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Experimental Investigation and Comparative Analysis of LM13 Hybrid Composite Reinforced with Zirconium Carbide and Carbon Short Fibres

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Matrix Composites (MMCs) are used in automotive, industrial, and aerospace applications due to their low mass, high strength, and structural rigidity. LM13 alloy has good mechanical properties and exhibits good castability. The aim of this work is to fabricate and compare the mechanical properties of LM13-Carbon short fibers composite and LM13-Carbon short fibers reinforced with Zirconium Carbide (ZrC) hybrid composites. Samples were prepared using LM13 reinforced with different volume concentrations of ZrC (0%, 2%, 4%, 6%) and constant volume of chopped carbon fibers (10%) which are pre-heat temperatures at 900°C and are casted using a stir casting process. Tensile test, hardness, Corrosion, and wear tests were conducted. The mechanical properties evaluation reveals that tensile strength, hardness, wear, and corrosion resistance vary with the hybrid combinations. The findings indicate that the integration of ZrC increases the material's hardness, wear and corrosion resistance, whereas carbon fibers increase the material's tensile strength.

Keywords: Zirconium carbide; carbon short fibres; aluminium; hybrid composite; mechanical properties

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Metal matrix composites (MMCs), particularly those reinforced with carbon fibers, have gained significant attention due to their superior strength, wear resistance, and corrosion resistance, making them suitable for aerospace, automotive, and petrochemical applications. Researchers have explored different matrices (aluminium, copper) and reinforcements (carbon fibers, agro-waste ash, ceramics) to optimize mechanical and tribological properties. The following studies highlight key advancements in the Carbon Fiber Reinforced MMCs field. Shirvanimoghaddam et al. [1] demonstrated that carbon fiber reinforcement enhances structural, physical, and mechanical properties of MMCs. Song et al. [2] observed that carbon fibers improve wear resistance by forming a solid lubrication film. Kumar et al. [3] reported that increasing carbon fiber content enhances corrosion resistance. Quadros et al. [4] found that nickel-coated carbon fibers in aluminium matrices improve compressive strength, elasticity, and hardness. Tang et al. [5] showed that aluminium-coated short carbon fibers provide better mechanical properties than nickel or copper-coated variants. Lei et al. [6] observed that higher loads and rotational speeds increase friction and wear, while higher carbon fiber content reduces them. Li et al. [7] found that 1% carbide content optimizes interface bonding, while excessive carbides degrade mechanical properties. Jia et al. [8] determined that 15% short carbon fiber maximizes flexural strength and fracture toughness in alumina composites. Deshpande et al. [9] noted that coated carbon fibers enhance hardness, unlike uncoated fibers. Simancik et al. [10] demonstrated that annealing improves interfacial bonding strength. Zhu et al. [11] reported that ZrC and carbon powder additions improve tensile strength and elongation in aluminium composites. Ramesh et al. [12] found that fiber-reinforced aluminium exhibits lower friction and wear rates. Hernández-Martinez et al. [15] concluded that shaker mill synthesis produces ZrC-aluminium composites with optimal properties. Hemanth [16] observed that nano-ZrC reinforcements enhance strength and hardness but slightly reduce ductility, altering fracture behavior from intergranular to cleavage mode. Sarada et al. [18] found that carbon and mica additions improve hardness and wear resistance in LM25 aluminium. Mohanavel et al. [19] reported that graphite and alumina dispersions enhance hardness, tensile, and flexural strength. Pazhouhanfar et al. [22] observed that TiB_2 reinforcement increases tensile strength but leads to

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ductile fracture via microvoid coalescence. Bhandare et al. [13] identified 630°C as the optimal casting temperature for improved wettability. Annigeri et al. [21] designed an optimized stirrer for uniform particulate distribution in composites. Tuan et al. [24] found that zirconia additions enhance the toughness of alumina composites. Aluminium matrix composites (AMCs) are widely reinforced with ceramic particles such as SiC, Al_2O_3, B_4C, TiC, and mica to enhance mechanical and tribological properties. However, recent studies have explored advanced reinforcements like Zirconium Carbide (ZrC) and carbon short fibers due to their unique advantages. Zirconium Carbide (ZrC) exhibits a monoclinic crystalline structure, providing high fracture toughness, wear resistance, thermal shock resistance, and superior surface finish (Kumar et al., 2021).

Carbon fibers are valued for their high tensile strength, stiffness, low thermal expansion, and excellent electrical/thermal conductivity (Shirvanimoghaddam et al., 2020). Additionally, carbon fibers contribute to lightweighting and self-lubrication in composites, making them ideal for aerospace and automotive applications. In this study, LM13 aluminium alloy is selected as the matrix due to its favorable properties: (i) Primary alloying elements: Magnesium (Mg) and Silicon (Si), (ii) Good mechanical strength, weldability, and extrudability. Application includes Aircraft structures, automotive components, and food/ beverage packaging (Davis, 2018). The growing demand for lightweight, high-strength materials in automotive and aerospace industries has led to extensive research on aluminum-based metal matrix composites (MMCs). Among these, LM13 aluminum alloy has gained attention due to its superior wear resistance, thermal stability, and mechanical strength. However, most studies have focused on single-reinforcement composites, with limited exploration of hybrid composites integrating Zirconium Carbide (ZrC) and Carbon Short Fibres (CSF).

Existing research primarily investigates individual ceramic or fiber reinforcements in aluminum alloys, overlooking the potential synergistic effects of combining ZrC and CSF. Moreover, while powder metallurgy and conventional casting methods have been widely studied, there is a lack of comprehensive analysis on stir casting as a cost-effective and scalable fabrication technique for such hybrid composites. The effect of reinforcement dispersion, stirring parameters, and microstructural evolution on mechanical and tribological performance remains insufficiently explored. This study addresses these gaps by developing a novel LM13-ZrC-CSF hybrid composite using stir casting and conducting a comparative analysis of its mechanical and tribological properties.

MATERIALS PREPARATION

Preparation of Hybrid Composites

Hybrid metal matrix composites are prepared using the stir casting process. Stir casting involves stirring the molten metal matrix to introduce the reinforcement component material. Table 1 and Table 2 display the chemical makeup and mechanical characteristics of LM13, respectively. A common method for creating composite materials is stir casting. The procedure of stir casting ensures that reinforcements are mixed uniformly. Table 3 displays the reinforcing composition in the aluminum matrix. In a graphite crucible, aluminum alloy rod is melted at 750 ˚C. For improved reinforcing, the carbon fibers and zirconium carbide are preheated to 950 ˚C. The carbon fibers are made of pitch. It is around 3 mm long and 10 µm in diameter. Zirconia particles are 50 µm in size. The molten aluminum alloy is then combined with the heated reinforcements in the graphite crucible. A stirrer with three 45-degree-angled blades is used to stir the mixture. For five minutes, the stirring is carried out at 500 rpm. The molten liquid is then put into a die that is 250 mm long and 50 mm in diameter. Under atmospheric circumstances, it is permitted to solidify. Figure 1 displays the cast samples.

Figure 1. Casted Composites.

Table 1. LM13 chemical composition.

Si	Cu	Mg	Fe	Mn	Ni	Al
11-13	2	0.3-0.7	0.6-1	0.2-0.5	0.2-0.5	Bal

Table 2. LM13 properties.

Property	Values
Density	2.69 g/cm^3
Thermal Conductivity	90 – 110 W/(m·K)
Coefficient of Thermal Expansion	23 – 24 µm/(m·K)
Melting Point	570 - 610°C
Electrical Conductivity	34 – 36 % IACS

Table 3. Compositions of Hybrid composites.

SI. No.	Al(Vol%)	ZrC(Vol%)	SCF(Vol%)
1	90	0	10
2	88	2	10
3	86	4	10
4	84	6	10

RESULTS AND DISCUSSION

The fabricated composite undergoes tensile testing to analyze the influence of reinforcements. These tensile tests are performed using a computerized universal testing machine, with specimens prepared according to the ASTM E8 standard. Figure 2 displays the machined tensile test samples. Additionally, the composite is evaluated for microhardness using a Vickers microhardness tester, with specimens conforming to ASTM E18 standards, as illustrated in Figure 3. Furthermore, the corrosion resistance of the composite is assessed following the ASTM G41 guidelines. The specimens used for corrosion testing are shown in Figure 4.

Figure 2. Tensile Test Specimens

Figure 3. Microhardness Test Specimens

Figure 4. Corrosion Test Specimens

Micro Structure

Figure 5 displays optical micrographs comparing the microstructures of unreinforced LM13 alloy and reinforced LM13 metal matrix composite (MMC). The carefully controlled casting parameters led to well-defined dendritic structures, likely due to the interaction between hard and soft reinforcement particles in the composite matrix [23-25]. Microscopic analysis showed a two-phase structure with contrasting light and dark regions. The refined microstructure resulted from heterogeneous nucleation, which encouraged the growth of fine dendritic networks across the MMC. This nucleation process also supported the formation of recrystallized grains. A stirring speed of 700 rpm during casting was crucial for achieving even particle dispersion, preventing agglomeration, and ensuring a homogeneous matrix [26]. When comparing the hybrid composite to the base LM13 alloy (Figure 5a), some interfacial segregation was observed. Importantly, the reinforcement particles hindered dendritic arm growth, leading to smaller interdendritic spacing. As seen in Figure 5b, the optimized casting process, which included solid reinforcement particles, effectively produced recrystallized grains in the MMC structure.

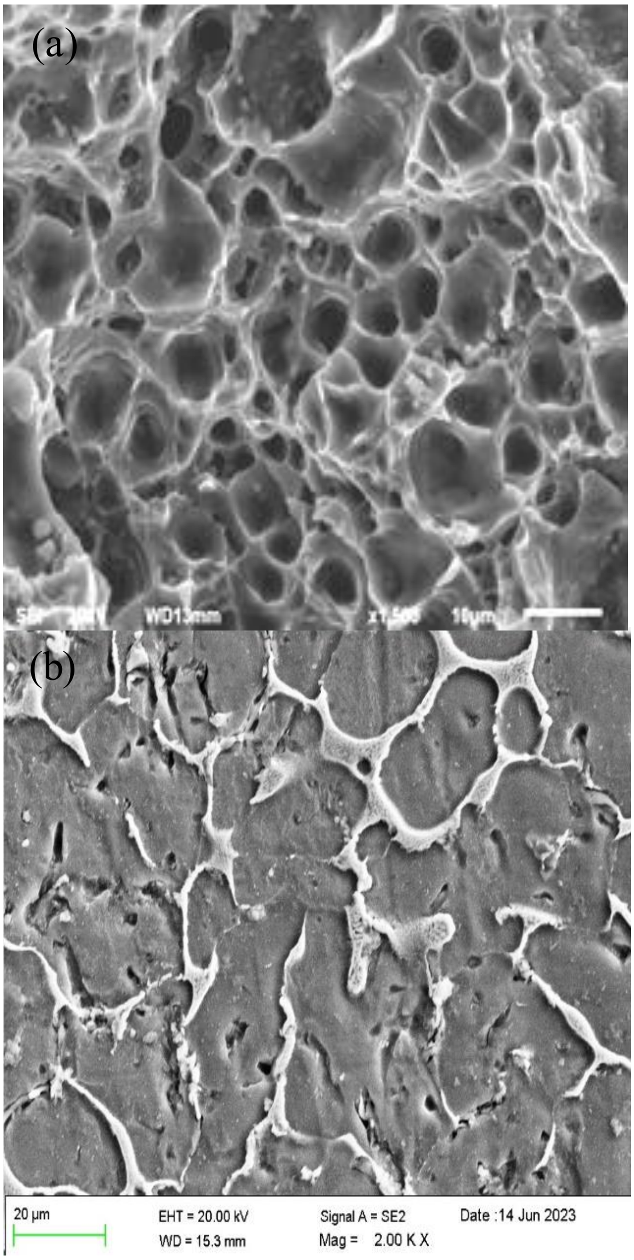

Figure 5. a) Microstructure of LM13 alloy; b) Microstructure of LM13 MMC.

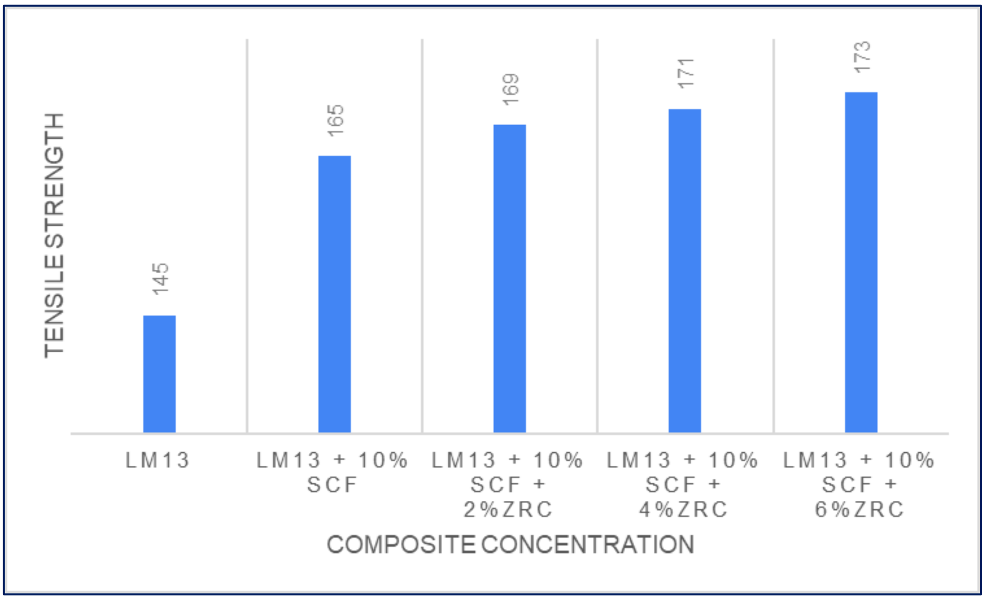

Figure 6. Effect of reinforcement on tensile strength.

Effect of Reinforcements on Tensile Strength

Figure 6 demonstrates the influence of different reinforcements on the tensile properties of LM13 aluminum matrix composites. The unreinforced LM13 alloy shows a baseline tensile strength of 145 MPa. Incorporation of 10% short carbon fibers (SCF) leads to a substantial enhancement, increasing the strength to 165 MPa, which underscores the superior reinforcing efficiency of carbon fibers. This improvement is attributed to the fibers' exceptional load-bearing capacity and stress transfer characteristics within the composite structure. Additional reinforcement with zirconium carbide (ZrC) particles produces further strength improvements, though with diminishing returns. The composite containing 2% ZrC achieves a tensile strength of 169 MPa, while 4% ZrC increases it marginally to 171 MPa. The maximum strength of 173 MPa is obtained with 6% ZrC addition. These results indicate that while ZrC contributes to strengthening, its effect becomes less significant at higher concentrations, suggesting an optimal reinforcement threshold. The comparative analysis reveals that short carbon fibers provide the most substantial strengthening effect, while ZrC particles offer supplementary reinforcement with progressively smaller strength increments as their content increases. This behavior highlights the dominant role of fiber reinforcement in enhancing the composite's mechanical performance.

Effect of Reinforcements on Hardness

Figure 7 displays the Vickers microhardness measurements for LM13 aluminum alloy composites incorporating short carbon fiber (SCF) and zirconium carbide (ZrC) reinforcements. The base LM13 alloy exhibits a microhardness value of 60.2 VHN. Introduction of 10% SCF reinforcement results in a hardness increase to 68 VHN, representing a limited enhancement due to the inherent hardness limitations of carbon fibers relative to ceramic materials. The hardness profile shows more substantial improvement with ZrC particle incorporation. The composite containing 10% SCF and 2% ZrC demonstrates a significant hardness increase to 82 VHN, highlighting ZrC's superior hardening capability. Progressive additions of ZrC yield further hardness gains, with 4% ZrC achieving 91 VHN and the maximum 6% ZrC content reaching 97 VHN. This enhancement mechanism stems from ZrC particles' exceptional resistance to deformation, which substantially improves the composite's wear resistance properties. Microhardness variations across samples correlate directly with the localized distribution of reinforcement particles at indentation sites. The peak hardness value recorded in Sample 4 conclusively establishes that while SCF contributes to general mechanical property enhancement, ZrC reinforcement exerts the predominant influence on the composite's hardness characteristics. These findings demonstrate the complementary roles of different reinforcement types in optimizing composite material properties.

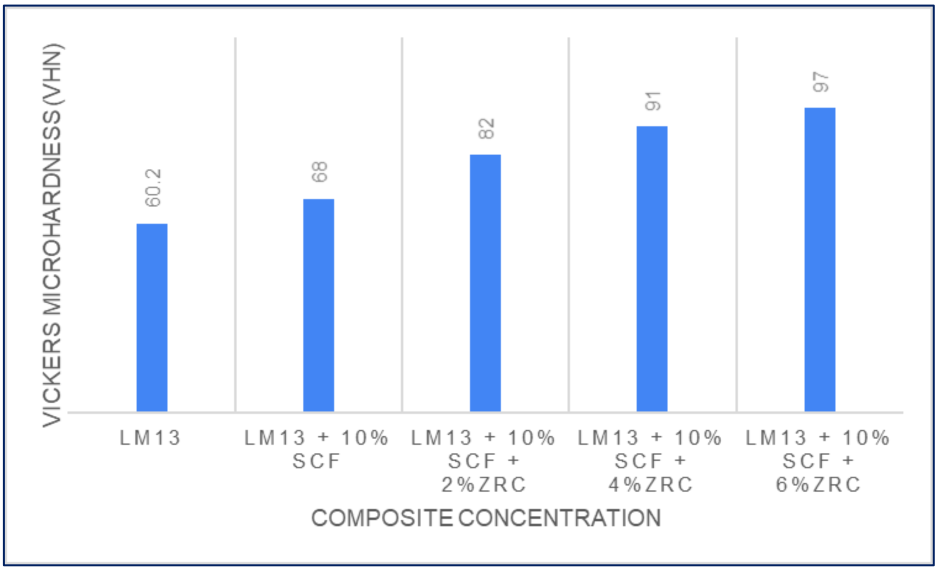

Figure 7. Effect of Reinforcement on Hardness.

Effect of Reinforcements on Corrosion Rate

Figure 8 presents the corrosion performance of LM13 aluminum alloy composites reinforced with short carbon fibers (SCF) and zirconium carbide (ZrC). The unreinforced LM13 alloy serves as the baseline for comparison, while the composite containing 10% SCF shows a corrosion rate of 0.00875, representing only marginal improvement. This limited enhancement stems from carbon fibers' tendency to form galvanic couples with the aluminum matrix, which can accelerate corrosion in certain environments. The introduction of ZrC particles demonstrates a more substantial protective effect. With 2% ZrC addition, the corrosion rate decreases to 0.0074, showing ZrC's superior corrosion-inhibiting properties. This improvement becomes more pronounced at higher ZrC concentrations, with 4% ZrC reducing the rate to 0.0061 and 6% ZrC achieving the lowest corrosion rate of 0.0054. The ceramic ZrC particles create a more effective barrier against corrosive agents compared to SCF, while simultaneously minimizing galvanic corrosion by reducing electrical continuity in the composite.

These results establish a clear hierarchy in corrosion protection mechanisms: while SCF provides limited benefits, ZrC serves as the primary corrosion-inhibiting phase. The composite with 6% ZrC exhibits the optimal combination of reinforcement materials, offering superior durability in aggressive environments. This study demonstrates that strategic selection and combination of reinforcement materials can significantly enhance the corrosion resistance of aluminum matrix composites.

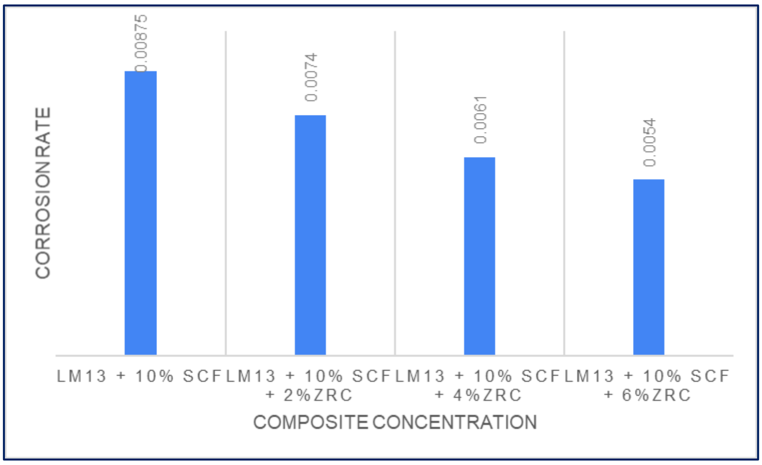

Figure 8. Effect of reinforcement on corrosion rate.

Effect of Reinforcements on Wear Rate

The wear behavior of LM13 aluminum alloy composites was evaluated through Pin-on-Disc testing in accordance with ASTM G99 standards, using an EN31 steel disc as the counterface. Tests were performed under a constant load of 20 N over a sliding distance of 1000 m to assess the impact of reinforcement on wear resistance. Figure 9 (a-d) presents the wear rate trends for composites incorporating short carbon fibers (SCF) and zirconium carbide (ZrC). Results demonstrate a consistent inverse relationship between reinforcement content and wear rate. The unreinforced LM13 alloy, owing to its inherent softness, exhibited the highest wear rate. While the addition of 10% SCF yielded moderate improvement, the most substantial enhancement in wear resistance was achieved through ZrC reinforcement. The composite containing 6% ZrC displayed the lowest wear rate, underscoring ZrC's effectiveness as a hard, abrasive-resistant phase that mitigates material loss. Microstructural analysis revealed that delamination wear a predominant failure mechanism in aluminum alloys was more pronounced in lightly reinforced samples. These regions experienced accelerated wear due to insufficient reinforcement, leading to localized material removal. In contrast, composites with higher ZrC content demonstrated superior interfacial integrity, effectively resisting delamination and maintaining structural stability under sliding conditions. The findings highlight ZrC's critical role in enhancing wear performance, particularly at elevated reinforcement concentrations.

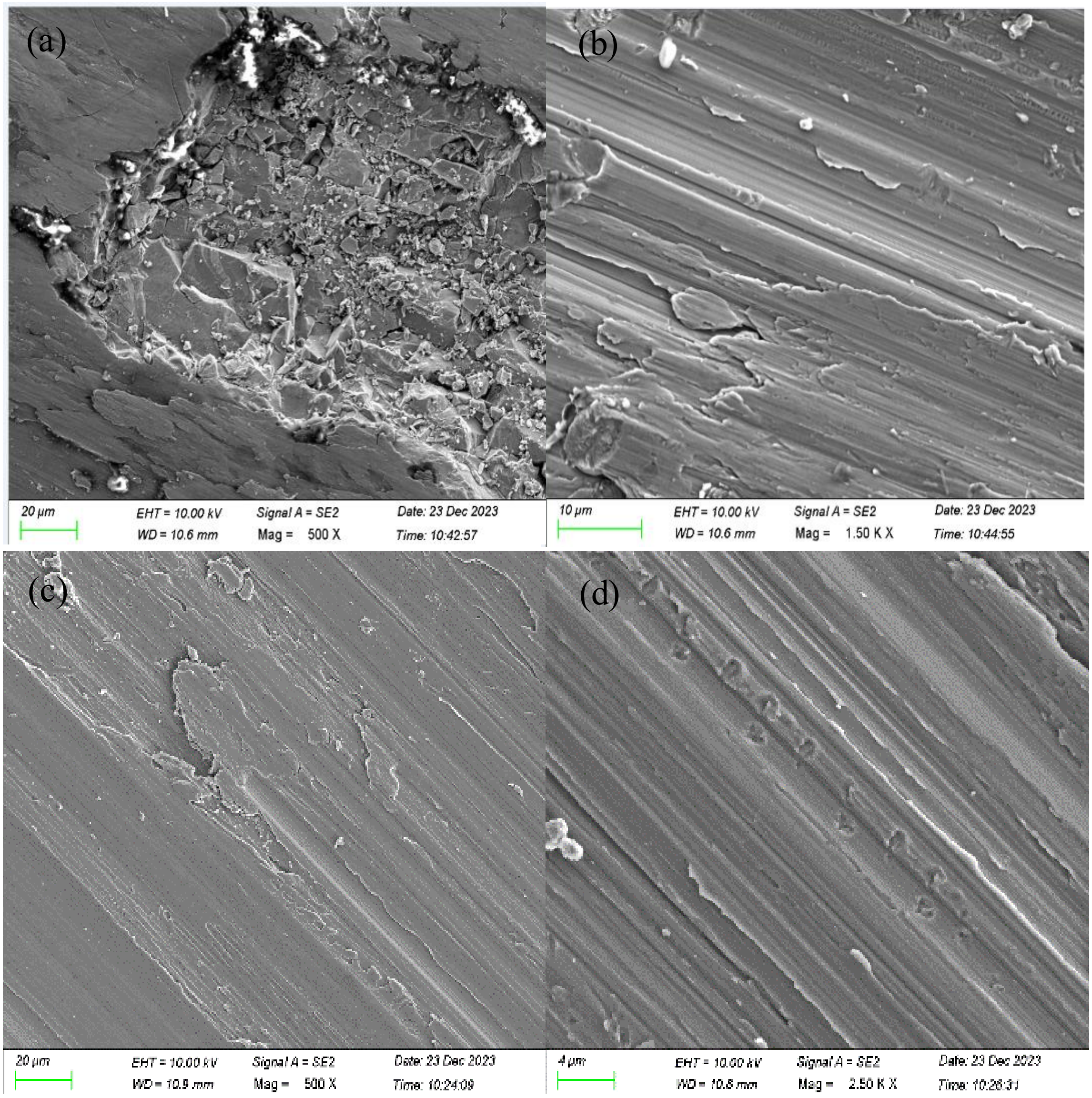

Figure 9. a-LM13 alloy, b-LM13 with 2% ZrC and 10% SCF, c-LM13 with 2% ZrC and 10% SCF, d-LM13 with 2% ZrC and 10% SCF.

CONCLUSION

This study successfully developed and analyzed the mechanical properties of LM13 composites reinforced with short carbon fibers and LM13 hybrid composites containing both short carbon fibers and zirconium carbide (ZrC) using the stir casting process. The composites were fabricated with a fixed 10% short carbon fiber volume fraction and varying ZrC concentrations (0%, 2%, 4%, and 6%). The study comprehensively evaluates the effects of short carbon fibers (SCF) and zirconium carbide (ZrC) reinforcements on the mechanical, wear, and corrosion properties of LM13 aluminum alloy composites. The results indicate that the incorporation of these reinforcements significantly enhances the composite's overall performance. The addition of SCF greatly improves tensile strength, increasing from 145 MPa (pure LM13) to 165 MPa with 10% SCF. Further enhancement is observed with ZrC additions, reaching a maximum of 173 MPa at 6% ZrC. This suggests that while SCF provides primary reinforcement, ZrC contributes additional strength. Hardness improves progressively with increasing ZrC content, reaching 97 VHN at 6% ZrC. The results indicate that SCF has a limited impact on hardness, whereas ZrC, due to its ceramic nature, significantly enhances the material's resistance to deformation. Corrosion rate decreases with increasing ZrC content, with the lowest rate (0.0054) observed at 6% ZrC. While SCF improves corrosion resistance slightly, ZrC provides superior protection due to its inert nature, reducing the material's susceptibility to degradation. Wear rate declines as reinforcement content increases, with higher ZrC concentrations offering superior resistance. The presence of SCF and ZrC prevents delamination wear, ensuring longer material durability. Overall, the study confirms that hybrid reinforcement with SCF and ZrC optimally enhances the mechanical, corrosion, and wear resistance properties of LM13 composites, making them suitable for high-performance applications.

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