Optimizing Al6061-Based Hybrid Metal Matrix Composites: Unveiling Microstructural Transformations and Enhancing Mechanical Properties Through Ni and Cr Reinforcements

Raj Kumar[1*], Kedar Narayan Bairwa[2]
[1]Swami Keshvanand Institute of Technology, Management & Gramothan, Jaipur
[2]Regional College for Education Research and Technology, Jaipur

*Author to whom correspondence should be addressed:
Email: raj.kumar@skit.ac.in

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Abstract: This study investigates the development of Al6061-based Hybrid Metal Matrix Composites (HMMCs) reinforced with nickel (Ni) and chromium (Cr) to enhance their mechanical properties. Employing the stir casting method, the research aimed to achieve a homogeneous distribution of Ni and Cr particles, varying from 1 to 3 wt.%, in the Al6061 matrix. Additional elements like graphite (up to 3 wt.%) and magnesium (1 wt.%) were incorporated to improve self-lubrication and wettability. The fabrication process involved precise temperature control at 750°C and automatic stirring to ensure even dispersion of the reinforcing particles. The composites were then molded, solidified, and prepared for mechanical testing. SEM-EDS analysis was utilized to analyze the elements' distribution and the composites' microstructural integrity. Mechanical tests, including tensile, flexural, and hardness tests, followed ASTM standards. Significant findings revealed that the specimen with two wt.% Ni and two wt.% Cr (designated as SM2) demonstrated the most balanced improvement in mechanical properties: a tensile strength of 236.08 MPa, a flexural strength of 417.70 MPa, and a hardness of 127.00 HRB. However, an increase in Ni and Cr content beyond 4 wt.% led to non-homogeneous dispersion, manifesting as cracks, voids, and agglomeration, negatively impacting ductility and elongation properties. The study's unique contribution lies in its detailed examination of the effects of varying Ni and Cr concentrations on the mechanical properties of Al6061-based composites, providing valuable insights for material optimization in high-performance applications. This research underscores the delicate balance required in composite material design, particularly in enhancing specific mechanical properties without compromising overall material integrity. It provides crucial insights into the role of Ni and Cr reinforcements in Al6061 composites, highlighting their potential for engineering applications that demand high strength, flexibility, and hardness.

Keywords: Al6061; Nickel; Chromium; Stir Casting; SEM; EDS; Mechanical Behavior

1. Introduction

The progress of engineering and technology heavily depends on the development of new and modified materials. Material engineering is one of the most widespread technologies to create more unique materials with excellent engineering properties. Composite material is one of the sectors belonging to such engineering. Several materials (metals and non-metals) are used to form a composite material to enhance their workability and the area of their utilization. Among these, composite materials are currently gaining significant attention. Metal matrix composites (MMC) are especially noteworthy, as they uniquely combine the desirable qualities of strength, hardness, wear resistance, thermal conductivity, and coefficient of thermal expansion. By adjusting the weight ratio of the metal matrix and reinforced particles, these composites can be customized to meet specific product requirements. As a result, they are highly suitable for innovative designs in various industries[1,2]. The high strength, outstanding weldability, and excellent corrosion resistance of Al 6061 have led to the popularity of aluminum matrix composites (AMCs) for producing high-tech replacement components for use in industries as diverse as automotive, aerospace, and medicine. Researchers have focused on developing MMCs with different reinforcements to improve their properties per investigations carried out by[3),4)] one of the constituents of AMC is aluminum alloy or aluminum" which is known as the matrix phase as well as a percolating network of forms. It serves as reinforcement in the aluminum alloy matrix, and other constituents, generally ceramic and nonmetallic materials like Al2O3 and SiC, were embedded. [5]Stir casting was utilized to produce hybrid metal matrix composites based on aluminum, with various levels of graphite reinforcement and 10% silicon carbide (SiC). A Decrease in the coefficient of thermal expansion (CTE) and an increase in the thermal conductivity (TC) at elevated temperatures resulted from increased graphite reinforcing, as did an increase in hardness and tensile strength. Researchers looked at Al6061 matrix composites fortified with Al_2O_3 and graphene particles. [6]investigated the mechanical properties of Al6061 hybrid metal matrix composites (HAMMCs) reinforced with SiC, Al_2O_3, and fly ash via stir-casting. They observed that increasing the weight percentage of SiC and Al_2O_3 improved tensile strength, yield strength, and hardness while impact strength remained largely unaffected. Specifically, a 20% total reinforcement ratio showed high hardness and yield strength, with a decrease in wear rate, demonstrating the potential of HAMMCs in enhancing mechanical performance for various engineering applications. [7]fabricated MMCs to examine the impact of % wt. of reinforced particles on the mechanical and physical properties of MMCs. The Al 6061 alloy has been taken as a matrix while SiC and Gr particles in different wt. % has been accepted as reinforced material. The MMCs were fabricated using stir casting. The theoretical densities of all fabricated MMCs are higher than experimental densities. The Al 6061/SiC/Gr MMCs exhibited superior mechanical properties compared to Al 6061/SiC MMCs. [8] Examine the mechanical and physical properties of Al-based B4C-filled MMCs. The MMCs have been fabricated in different wt. % of B_4C using the stir casting method. A comparison has also been made between the properties of Al alloy and fabricated MMCs. The mechanical properties of MMCs increase with the increase in % wt. of B_4C. Also, MMCs exhibited better mechanical properties than Al alloys. [9]developed a functionally graded composite of Al6063 and Al8011, reinforced with Si3N4, using friction stir processing (FSP) for aerospace and defense applications. The composite exhibited enhanced mechanical properties, achieving a tensile strength of 133.05 N/mm² and a hardness of 59 HV. The study confirmed improved thermal and corrosion resistance, marking significant potential for lightweight, high-strength material applications in demanding environments. [10]investigated the mechanical properties of Al 6061 hybrid composites reinforced with AlN-SiC nanoparticles using stir casting. The study found that adding 3% and 6% of AlN and SiC nanoparticles significantly improved the composites' tensile strength, compressive strength, and hardness. Specifically, tensile strength increased from 328 to 385 MPa, compressive strength increased from 145 to 178 Mpa, and hardness rose from 302 to 724 VHN. These enhancements suggest Al 6061-based hybrid composites with nanoparticle reinforcement could be advantageous in applications demanding higher mechanical performance.

[11]studied the tensile behavior of a composite sample made from aluminum with varying percentages of graphite and nickel. The results showed that the specimen with 3% graphite and 1.5% nickel had the best tensile properties and excellent elongation at break properties. [12]found that increasing the reinforcing fraction in Al+Gr+CNT composites increased the material's hardness. Vickers Micro-hardness comparison graphs showed that the sintered specimens had higher hardness than cold-pressing compacts. [13]explored the production of AMCs by varying the ratios of aluminum in composite mixtures consisting of two or more materials. Adding chromium and nickel to AA6061 resulted in a composite with better flexural abilities and tensile strength than pure materials. The study also highlighted the importance of material selection for electrodes in the fabrication process. Using various copper weight percentages, [14]looked into the mechanical characteristics of composites made of aluminum. Adding 2% copper resulted in the highest tensile strength and elongation at break properties. Researchers looked at Al6061 matrix composites fortified with Al2O3 and graphene particles. Homogeneous distribution of reinforcement particles on Al matrix grain boundaries was observed, with improved hardness, ultimate strength, and yield strength but decreased elongation values as reinforcement particle weight percentages increased[15]. Aluminum composites with RHA and SiC particles were fabricated using double-stir casting. Research was conducted into the hybrid composites' mechanical properties, including their hardness, density, and porosity. Hardness and porosity were found to increase with increasing reinforcement volume fractions, while density was found to decrease. As the reinforcement weight fraction in aluminum metal matrix composites (AMMCs) rises, the material's ultimate tensile strength (UTS) and yield strength rise while the material's elongation falls[16]. They used chrome-containing leather waste (CCLW) to extract chromium and create composite materials through friction stir processing. Single-tool pass composites outperformed double and triple passes, displaying enhanced hardness and tensile strength compared to the base aluminum alloy[17]. Chromium (Cr) enhances corrosion resistance and mechanical properties when added to materials such as chromium oxide[18].

Experiments were conducted on aluminum by incorporating SiC and alumina. Results revealed improved mechanical properties—hardness, yield strength, and ultimate strength—with increasing weight percentage of reinforcement. However, elongation decreased, and the material transitioned from ductile to brittle behavior[19]. [20] Explored the preparation of Al6061–5%SiC–TiB_2 hybrid composites via stir casting, varying TiB_2 weight fractions. Optimal parameters and the addition of Potassium Hexafluorotitanate enhance interfacial bonding. Increasing TiB_2 content boosts mechanical properties, while SiC contributes to enhanced hardness. Fracture analysis indicates a ductile mode of failure. Aluminum is favored among non-ferrous metals because of its high thermal conductivity, low corrosion susceptibility, and high strength despite its low hardness, melting temperature, and wear resistance. AMMCs are more versatile than aluminum and are therefore favoured[21)]. SEM is a powerful imaging technique that employs a concentrated electron beam to generate sample images. As the electron beam interacts with the sample's atoms, it signals information about the surface composition and topography[22)]. [23)]fabricated Al alloy 6061-based MMCs to study the impact of % wt. of ceramic particulates on properties. The Al alloy 6061 has been taken as a matrix, while Al2O3 particles are in different wt. % have been considered as reinforcement material. The MMCs were fabricated with stir casting. The SEM images of fabricated MMCs were captured to examine the microstructure. It has been found from the analysis of SEM images that an Al2O3 particle homogeneously distributes in MMCs. Also, adding Al_2O_3 in MMCs enhances the microhardness and brittleness of Al alloy. The hardness and brittleness of MMCs are enhanced with increased reinforcement in MMCs.

SEM is used for observing specimen surfaces by targeting secondary electrons with a fine electron beam, and surface topography can be observed through 2D scanning[24)]. SEM is commonly used in microstructure analysis of composite materials, where it accurately measures small features and produces high-pixel images. Sample preparation plays a significant role in achieving better results, with different grit sizes of emery papers used for polishing and finishing the specimens with Keller's reagent[25)]. [26)]*developed a new conventional process for the fabrication of homogenous MMCs. For the fabrication of MMCs, Al alloy LM4 has been considered as a matrix, while SiC particulates have been considered as reinforcement material. Different MMCs have been fabricated using different weight percentages of SiC particulates. Also, they examine the effect of wear conditions on the wear of fabricated composites. It has been revealed from the SEM images of fabricated MMCs that the proposed method for the fabrication is beneficial for the fabrication of homogeneous MMCs. On the other hand, the result obtained after wear analysis indicates that adding SiC enhances the wear resistance of MMCs compared to the matrix.* [27)]explored the mechanical properties of Al7075 alloy for automotive applications through the synthesis and analysis of Al7075 hybrid composites. The composites were reinforced with aluminum oxide (Al_2O_3) and boron carbide (B4C) using a sand mold process in an electric resistance furnace. The research examined the mechanical behavior of these composites with varying B4C weight percentages from 2% to 6%, keeping Al_2O_3 content constant at 2%. The results showed improvements in compressive strength and hardness with adding Al_2O_3/B_4C, although tensile strength decreased. The microstructure analysis revealed a finer grain size in the aluminum matrix due to B_4C particles, enhancing the interfacial connection between the reinforcing particles and the matrix. This research provides valuable insights into developing advanced lightweight materials with improved mechanical properties for automotive applications.

The fabrication and characterization of Hybrid Metal Matrix Composites (HMMCs) using diverse aluminum grades are well-documented in the literature, but scant information exists on Al6061-Ni-Cr hybrid composites. This study bridges the gap by utilizing stir casting to vary Ni and Cr weight percentages, aiming to elucidate their effects on microstructure and mechanical properties.

2. Materials and Methods

2.1 Materials

The metal matrix was Al6061, and the reinforcements were powdered nickel and chromium.

Table 1:Elemental composition of Al6061

Element	Mg	Si	Fe	Cr	Cu	Pb
wt.%	0.81	0.45	0.39	0.25	0.24	0.24
Element	Zn	Ti	Mn	Sn	Ni	Al
wt.%	0.14	o.15	0.14	0.001	0.05	Rest

The choice of 1-3 wt.% for Ni and Cr, 3 wt.% for graphite, and one wt.% for magnesium in the hybrid metal matrix composites (HMMCs) for optimal results is likely based on a careful balance between achieving enhanced mechanical properties and avoiding potential drawbacks. Higher weight percentages may lead to non-homogeneous dispersion, increased porosity, or other issues that could compromise the overall performance and integrity of the composite material. Fixed-weight percentages of graphite and magnesium were added to the composites, with a maximum of 3 wt.% of graphite and one wt—% of magnesium to improve their self-lubrication and wettability properties, respectively. Al6061's elemental makeup is displayed in Table 1.

Table 2 Material and reinforced particles used for fabrication of HMMC

Hybrid Metal Matrix Composites	Matrix	Reinforced Particles	
	Al6061	Nickel	Chromium
Images			
Purity	Tempered	99.16%	99.60%
Particle Size	-	44 µm	44 µm

Table 3:Properties of Matrix and Reinforced Particles

Hybrid Metal Matrix Composite	Matrix	Reinforced Particles	
	Al6061	Nickel	Chromium
Purity	Tempered	99.16%	99.60%
Particle Size	-	44 µm	44 µm
Melting Point (°C)	652	1450	1900
Density (kg/m^3)	2.7	8.89x10^{-3}	7.10x10^{-3}
Ultimate Tensile Strength (MPa)	128.05	345	370
Yield Strength (MPa)	91.27	70	131
Flexural Strength (MPa)	299.71	390	310
Elongation	0.16	0.42	0.2
Hardness (HRB)	79.80	85	80

2.2 Fabrication of HMMCs

Table 4: Planning to make HMMCs reinforced with micron-sized Ni and Cr particles with fixed Mg and Gr weights.

Designation	**Specimen**	**Al6061**		**Ni**		**Cr**		**Gr**		**Mg**	
		grams	**wt.%**	**grams**	**wt.%**	**grams**	**wt.%**	**grams**	**wt.%**	**grams**	**wt.%**
Al6061/1 Ni/1 Cr	SM1	470	94	5	1	5	1	15	3	5	1
Al6061/2 Ni/2 Cr	SM2	460	92	10	2	10	2	15	3	5	1
Al6061/3 Ni/3 Cr	SM3	450	90	15	3	15	3	15	3	5	1

The fabrication process of Al6061-based Hybrid Metal Matrix Composites (HMMCs) involved the stir casting method, a cost-effective and efficient technique for producing metal matrix composites.

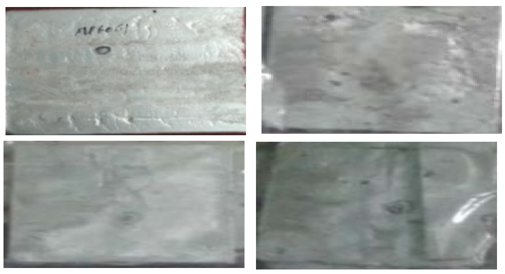


Fig.1: Developed hybrid metal matrix composite

The process can be summarized as follows:

Alloy Preparation: The base metal matrix was Al6061, a popular aluminum alloy known for its high strength and corrosion resistance. The alloy pieces were cured, cleaned with nitric acid and water, and dried. **Reinforcement Particle Preparation:** Nickel and chromium were used to reinforce particles in powder form. The particles were heated and mixed with the Al6061 matrix in a graphite crucible at 750°C. This temperature is crucial for a proper bond between the matrix and the reinforcement particles. **Addition of Enhancing Elements:** Magnesium and graphite were added to the composites in fixed-weight percentages. Magnesium improved wettability, while graphite contributed to self-lubrication. **Stir Casting Process:** The mixture was subjected to automatic stirring, creating a vortex in the molten alloy. This facilitated the gradual introduction of the reinforcement particles. The addition of graphite and magnesium during stirring ensured their uniform distribution, contributing to the overall properties of the composites. **Molding and Solidification:** Once the stirring process was complete, the composite material was poured into molds and allowed to solidify. This step ensured that the reinforcing particles were evenly dispersed throughout the matrix. The process is repeated for desired weight percentages. This ensures high-quality metal matrix composites MMCs[28),29),30), and 31)]. Figure 1 shows the composite metal after it had solidified in the casting molds. Once the casting had hardened, it was removed from the mold, and various samples were prepared for mechanical testing by ASTM standards.

2.3 Characterization of Materials

2.3.1 Analysis of the Elements' Dispersion Using SEM-EDS

A composite material's overall performance is greatly influenced by its microstructure. The microstructure, particle size and shape of the reinforcement material, and its distribution within the alloy all impact composites' mechanical and physical properties. Modern methods such as scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) were used to examine the material properties of the hybrid composites. The FEI Nova Nano FESEM 450 equipment was used for this [32)].

2.4 Mechanical Test

2.4.1 Tensile Test

The maximum stress a material can endure before breaking is known as its ultimate tensile strength. Yield strength, or the stress at which plastic deformation starts in a material, is the stress at which that material transitions from an elastic to a plastic behavior. When a material is stretched past its elastic limit, it tends to bend elastically. Both percent elongation and percent reduction in cross-sectional area are used to calculate ductility.

By ASTM E08-82 guidelines, tensile tests were performed on samples of the as-cast aluminum alloy and the composite material. With a strain rate of 2 mm/min and a temperature of 30°C, an all-purpose testing device (INSTRON) was employed. Test specimens were machined from the lathe and shaper machines, adhering to the dimensions provided in Figure 2 and standardized to a diameter of 3.18 mm according to BS 2789:2002. When subjected to a 50 kN load, various characteristics such as Young's modulus, yield strength, ultimate tensile strength, and elongation (which measures ductility) were assessed according to ASTM E8-82 standards[33)].

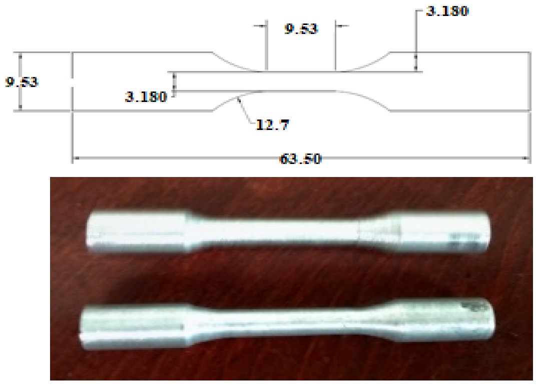


Fig.2: Tensile test specimen

2.4.2 Flexural Test

It is also known as the bend test used to determine bending stress. As per Figure 3 for flexural testing of all HMMCs, the test samples were fabricated according to the ASTM D3039-76 standard, with dimensions of 100 mm x 10 mm x 2 mm, respectively. An INSTRON universal testing device was used for the flexural test, including compressive and tensile testing. A rectangular cross-section sample was placed on two supporting pins, and a loading force was applied to the center of the sample using a loading pin. This test assessed the sample's strength and flexibility as it bends, with the ultimate goal of determining the maximum load it can withstand without breaking[34)].

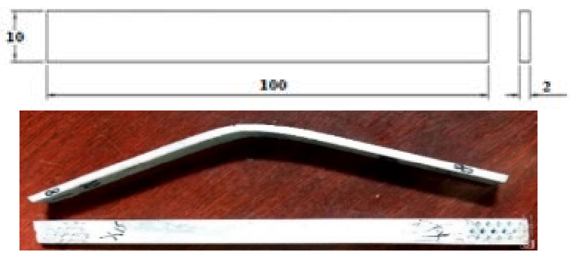


Fig.3: Flexural test specimen

2.4.3. Hardness Test

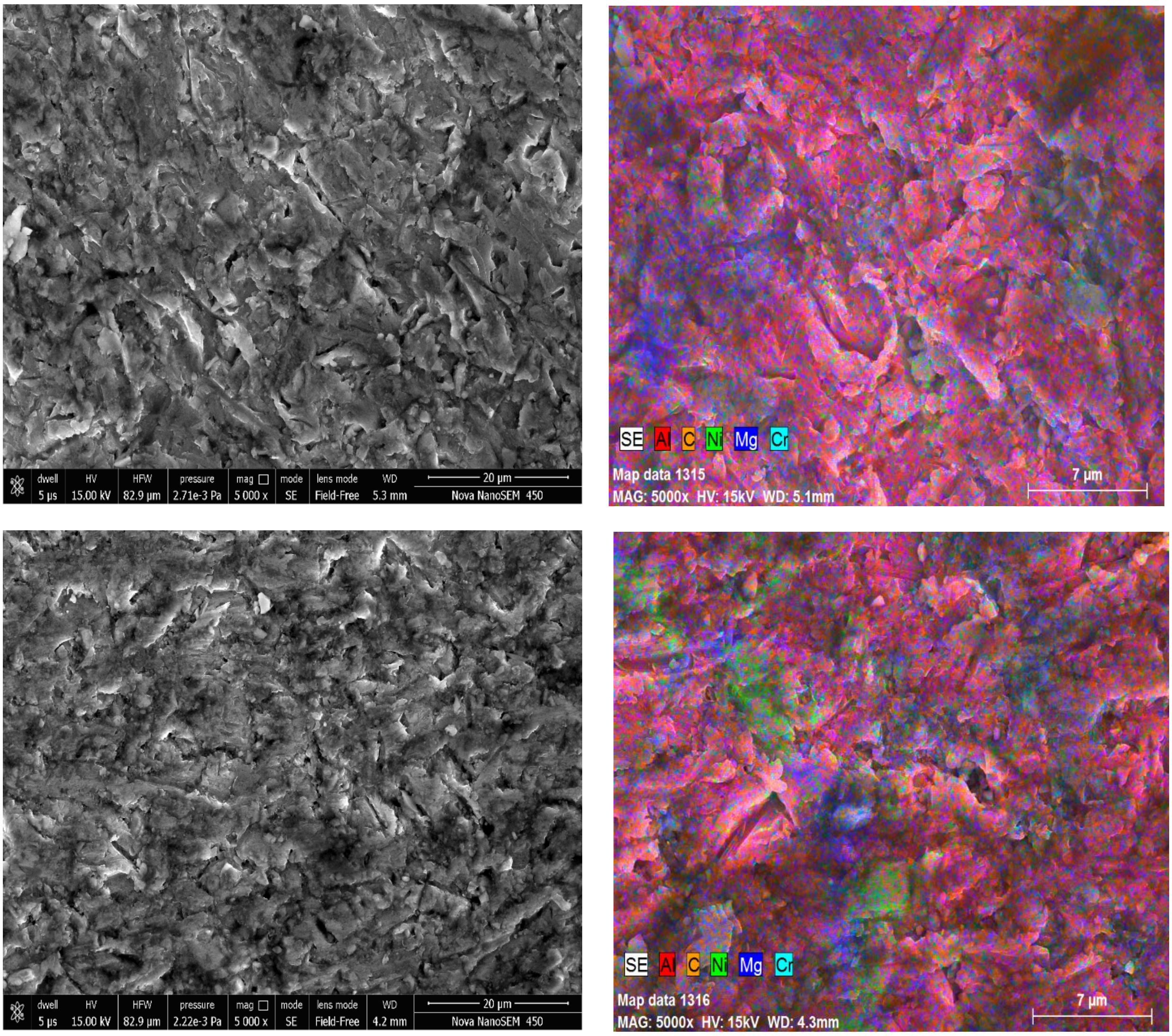
A Rockwell hardness machine was utilized to conduct the hardness test. It is generally used when quick and direct reading is desired. This test uses a standard ball indenter of hardened steel, tungsten carbide, or a diamond cone indenter 120° angle with a spherical tip. The surface of the specimen, as shown in Figure 4, was indented with a diamond cone indenter, and a dial gauge calibrated to the B-scale was used to display the hardness value[35]. The process was repeated five times for each type of specimen according to ASTM-10 standards to ensure precision in calculating the hardness value[36].

3. Results and Discussions

3.1 Morphologies of Developed HMMCs

Figure 5 displays the morphology of SM1, SM2, and SM3 specimens. The SEM images at 5000X magnification depict a robust metallurgical bond between the interface material and hybrid composites, where the Al6061 powder particles have completely melted. It has been noted that a non-homogeneous dispersion occurs when the weight percentage of reinforced particles exceeds four wt.% (Ni+Cr). This is attributed to more cracks, voids, and agglomeration, possibly due to variations in the pour point or inadequate mixing.

EDS elemental analysis has shown the existence of matrix material and reinforced particles through Figures 6, 7, and 8. High-intensity peaks have been identified for the elemental peaks of aluminum, as well as for functional elements such as Nickel, chromium, magnesium, and graphite. Nonetheless, the microstructure's transition from ductile to brittle with increased weight percentages of particles in the base alloy is consistent with expectations. The results of the morphological study indicate that SM2 exhibits better homogeneity of reinforced particles compared to SM1 and SM3.



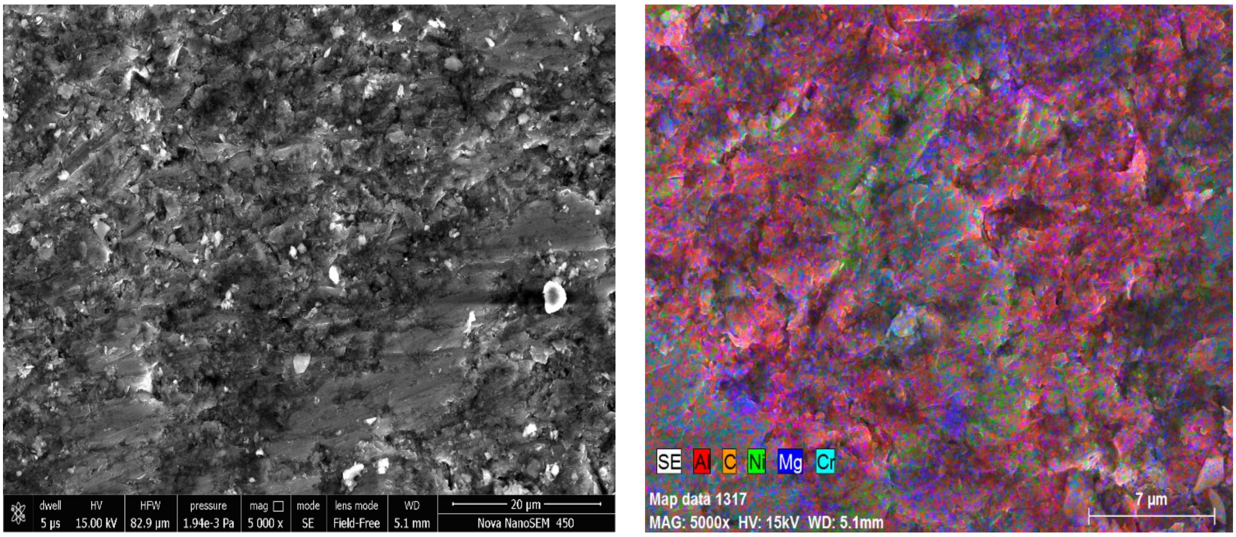
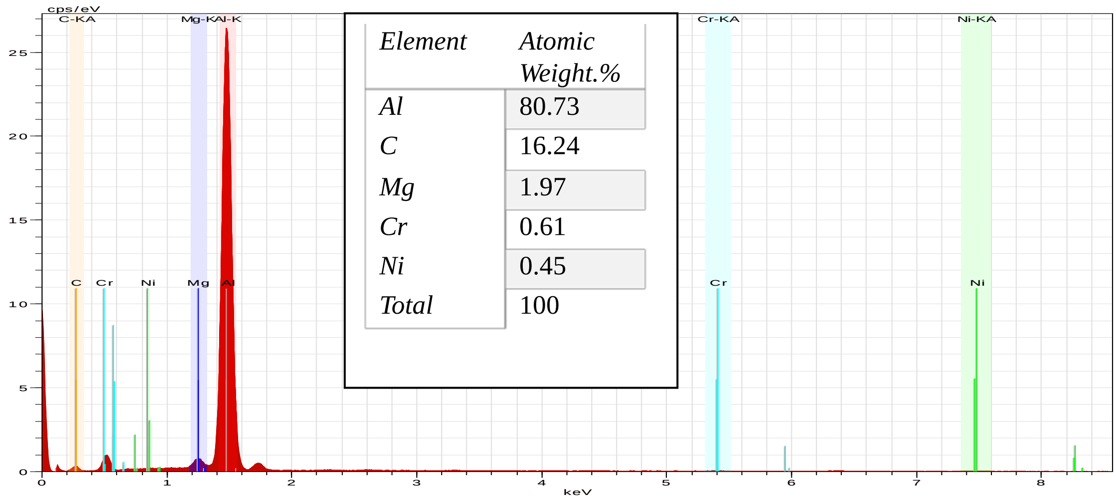
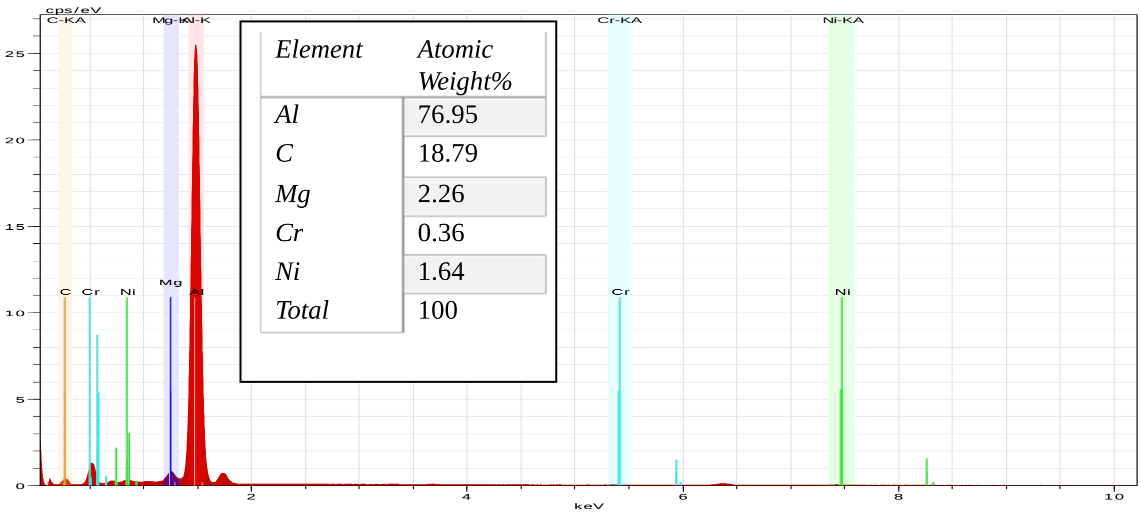


Fig. 5. SEM and EDS images of developed HMMCs SM1, SM2, & SM3



Element	*Atomic Weight.%*
Al	80.73
C	16.24
Mg	1.97
Cr	0.61
Ni	0.45
Total	100

Fig. 6: EDS pattern and elemental composition of developed HMMC-SM1



Element	*Atomic Weight%*
Al	76.95
C	18.79
Mg	2.26
Cr	0.36
Ni	1.64
Total	100

Fig. 7: EDS pattern and elemental composition of developed HMMC-SM2

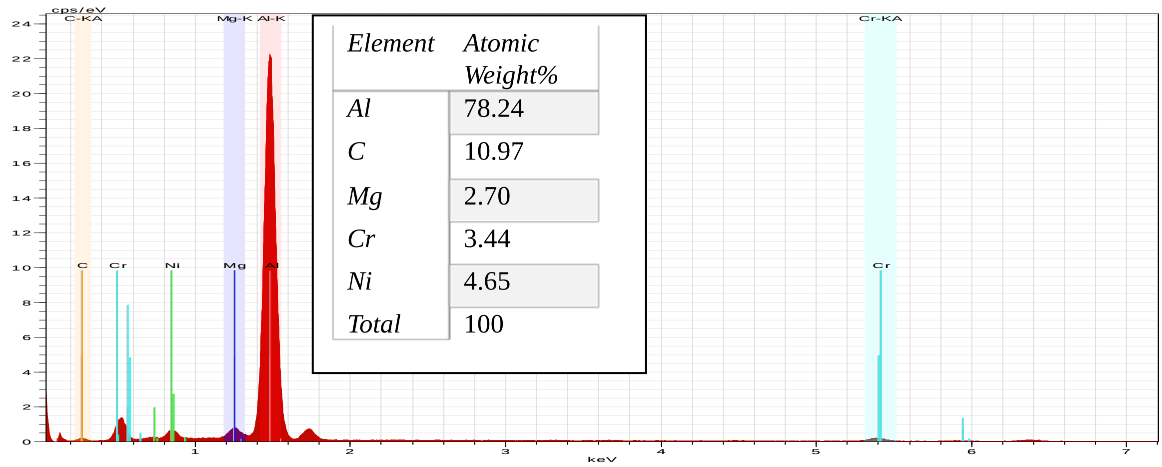


Fig.8: EDS pattern and elemental composition of developed HMMC-SM3

Table 5: Mechanical properties of developed composites

Sample No.	Reinforcement (wt.%)		Designation	YS (MPa)	UTS (MPa)	FS (MPa)	HRB	Elongation (%)
	Ni	Cr						
SM0	0	0	Al6061	91.27	128.05	299.71	79.80	0.16
SM1	1	1	Al6061/1 Ni/1 Cr	147.87	173.66	313.76	113.40	0.15
SM2	2	2	Al6061/2 Ni/2 Cr	169.87	236.08	417.70	127.00	0.11
SM3	3	3	Al6061/3 Ni/3 Cr	130.15	140.54	318.09	109.20	0.01

The SEM and EDS analyses provided crucial insights into the microstructure of the Al6061-based HMMCs. The formation of a strong metallurgical bond and high-intensity peaks for aluminum, nickel, chromium, magnesium, and graphite are significant. This confirms the effective incorporation of these elements into the matrix, essential for enhanced mechanical properties. However, the observation of non-homogeneous dispersion beyond four wt.% reinforcement suggests the limits of reinforcement loading, where excessive amounts could lead to detrimental effects such as voids and agglomeration. These imperfections can significantly impact the composite's mechanical properties, particularly its ductility and strength.

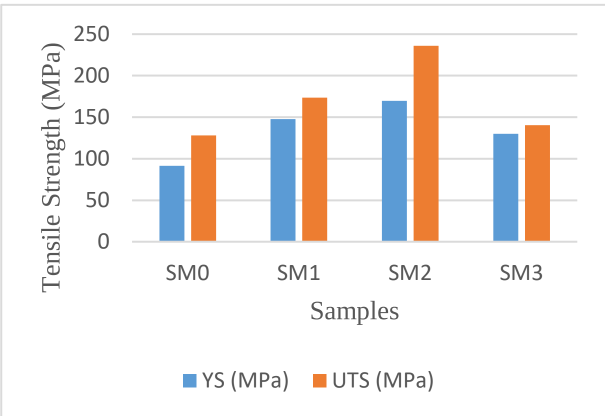


Fig.9: Variation in tensile strength of developed HMMCs

3.2. Tensile Strength

Figure 9 portrays the outcomes of tensile experiments conducted at room temperature, indicating how the weight percentage of reinforcing particles influences them.

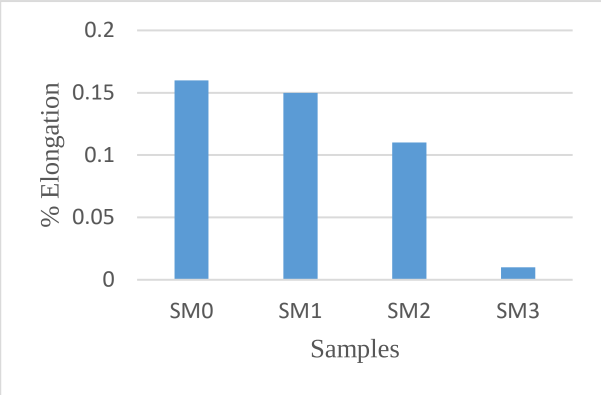


Fig. 10: The elongation of developed HMMCs exhibits variation

The data reveals that when the weight fraction of reinforcement particles reaches two weight percent of both Ni and Cr, the UTS and YS increase. An Al6061 matrix was strengthened by adding two weight percent of Ni and two weight percent of Cr particles, resulting in an impressive ultimate tensile strength of 236.08 MPa and yield strength of 169.87 MPa.The corresponding bar graph in Figure 10 demonstrates a steady decline in elongation upon adding Ni and Cr reinforcement particles to the Al6061 alloy. The increase in UTS and YS with adding Ni and Cr indicates improved strength properties. The decline in elongation suggests that, while the strength increased, the material's ductility decreased with higher concentrations of Ni and Cr. This trade-off between strength and ductility is an expected behavior in composite materials. This inverse relationship between elongation and particle content can be attributed to the rise in UTS and YS at higher particle concentrations.

The observed increase in ultimate tensile strength (UTS) and yield strength (YS) with the addition of Ni and Cr particles to the Al6061 matrix aligns with research findings that demonstrate improved mechanical properties through precipitation hardening of alloying elements and Ni-bearing dispersoid particles[37]. However, the accompanying decrease in elongation underscores the trade-off between strength and ductility, a characteristic behavior in composite materials. This inverse relationship can be traced back to the enhanced Cr diffusion towards the alloy surface and the formation of nickel-rich dispersoid particles, which contribute to the material's strength but reduce its ductility[38].

3.3 Flexural Strength

Figure 11 displayed that adding two wt.% of nickel and two wt.% of chromium to the Al6061 composite increases its flexural strength, thus improving its bending properties. However, further addition of these elements reduces the flexural strength of the composite[39]. This increase in flexural strength is attributed to the improved tensile strength resulting from the incorporation of nickel and chromium. Therefore, the newly formed composite can undergo more flexion and bear-induced stresses, making it more resistant to deformation and fracture. This enhanced performance is due to the improved tensile strength from incorporating these elements. An impressive flexural strength of 417.70 MPa has been achieved in a metal matrix composite (MMC) by combining only two weight percentages of Ni and Cr particles. This enhancement is attributed to improved ductile strength, making the composite more resistant to deformation and fracture. The improvement in flexural strength with adding two wt.% Ni and Cr align with the understanding that nickel improves thermal stability and mechanical properties at elevated temperatures, while chromium's effect predominantly affects the mechanical properties[40]. The enhanced bending properties and resistance to deformation and fracture can be attributed to the improved tensile strength resulting from these additions.

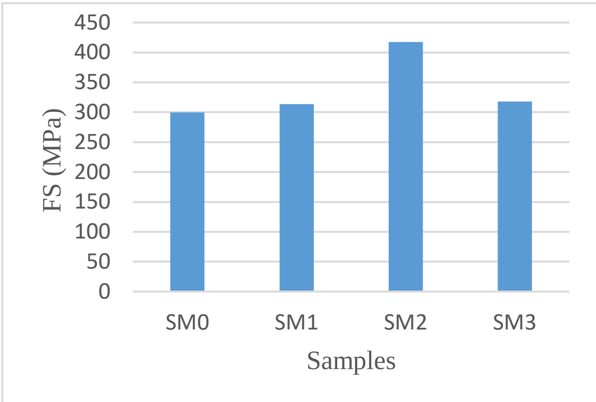


Fig.11: Variation in flexural Strength of developed HMMCs

3.4 Hardness

The hardness values in sample SM2 increase initially w.r.to base matrix Al6061 and then decrease, as shown in Figure 12. This phenomenon occurs because the Ni and Cr particles improve the crystallization of the composite material, enhancing its strength and hardness[41].

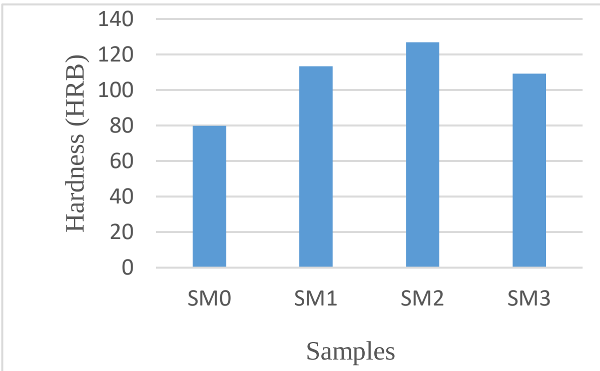


Fig.12: Variation on hardness of developed HMMCs

Additionally, the graphite particles in the composite material contribute to an increase in hardness by increasing its resistance against scratches and abrasions. This is because graphite is a solid lubricant with high resistivity against friction[42].

A remarkable achievement of attaining a hardness of 127.00 HRB has been observed in a Metal Matrix Composite (MMC) by introducing a mere two weight percent of each Ni and Cr particle, respectively. This is attributed to improved crystallization and the reinforcing effects of these elements. However, further additions might have led to a decline, possibly due to agglomeration. Therefore, incorporating this property in the composite material formed using Al6061 improves its hardness property. The observed increase in hardness values in sample SM2, followed by a decrease, is consistent with the findings that nickel and chromium additions improve the crystallization of the composite material, thereby enhancing its strength and hardness[43]. The role of graphite particles in increasing resistance against scratches and abrasions also contributes to this observed hardness. However, the decline in hardness with further additions could result from agglomeration, highlighting the need for careful optimization of these alloying elements.

4. Conclusions

This study explores the impact of adding Ni and Cr micro-particles to Al6061 alloy via stir casting, revealing significant enhancements in mechanical properties. SEM analysis demonstrates a uniform distribution of micron-sized Ni and Cr particles in Al6061/2 Ni/2Cr Hybrid Metal Matrix Composites. However, higher concentrations of these particles result in increased voids and agglomeration. EDS analysis confirms the presence of base Al material with reinforced Ni, Cr, magnesium (Mg), and graphite (Gr), added in specific proportions. Notably, integrating two wt.% each of Ni and Cr into the Al6061 alloy markedly improves its tensile strength (236.08 MPa), flexural strength (417.70 MPa), and hardness (127.00 HRB), surpassing the base alloy's performance. However, this enhancement in strength and hardness comes at the cost of reduced flexibility, especially in composites with three wt.% Ni and Cr, exhibiting minimal elongation (0.1%). The study suggests that Ni, Cr, Mg, and Gr are adequate reinforcements in hybrid composites where high mechanical strength and hardness are paramount without compromising wettability and self-lubrication. The findings of this study have significant implications for the design and application of Al6061-based HMMCs in various industries. These composites' enhanced strength, hardness, and reduced ductility make them suitable for applications with high wear resistance and strength, such as in aerospace, automotive, and industrial machinery components. However, the reduction in ductility should be a consideration in applications where flexibility and impact resistance are critical. Therefore, a careful balance between the reinforcement percentages and the desired material characteristics is essential for optimized performance.

Acknowledgment

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