the material. AA6061/CrC+TaC, a composite material reinforced using a combination of chromium carbide and tantalum carbide, exhibits the highest Young's modulus (91.085 GPa) among all reinforced composites. This results in a significant increase in stiffness (34.7%) compared to the unreinforced material. The difference in stiffness between AA6061/CrC (78.44 GPa) and AA6061/NbC (78.54 GPa) is minimal, with the addition of Niobium carbide resulting in a slightly larger rise in stiffness as shown in Figure 6. Based on the data, it can be concluded that adding ceramic particles such as chromium carbide, tantalum carbide, or their mixtures to AA6061 can greatly enhance the material's stiffness. The selection of a particular reinforcing particle can significantly impact the extent of improvement.

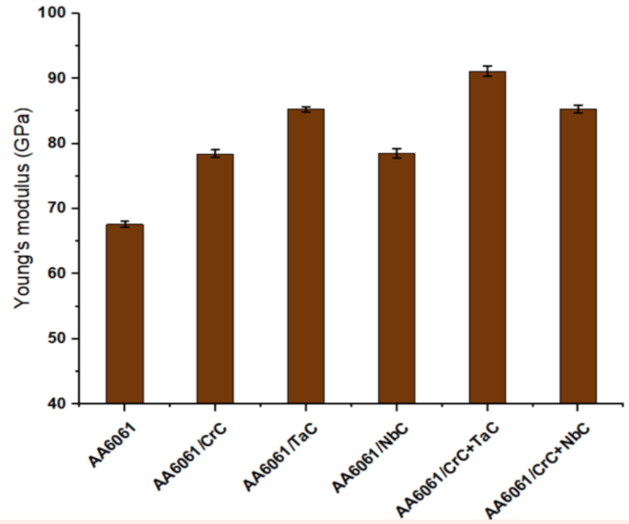

Figure 6: Effect of reinforcement on the Young's Modulus in different aluminum matrix composites (AMCs).

The longitudinal modulus quantifies the stiffness of various composite metal matrix materials in a direction parallel to their long axis. The longitudinal modulus of all reinforced composites (AA6061 with ceramic particles) is greater than that of the unreinforced AA6061, as shown in Figure 7. This demonstrates that including ceramic particles enhances the strength and rigidity of the material in the longitudinal direction. AA6061/CrC+TaC, a composite material reinforced with a combination of chromium carbide and tantalum carbide, exhibits the greatest longitudinal modulus among all reinforced composites, measuring at 140.18 GPa. This represents a significant gain in stiffness, with a 39.67% increase compared to the unreinforced material. Adding ceramic particles leads to an upward trend in the longitudinal modulus. Chromium Carbide (CrC) and Tantalum Carbide (TaC) provide substantial enhancements, with chromium carbide offering a 17.64% improvement and tantalum carbide offering a 29.47% improvement. Incorporating these particles (CrC+TaC and CrC+NbC) results in even greater enhancements (39.67% and 29.57%, respectively). In summary, the evidence validates that adding ceramic particles such as chromium carbide, tantalum carbide, or their mixtures effectively enhances the longitudinal stiffness of AA6061. The results also indicate that combining these ceramic particles can further enhance stiffness.

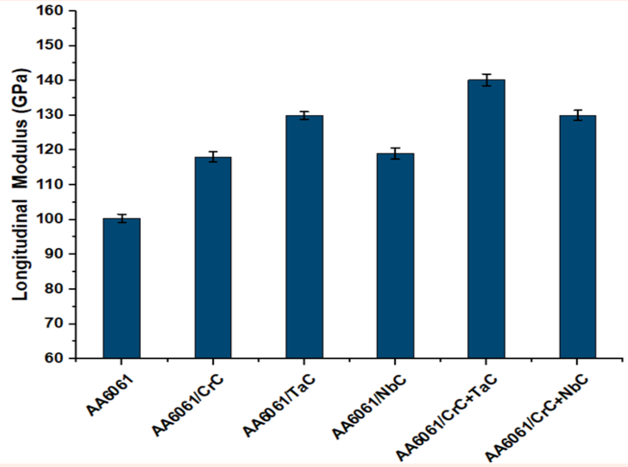

Figure 7: Effect of reinforcement on the Longitudinal Modulus in different aluminum matrix composites (AMCs).

Shear modulus is a measure of a material's rigidity under shearing forces, which tends to cause layers of the material to slide relative to each other. Higher values indicate a material that resists deformation more under shearing forces. All the reinforced composites except AA6061/NbC have a higher shear modulus than the unreinforced AA6061. Adding most ceramic particles strengthens the material against these shearing forces, as shown in Figure 8. AA6061/CrC+TaC (combination of chromium carbide and tantalum carbide) has the highest shear modulus (33.99 GPa), showing the most significant improvement (34.1%) in shear resistance compared to the unreinforced material. AA6061/NbC shows a slight increase (15.7%) in shear modulus compared to unreinforced AA6061. There is a trend of improvement in shear modulus with the addition of most ceramic particles, particularly chromium carbide and tantalum carbide (individually or combined). Possible reasons for the lower improvement in AA6061/include: The distribution of the niobium carbide particles within the composite might not be optimal for strengthening against shearing forces. The interfacial bonding between the niobium carbide particles and the aluminum matrix might be weaker than other reinforcements. The specific properties of niobium carbide particles might be less effective in improving shear resistance in this composite.

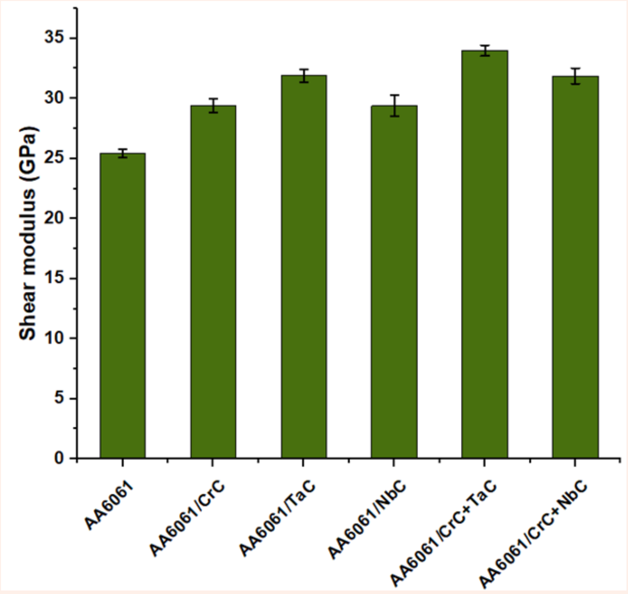

Figure 8: Effect of reinforcement on the Shear Modulus in different aluminum matrix composites (AMCs).

Microhardness behavior

The microhardness of all composites reinforced with ceramic particles (Chromium Carbide (CrC), Tantalum Carbide (TaC), and Niobium Carbide (NbC)) significantly surpasses that of the unreinforced AA6061 baseline. This enhancement can be attributed to the presence of the ceramic particles. These particles act as crystallographic obstacles within the metal matrix, hindering the movement of dislocations – microscopic defects that allow plastic deformation to occur. Consequently, the material exhibits a greater resistance to localized plastic deformation, translating to increased hardness. Among the reinforcements employed, Tantalum Carbide (TaC) demonstrates the most exceptional improvement in both microhardness and Vickers hardness. This suggests a particularly strong interaction between TaC particles and the AA6061 matrix, leading to a more effective restriction of dislocation movement. Composites containing a combination of ceramic particles (AA6061/CrC+TaC and AA6061/CrC+NbC) exhibit even higher microhardness compared to those with single reinforcements. This phenomenon might be due to synergistic effects between ceramic particles and their interaction with the matrix. These combined effects could lead to a more efficient restriction of dislocation motion and a further enhancement of hardness.

Additionally, reinforcements can improve the distribution of applied stresses throughout the composite, minimizing stress concentrations and preventing localized deformation, thus contributing to overall hardness. Hybrid reinforcements offer additional benefits, including the following: Possibly due to the synergistic effects of the reinforcements and their interaction with the matrix, the AA6061/CrC+TaC composite demonstrates the highest microhardness compared to other composites. Their role is to obstruct the movement of dislocations, which ultimately increases the resistance to plastic deformation they provide. All the reinforced composites have a higher Vickers hardness than the unreinforced AA6061, as shown in Figure 9. This confirms that adding ceramic particles significantly improves the material's indentation and plastic deformation resistance. AA6061/TaC (tantalum carbide reinforcement) has the highest Vickers hardness (114.4 HV), showing the most significant improvement (38.2%) in hardness compared to the unreinforced material. There is a clear trend of increasing hardness with adding ceramic particles. Individual reinforcements like Chromium Carbide (CrC) and Niobium Carbide (NbC) offer substantial improvement (14.5% and 26.2%, respectively). Combining these particles (CrC+TaC and CrC+NbC) leads to even greater improvements in hardness (56.3% and 43.5%, respectively).

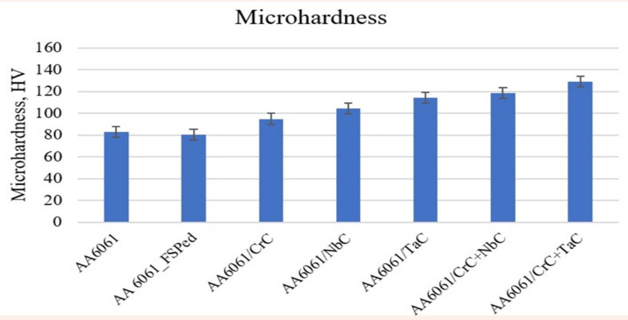

Figure 9: Effect of reinforcement on microhardness.

Conclusion

This research highlights the effectiveness of ceramic particle reinforcement, particularly combinations like CrC+TaC, in significantly improving the stiffness of AA6061. The effectiveness of transition metal carbide reinforcements in refining the grain size of AA6061 nanocomposites produced via FSP. The findings offer valuable insights for developing novel materials with enhanced mechanical properties through optimized grain size control. Reinforcing AA6061 with ceramic particles, particularly CrC, TaC, or their combination (CrC+TaC), significantly enhances resistance to shearing forces. However, the choice of reinforcing particle can influence the degree of improvement, as observed with NbC. The combination of ceramic particles shows even higher microhardness than those with single reinforcements. This phenomenon suggests potential synergistic effects between the different particles and their interaction with the matrix, leading to a more efficient restriction of dislocation motion and further hardness enhancement.

References

1. Raja R, Shanmugam R, Jannet S, Kumar GBV, Venkateshwaran N, et al. (2023) Development of Al-Mg_2Si alloy hybrid surface composites by friction stir processing: Mechanical, wear, and microstructure evaluation. Materials 16(11): 4131.
2. Peter PI, Oki M, Adekunle AA (2020) A review of ceramic/bio-based hybrid reinforced aluminium matrix composites. Cogent Engineering 7(1): 1727167.
3. Alazwari MA, Moustafa EB, Khoshaim AB, Taha MA (2023) Mechanical and wear evolution of in situ synthesized Ti–Cu alloy matrix hybrid composite reinforced by low-cost activated carbon and silica fume waste ceramic for industrial applications. Journal of Materials Research and Technology 22: 2284-2296.
4. Kareem A, Qudeiri JA, Abdudeen A, Ahammed T, Ziout A (2021) A review on AA 6061 metal matrix composites produced by stir casting. Materials 14(1): 175.
5. Sufiiarov V, Borisov A, Popovich A, Erutin D (2023) Effect of TiC particle size on processing, microstructure and mechanical properties of an inconel 718/TiC composite material made by binder jetting additive manufacturing. Metals 13(7): 1271.
6. Zainelabdeen IH, Al-Badour FA, Adesina AY, Suleiman R, Ghaith FA (2023) Friction stir surface processing of 6061 aluminum alloy for superior corrosion resistance and enhanced microhardness. International Journal of Lightweight Materials and Manufacture 6(1): 129-139.

7. Barati M, Abbasi M, Abedini M (2019) The effects of friction stir processing and friction stir vibration processing on mechanical, wear and corrosion characteristics of Al6061/SiO_2 surface composite. Journal of Manufacturing Processes 45: 491-497.
8. Tabandeh-Khorshid M, Ajay K, Omrani E, Kim C, Rohatgi P (2020) Synthesis, characterization, and properties of graphene reinforced metal-matrix nanocomposites. Composites Part B: Engineering 183: 107664.
9. Chandradass J, Thirugnanasambandham T, Jawahar P, Kannan TTM (2021) Effect of silicon carbide and silicon carbide/alumina reinforced aluminum alloy (AA6061) metal matrix composite. Materials Today: Proceedings 45(7): 7147-7150.
10. Abushanab WS, Moustafa EB, Melaibari AA, Kotov AD, Mosleh AO (2021) A novel comparative study based on the economic feasibility of the ceramic nanoparticles role's in improving the properties of the AA5250 nanocomposites. Coatings 11(8): 977.
11. Moustafa EB, Alazwari MA, Abushanab WS, Ghandourah EI, Mosleh AO, et al. (2022) Influence of friction stir process on the physical, microstructural, corrosive, and electrical properties of an Al–Mg alloy modified with Ti–B Additives. Materials 15(3): 835.
12. Çinici H, Karakoç H, Şahin Ö, Ovalı İ (2023) Investigation of microstructure, mechanical, and tribological properties of SiC/h-BN/Gr hybrid reinforced Al6061 matrix composites produced by hot extrusion method. Diamond and Related Materials 136: 110028.
13. Zoalfakar SH, Mohamed MA, Abdel Hamid M, Megahed AA (2022) Effect of friction stir processing parameters on producing AA6061/tungsten carbide nanocomposite. Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering 236(2): 653-667.
14. Djouider F, Alhawsawi A, Elmoujarkach E, Banoqitah E, Alharazi M, et al. (2023) The role of friction stir processing parameters and hybrid ZrC/WC reinforcement particles in improving the surface composite dissimilar matrix's dynamic behavior and microstructure refinement. Coatings 13(8): 1393.
15. Huang G, Hou W, Shen Y (2018) Evaluation of the microstructure and mechanical properties of WC particle reinforced aluminum matrix composites fabricated by friction stir processing. Materials Characterization 138: 26-37.
16. Moustafa EB, Melaibari A, Alsoruji G, Khalil AM, Mosleh AO (2022) Tribological and mechanical characteristics of AA5083 alloy reinforced by hybridising heavy ceramic particles Ta2C & VC with light GNP and Al_2O_3 nanoparticles. Ceramics International 48(4): 4710-4721.
17. Abushanab WS, Moustafa EB, Goda ES, Ghandourah E, Taha MA, et al. (2023) Influence of vanadium and niobium carbide particles on the mechanical, microstructural, and physical properties of AA6061 aluminum-based mono- and hybrid composite using FSP. Coatings 13(1): 142.
18. Moustafa EB, Djouider F, Alhawsawi A, Elmoujarkach E, Banoqitah E, et al. (2023) A comprehensive investigation of BN and VC reinforcements on the properties of FSP AA6061 composites. Lubricants 11(12): 507.
19. Selvamani ST, Bakkiyaraj M, Palani S, Yoganandan G (2022) Corrosion behavior and analysis on friction stir welded aluminium matrix composites. Surface Topography: Metrology and Properties 10: 025036.
20. Moustafa EB, Melaibari A, Basha M (2020) Wear and microhardness behaviors of AA7075/SiC-BN hybrid nanocomposite surfaces fabricated by friction stir processing. Ceramics International 46(10): 16938-16943.
21. Alam MA, Ya HB, Azeem M, Mustapha M, Yusuf M, et al. (2023) Advancements in aluminum matrix composites reinforced with carbides and graphene: A comprehensive review. Nanotechnology Reviews 12(1).
22. Abdelhady SS, Elbadawi RE, Zoalfakar SH (2023) Investigation of the microstructure, mechanical and wear performance of friction stir-processed AA6061-T6 plate reinforced with B_4C particles surface composite. Journal of Composite Materials 57(14): 2297-2310.
23. Ramesh B, Elsheikh AH, Satishkumar S, Shaik AM, Djuansjah J, et al. (2022) The influence of boron carbide on the mechanical properties and bonding strength of B_4C/Nickel 63 coatings of brake disc. Coatings 12(5): 663.
24. Kumar TS, Thankachan T, Shalini S, Čep R, Kalita K (2023) Microstructure, hardness and wear behavior of ZrC particle reinforced AZ31 surface composites synthesized via friction stir processing. Scientific Reports 13: 20089.
25. Moustafa EB, Mikhaylovskaya AV, Taha MA, Mosleh AO (2022) Improvement of the microstructure and mechanical properties by hybridizing the surface of AA7075 by hexagonal boron nitride with carbide particles using the FSP process. Journal of Materials Research and Technology 17: 1986-1999.
26. Boopathi S, Jeyakumar M, Singh GR, King FL, Pandian M, et al. (2022) An experimental study on friction stir processing of aluminium alloy (AA-2024) and boron nitride (BN_p) surface composite. Materials Today: Proceedings 59: 1094-1099.
27. Manivannan A, Sasikumar R (2018) Fabrication and characterization of aluminium boron nitride composite for fins. Materials Today: Proceedings 5(2): 8618-8624.
28. Padhy GK, Wu CS, Gao S (2018) Friction stir based welding and processing technologies - processes, parameters, microstructures and applications: A review. Journal of Materials Science & Technology 34(1): 1-38.
29. Wang L, Xie L, Shen P, Fan Q, Wang W, et al. (2019) Surface microstructure and mechanical properties of Ti-6Al-4V/Ag nanocomposite prepared by FSP. Materials Characterization 153: 175-183.
30. Suman S, Sethi D, Meher A, Bhargava M, Saha Roy B (2022) Effect of tool rotational speed on microstructure and mechanical properties of AA6061/SiC surface composites using friction stir processing. Materials Today: Proceedings.
31. 31 Moustafa E (2017) Effect of multi-pass friction stir processing on mechanical properties for AA2024/Al_2O_3 nanocomposites. Materials 10(9): 1053.
32. Youness RA, Amer MS, Taha MA (2023) Comprehensive *in vivo* and *in vitro* studies for evaluating the bone-bonding ability of $Na_2O–CaO–SiO_2–B_2O_3–Ag_2O$ glasses for fracture healing applications. Journal of Inorganic and Organometallic Polymers and Materials 33: 4068-4082.
33. Abushanab WS, Moustafa EB, Youness RA (2023) Mechanical behavior and tribological properties of hydroxyapatite/hardystonite/zirconia hybrid nanocomposites for orthopedic applications. Applied Physics A 129(6).