Influence in Mechanical Behaviour of Tungesten Carbide (WC) and Coconut Shell Fly Ash (CSFA) Reinforced Al7075 Based Metal Matrix Composites

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Abstract: The development of advanced materials with superior mechanical properties has gained significant attention in engineering and industrial applications. Consequently, finding methods to use them that are both productive and environmentally safe has always been a hurdle for scientific applications. The aim of the study was to examine the mechanical properties of tungsten carbide (WC) and Coconut Shell Fly Ash (CSFA) reinforced aluminum matrix composites. The composites are synthesized using a stir-casting technique, ensuring uniform distribution of the reinforcements within the matrix. Mechanical properties, such as tensile strength, hardness, and impact resistance, are evaluated and compared to the unreinforced Al7075 alloy. The optimal reinforcement composition of 6 wt. % WC and 3 wt. % CSFA resulted in a maximum tensile strength of 157.38 MPa, representing a 30% increase over unreinforced Al7075. However, this enhancement was accompanied by a decrease in ductility, highlighting the trade-off between strength and ductility commonly observed in composite materials. Additionally, the impact energy reached a peak of 0.916 J/mm² at the same optimal composition, but further increases in reinforcement content led to a decline in impact energy due to micro-porosity. The Flexural strength improved from 61.5 MPa at 0 wt% of WC-CFSA to 92.1 MPa with 9 wt. % WC and 3 wt. % CSFA, same as the hardness of the composites also showed a significant increase, achieving a maximum value of 86.16 HRBwith 9 wt. % WC and 3 wt. % CSFA, attributed to improved load bearing capacity and reduced porosity. These findings emphasize the importance of optimizing reinforcement composition to enhance the mechanical properties of Al7075 composites.

Keywords: Hybrid aluminum matrix composites, Tungsten carbide (WC), Coconut shell flyash (CSFA), Stir casting process, Mechanical properties.

I. INTRODUCTION

Aluminium Matrix Composites (AMC) are used in advanced engineering applications such as automotive and aerospace industries and lightweight high strength applications to fulfill the emerging industrial requirements due to their good mechanical and tribological properties. Al7075 reinforced with B_4C composites produced by casting route showed the improvement in hardness and tensile properties [1-3]. Aluminum-based Metal Matrix Composites (Al-MMCs) have emerged in the late years as promising advanced technological materials giving elevated performance over bulk aluminum alloys [4]. Some of the applications of Al-MMC that are illustrated in Fig 1.

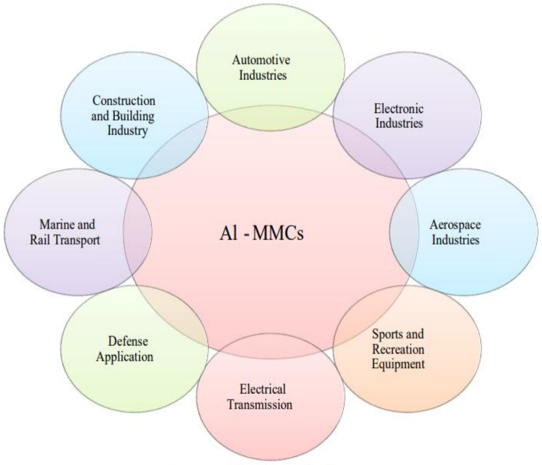

Fig 1. Application of Al-MMCs

Materials can be modified to enhance their mechanical properties through two primary methods: bulk alteration and surface alteration. In other words, to bring changes in mechanical properties and characteristics of material, user may go for methods like casting, heat treatment and cryogenic processing where the structure of the whole material is altered. These practices enable control over the material's organization at extremely small scale as to improve in strength, hardness, and durability. On the other hand, surface alteration is aimed at some sort of change in the properties of the surface layers of the material, which is intended to enhance its mechanical characteristics. In the present work, methods of diffusion, surface coating, and surface alloying, using atoms/molecules as well as layer-depositing techniques, have been applied to establish a surface layer with desired properties. In this way, bulk and surface modification treatments contribute to enhanced wear resistance, and corrosion, as well as improved general performance for utilization in different industries such as aerospace, automotive, and engineering [5-7]. The study systematically reveals that the incorporation of coconut shell ash (CSA) as a reinforce in aluminium alloys (Al) enhances a considerable improvement in its mechanical properties such as corrosion, friction, wear, and strength. This green hybrid material is particularly suitable for aerospace, automotive, marine, and industrial use [8]. The incorporation of coconut shell ash to aluminum alloys improves its mechanical properties of high corrosion protection, low rates of wear and high surface strength at low velocities [9]. The population increases the adverse effects of waste production because it has subjected human health and the environment to severe conditions. However, this problem is resolved by the innovative use of CSA, which eventually makes it an environmentally sound and cost-efficient approach. This process allows a long contact of liquid reinforcement with metal matrix, which results in interfacial reactions. Here are the potential researches objectives are:

1. Fabricate composites based on Al7075 with different contents of WC and CSFA by an appropriate method.
2. Analyze the microstructural properties, including the distribution and bonding of WC and CSFA within the Al7075 matrix.
3. Determine the tensile strength, hardness, impact strength and wear three types of composites.

The present study is useful in promoting material science to improve the mechanical properties of the Al7075-based MMCs reinforced with WC and CSFA. This unique method satisfies current trends, such as lightweight and high-strength materials that are suitable for aerospace, automotive, and structures. WC improves hardness and wears resistance while the effective and environmentally friendly and economical CSFA improves on the lightweight effect but still supplements the reinforcement effects. This present work identifies synergistic effects on tensile strength, hardness, and thermal stability by perfecting the ratio and distribution of these reinforcements. They are not only useful in providing a sustainable route to the formation of high performance MMCs but also provide deep insights into the design of the material as well as real life engineering applications.

II. LITERATURE REVIEW

The development of AMCs with various reinforcements has been extensively explored to enhance mechanical properties and material performance. Ahmad et al. investigated Al-7075/TiO2 MMCs with TiO2 concentrations ranging from 2% to 10% [10]. The optimal composition of 8% TiO2 demonstrated significant improvements in damping and flexural properties, with a maximum modulus of 98.9GPa at 25 °C. Microstructural analyses confirmed the uniform distribution of reinforcements and mechanical enhancements. Building on the improvements in AMCs, Prince et al. reinforced Al7075 with ZrB2 (2–8%) and a fixed 2% ZrC, achieving a 14% increase in hardness, 11% in tensile strength, and 13% in compressive strength [11]. These composites exhibited superior hardness (96 HRB), tensile strength (423MPa), and compressive strength (385MPa), demonstrating the synergy of dual reinforcements. Similarly, Bhowmik et al. introduced fly ash into Al7075, finding that increasing fly ash content raised porosity but enhanced micro-hardness (13.64%) and tensile strength (23.57%) at 9wt% fly ash [12].

Focusing on alternative reinforcements, Basavaraj and Bharat examined Al-SiC composites and observed that SiC improved hardness and impact strength, while coconut shell reinforcement adversely affected these properties [13]. Tensile strength was influenced by varying coconut shell ash content, highlighting the importance of reinforcement type. Nishanth B N et al. further optimized AMCs by incorporating Si3N4 into Al6082, achieving superior mechanical properties with 9 wt% Si3N4. SEM analyses revealed uniform reinforcement distribution and significant microstructure refinement [14].

Incorporating in situ techniques, Kumar et al. reinforced Al-Cu MMCs with TiC, achieving a 15% increase in yield strength and a 24% rise in ultimate tensile strength compared to the monolithic alloy [15]. Their findings emphasized the potential of in situ processes for enhancing material properties. Mathur et al. also highlighted the influence of manufacturing parameters, such as pouring conditions and sand melting points, on the mechanical properties of Al-SiC composites [16]. Advancements in manufacturing techniques were further explored by Thomas et al., who optimized the stir casting process for Al alloy (LM6)-SiC MMCs. Modified feeders and stirrers ensured uniform SiC distribution, significantly improving material homogeneity [17]. Similarly, Rebba et al. produced Al2024-MoS2 MMCs and observed enhanced tensile strength and hardness, with improved reinforcement distribution validated through optical micrographs [18].

Investigating hybrid reinforcements, Srikanth B. G et al. utilized WC (1–3%) and fly ash (2–6%) in Al6061 composites [19]. The optimal combination of 6% fly ash and 3% WC yielded the best mechanical properties, demonstrating the benefits of hybrid reinforcements. Aravindan et al. focused on Mg alloy (AZ91D)-SiC MMCs, where mechanical properties improved with higher SiC content but increased porosity. T6 heat treatment further enhanced the composites' performance [20]. Finally, Pradhan et al. explored Al-Fe aluminide MMCs, finding that these composites exhibited significantly improved mechanical properties compared to the base alloy [21]. This work underscored the potential of aluminide reinforcements in AMCs for achieving superior performance metrics

III. MATERIALS AND METHODS

Aluminium alloy 7075 or Al7075 has been chosen as the matrix material because of higher strength to weight ratio, better corrosion resistance, and more suitable for aerospace application. Aluminum of this grade has been purchased from SPECIAL METAL MART which is situated in Mumbai, India. Al7075 is lighter and further demonstrates better corrosion resistance than other aluminum grades because it contains Zn as the main alloying element. These aspects explain why manufacturing aircraft parts is most favorable with this kind of material [22]. The proportion of the compounds in Al7075 is contained in Table 1. The presence of the given ingredients offers added strength, preferred physical characteristics, and improved corrosion protection to Al7075.

Table 1: Chemical Composition of Al7075 Aluminum Alloy (wt. %)

Material	Zn	Mg	Cu	Si	Mn	Fe	Cr	Ti	Al
Weight	6.024	1.606	1.48	0.059	0.253	0.256	0.280	0.41	Remainder

III.1 Selection of Reinforcement Particles

However, in this present study, Tungsten Carbide (WC) and Coconut Shell Fly Ash (CSFA) have been used as reinforcement particles since they tender the required effects within the composite material [23]. WC as shown in figure 2 has been selected because of its high indexes of hardness and wears resistance which in turn plays a vital role in increasing the mechanical properties and the durability of the MMC.

On the other hand, CSFA, an environmentally friendly and cost effective by product, is introduced as filler which has property of reducing overall material density and minimizing formation of pore during stirring as depicted in figure 3 so as to maximize material integrity. The mean size of WC has been kept constant at 2 microns so that it can effectively distribute in the matrix and also increase mechanical reinforcement property of the composite material. The CSFA particles have a mean size of 62 microns, which have been found to eliminate large voids and enhance the particle bonding within the composite improving the structural homogeneity of the composite [24]. This overlap of reinforcements is expected to result in a synergistic reinforcement for a composite material with desirable mechanical properties for general use in demanding applications.

Fig 2. Tungsten carbide

Fig 3. Coconut shell fly ash

III.2 Fabrication methodology

The material processing technique chosen in this work has used stir casting as illustrated in figure 3& 4, a process ideal for developing hybrid composites. This method is preferential because it enables the achievement of an even dispersion of the reinforcement particles in the metal matrix to improve mechanical properties. Five different composite matrices have been produced by preparing different weight % of WC in the composite ranging from 0wt% to 9wt% in steps of 3wt% while keeping the CSFA weight % constant 3wt%. Consequently, the compositions of the composites have had Al7075 alloy weight percentages between 100% and 88%.

Table 2: Al7075 alloy weight percentage of WC and CSFA

Samples	Wt. % of Al7075	Wt.% of WC	Wt. % of CSFA	Cumulative wt% of WC+CSFA
1	100	0	0	0
2	97	0	3	3
3	94	3	3	6
4	91	6	3	9
5	88	9	3	12

The fabrication process has commenced with heating the Al7075 alloy to 800°C in a controlled furnace environment. This high temperature is critical to ensure that alloy is well molten and well mixed and ready for processing. At the same time WC and an iron-carbon alloy known as CSFA have been pre-heated to 250[°C] for a period of half an hour. This step is significant to accomplish in order to enhance the method because any remaining water will produce gas bubbles within the mould, which is undesirable for the cast produced. To further improve the quality of the molten material scum powders that have been added to avoid formation of slags which brings in impurities which act as deterioration of the composite structure. After all the aluminium has entirely liquefied and achieved a uniform structure, the reinforcement particles (WC & CSFA) are then added. For the purpose of the experiment, continuous stirring has been conducted at 800 rpm to enhance the distribution of the reinforcement particles with the matrix. After the next phase, the so obtained mixture is heated at a temperature above 800°C for 15 minutes. This supplementary heating results in increased interfacial adhesion between the aluminium matrix and the reinforcement particles thus leading to improved mechanical properties of the developed composite. Last but not least, the molten blend has been poured into dies to make specimens for mechanical tests and the results obtained are invaluable to assess the performance of the material under changing loads. It has been established that this high-velocity fabrication process has facilitated the production of new hybrid composites that boast of improved mechanical characteristics that can favorably be deployed across a myriad of industries with emphasis being laid on aerospace as well as automotive industries. This work has offered an insight into the improvement of performance characteristics of metal matrix composites to future research on actual application of advanced materials.

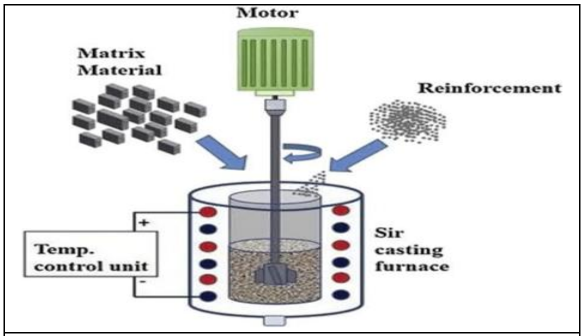

Fig 4. Schematic diagram of stir casting process

Fig 5. Stir casting setup for synthesizing aluminum 7075 based hybrid composites

III.3 Preparation of Sample

The casting process was followed by the pouring of molten aluminum into split open cast iron (C.I) dies where the later solidified. After the formation of aluminum alloy, the diese ejected the castings and aluminum alloy get ready for other use. Then the cast components were checked and the sizes as well as the surface finishes of the components were ensured. As shown in figure 6, 7 and 8 the resulting components demonstrated the desired shape and quality, underscoring the effectiveness of the casting process.

Fig 6. Tensile test specimen

Fig 7. Impact test specimen

Fig 8. Hardness test specimen

III.4 Testing

A comprehensive insight into the material's mechanical behaviour of materials is crucial, as it helps predict their performance in real-world applications, ensures safety and reliability, and informs design choices in engineering. Therefore, mechanical properties of prepared specimens have been thoroughly analyzed through a detailed series of tests performed at ambient temperature, which included evaluations of hardness, tensile strength, and impact resistance. Tensile tests were performed using a universal testing machine (UTM), with specimens meticulously prepared in accordance with ASTM E 8M standards as shown in figure 9.

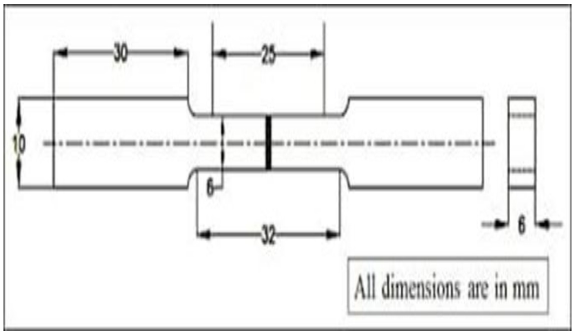

Fig 9. Standard tensile test specimen

Each test was repeated three times to establish average values for tensile strength, and elongation at break, thereby ensuring both reliability and accuracy. Understanding these properties is essential, astensile strength indicates the maximum stress a material can withstand, and elongation reflects ductility. Such information is crucial for selecting materials for various applications, particularly in industries like construction and aerospace, where performance and safety are paramount.

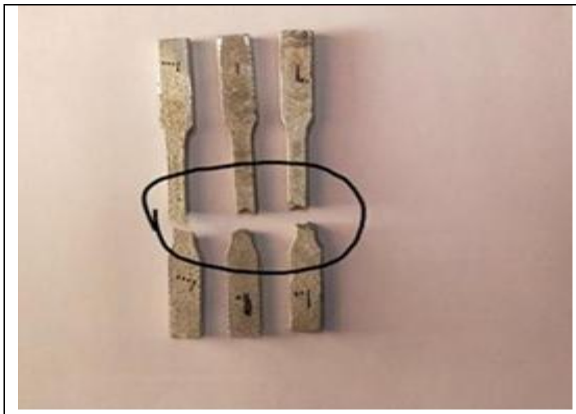

Fig 10. Tensile test specimen after testing

Fig 11. Tensile test specimen before testing

Charpy impact test has been conducted to evaluate the impact resistance of the specimens, with three tests performed for each sample to obtain average impact values. This analysis yielded valuable insights into the material's toughness and susceptibility to brittle fracture, which are crucialfor applications subjected to sudden impacts, such as in construction and automotive industries.

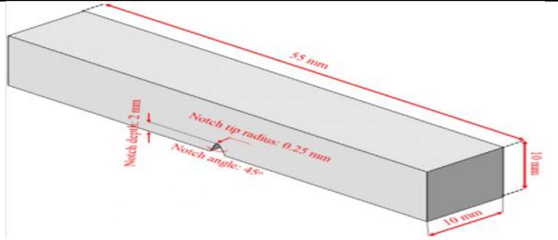

Fig 12. Standard impact test specimen

Fig 13. Impact test specimen before testing

Fig 14. Impact test specimen after testing

Hardness of these specimens has been assessed using a Rockwell hardness testing machine, following ASTM standards. Each specimen underwent three indentations to guarantee precise average hardness values and to assess its resistance to deformation.

Fig 15. Hardness test specimen after testing

Fig 16. Rockwell hardness testing machine

IV. RESULTS AND DISCUSSIONS

IV.1 Tensile Strength

A graphical representation of the relationship between tensile strength and WC-CSFA weight percentage is illustrated in Figure 17. The UTS of the pure Al7075 alloy was recorded at 121.15MPa. This serves as the baseline strength for comparison. Adding 3% CSFA alone (Al7075 – 97 sample) increased the UTS slightly to 128.34MPa. This moderate increase suggests that the addition of CSFA alone has a strengthening effect on the alloy. Introducing WC at 3% along with 3% CSFA (Al7075 – 96 samples) raised the UTS further to 136.07MPa. This implies that WC has a significant impact on the load-bearing capacity of the alloy due to its inherent hardness and reinforcement effect. At 6% WC with 3% CSFA (Al7075 – 91 sample), the UTS reached its highestvalue of 157.38MPa, indicating an optimal level for maximum tensile strength. This may be due to an ideal dispersion of WC particles, enhancing strength through effective load transfer. However, when WC content was increased to 9% (Al7075 – 88 sample), the UTS slightly decreased to 141.66MPa. This reduction might suggest that excessive WC content could lead to particle agglomeration, reducing the composite's ability to transfer stress effectively across the matrix.

The combined presence of CSFA and an optimized

WC weight percentage creates a synergistic strengthening effect, significantly enhancing the composite material's load-bearing capacity. This trend emphasizes the critical role of carefully optimizing reinforcement composition to fully capitalize on the mechanical advantages offered by these particles.

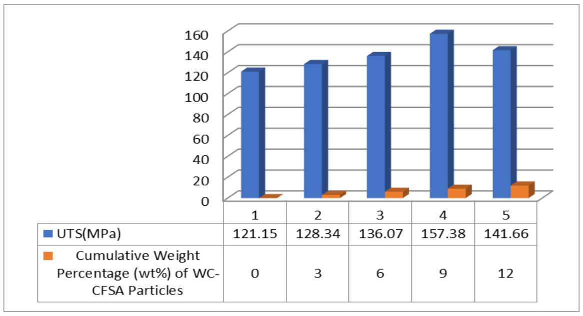

Fig 17. Variation of tensile strength of hybrid composites

IV.2 Percentage Elongation (% Elongation)

Graphical representation of the relationship between percentage elongation and WC-CSFA weight percentage is illustrated in Figure 18. The % elongation of the base Al7075 alloy was 6.46%, indicating its relatively good ductility. As WC content increased, % elongation decreased, falling to 5.32% for Al7075 – 97 (3% CSFA only) and further reducing to 5.01% with the addition of 3% WC (Al7075 – 96). At higher WC contents (6% and 9%), % elongation dropped even further, reaching 4.76% and 3.93% for Al7075 – 91 and Al7075 – 88 samples, respectively. This inverse relationship between WC content and elongation indicates that as more rigid WC particles are added, the alloy becomes less capable of stretching before fracture. This reduced ductility is a common effect in particle-reinforced composites, as rigid particles restrict the plastic deformation of the aluminium matrix.

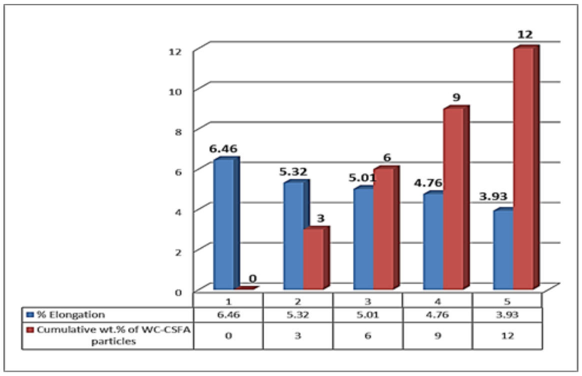

Fig 18. Variation of % Elongation of hybrid composites

IV.3 Impact Strength

Impact strength, which reflects the material's ability to absorb energy, was initially 0.605 J/mm² for the unmodified Al7075. Adding 3% CSFA alone slightly increased impact strength to 0.657 J/mm² (Al7075 – 97), likely due to the fibrous reinforcement's role in energy dissipation. With a 3% addition of WC alongside CSFA (Al7075 – 96), impact strength rose to 0.756 J/mm², demonstrating the beneficial effects of WC in enhancing the composite's resistance to sudden forces. The impact strength continued to rise with further WC additions, reaching 0.825 J/mm² for Al7075 – 91 (6% WC) and peaking at 0.916 J/mm² with 9% WC (Al7075 – 88). This progressive increase suggests that WC particles help absorb impact energy by enhancing the toughness of the composite, possibly through mechanisms such as crack deflection and energy dissipation within the matrix-reinforcement interface. Graphical representation of the relationship between impact energy and WC-CSFA weight percentage is illustrated in Figure 19.

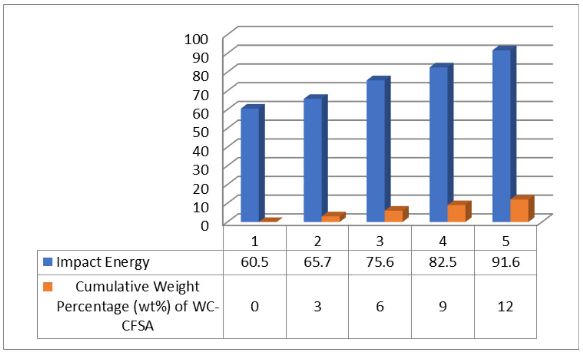

Fig 19. Variation of impact strength of hybrid composites

IV.4 Flexural Strength

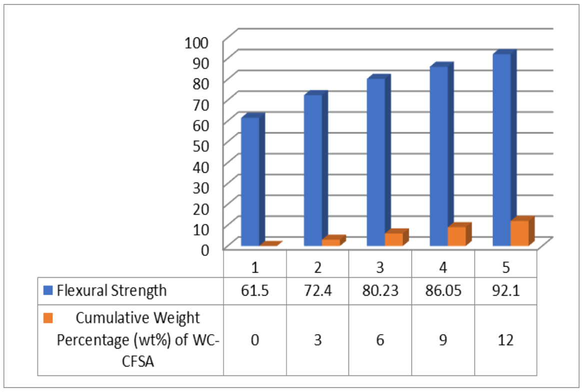

Fig. 20 Flexural Strength (FS) vs. Cumulative Weight Percentage (wt%) of WC-CFSA Particles

Figure 20 shows the relationship between the cumulative weight percentage (wt%) of WC-CFSA particles and the flexural strength (FS) of the material. It demonstrates a linear increase in flexural strength as the wt% of WC-CFSA particles increases. The flexural strength starts at approximately 61.5 MPa when the WC-CFSA content is 0% and reaches around 92.1 MPa at 12 wt%. This trend indicates that adding WC-CFSA particles significantly enhances the flexural strength of the material, highlighting their effectiveness as a reinforcement component in the composite.

IV.5 Hardness (HRB):

The hardness of the base Al7075 alloy was recorded at 74.66 HRB. With the addition of 3% CSFA (Al7075 – 97), the hardness increased to 76.16 HRB, suggesting a minor strengthening effect. With the inclusion of 3% WC (Al7075 – 96), hardness increased further to 78.16 HRB, indicating that WC particles effectively reinforce the matrix, likely through obstructing dislocation movement. At 6% WC content (Al7075 – 91), hardness reached 82.16 HRB, and the highest hardness value, 86.16 HRB, was observed at 9% WC (Al7075 – 88). This trend reflects the hardening effect of WC, as higher concentrations of these hard particles increase resistance to indentation. The presence of CSFA may also contribute slightly by distributing load, but WC appears to be the primary contributor to hardness improvement. The incorporation of WC and CSFA particles into the aluminium matrix played a pivotal role in enhancing hardness. Notably, the combined reinforcement of 12wt% WC and CSFA particles achieved a peak hardness of 86.16 HRB. Graphical representation of the relationship between Hardness and WC-CSFA weight percentage is illustrated in Figure 21.

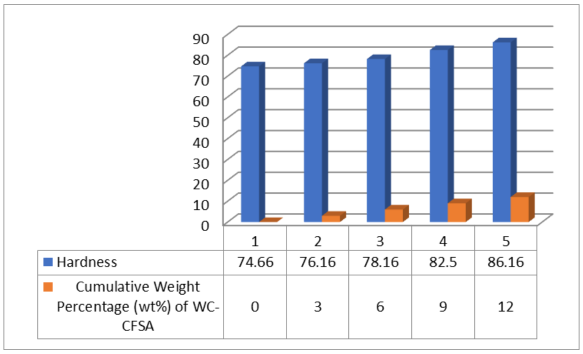

Fig 21. Variation of Hardness of hybrid composites

These findings highlight the potential of WC and CSFA as effective reinforcements for improving the mechanical properties of aluminium composites, suggesting expanded applicability across various industries.

The results for tensile test, % elongation, impact strength and hardness have also been presented in table 3. Furthermore, this study underscores the importance of optimizing both the content and distribution of reinforcement particles to achieve target mechanical properties. The results indicate that a well-controlled addition of WC and CSFA can lead to substantial improvements in hardness, strength, and impact resistance, making these composites suitable for applications where enhanced mechanical resilience is required.

Table 3: Mechanical properties of Al7075 alloy with varying weight percentage of WC and constant3 wt. % of CSFA particulates

Sample no.	Ultimate tensile test(MPa)	% Elongation	Impact Strength J/mm^2	Hardness (HRB)	Flexural Strength
Al 7075 – 100	121.15	6.46	0.605	74.66	61.5
Al7075 – 97 WC-0 / CSFA-3	128.34	5.32	0.657	76.16	72.4
Al7075 – 96 WC-3 / CSFA-3	136.07	5.01	0.756	78.16	80.23
Al7075 – 91 WC-6 / CSFA-3	157.38	4.76	0.825	82.16	86.05
Al7075 – 88 WC-9 / CSFA-3	141.66	3.93	0.916	86.16	92.1

V. CONCLUSIONS

The study of WC and CSFA reinforced Al7075-based metal matrix composites highlights their significant influence on mechanical behavior. The incorporation of WC contributes to enhanced hardness, wear resistance, and strength due to its high hardness and rigidity, while CSFA offers improved lightweight characteristics and cost-effectiveness, acting as a sustainable alternative to conventional reinforcements. The following results are:

The incorporation of WC and CSFA reinforcement particles significantly enhanced the tensile strength of Al7075 composites. Notably, the optimal composition of 6 wt. % WC and 3 wt. % CSFA yielded a maximum tensile strength of 157.38MPa, representing a remarkable 30% increase compared to unreinforced Al7075. However, the ductility of the composites exhibited a decreasing trend with increasing weight percentages of reinforcement particles. This trade–off of strength for ductility is as expected since inclusion of hard reinforcement particles generally leads to improved mechanical strength but at the same time reduce the ductility.

It was found that the impact energy of Al7075 composites increases with the reinforcement content due to the combined contribution of WC and CSFA particles. The desired weight percentage ratio of 6%WC and 3%CSFA resulted to average impact energies of 0.916 J/mm². However, the effect of further addition of reinforcement particles beyond this concentration was found to reduce impact energy. These composites experience a decline in impact resistance because the introduction of micropores increases with the rise in reinforcement contents which may act as stress concentrators. This study is important as it reveals that there is need to work on the reinforcement content for intensive impact energy improvement in Al7075 composites.

The results revealed that the reinforcement stratification of Al7075 composites was directly proportional to the extent of increase of the overall hardness of the matrix. More significantly, the measured maximum hardness of the composite containing 9 wt. % of WC and 3 wt. % of CSFA was 86.16 HRB. The addition of WC-CFSA particles has shown substantial improvements in the flexural strength of the system where the strength increases progressively with the cumulative weight percentage. Flexural strength improved from 61.5 MPa at 0 wt% of WC-CFSA to 92.1 MPa at 12 wt%. In that case, the composite should have markedly improved its mechanical properties, and its strength maximally occurred at 12 wt%. This trend emphasizes that the WC-CFSA particle distribution and bonding played a critical role in getting superior mechanical performance. The experimental results confirm that the introduction of WC-CFSA particles is an effective means of enhancing the mechanical strength of materials, making them suitable for applications requiring more durability and resilience. This optimal hardness can be credited to the improvement of load-bearing capability and, conversely, reduced porosity. In conclusion, it is established that the inclusion of WC and CSFA into Al7075 increases tensile strength, impact strength, and hardness of Al7075. However, the problem is a loss of ductility, and the maximum mechanical advantages reach are at 6% of WC. Other than this peak, tensile strength gets to reduce with increasing concentration, perhaps through particle agglomeration and inefficient stress transfer among the constituting particles.

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