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Characteristic Studies of Duralumin with the Reinforcement of Titanium Carbide and Graphite using Powder Metallurgical Method

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Abstract:
This paper focuses on the synthesis of duralumin, an aluminum-copper alloy, using recycled materials such as automobile scrap for aluminum and waste wires for copper. Duralumin is well-known for its exceptional strength-to-weight ratio, making it ideal for applications in aerospace and automotive industries. The project highlights the use of sustainable recycling practices by repurposing aluminum and copper from end-of-life vehicles and electrical waste. This approach reduces energy consumption by approximately 95% compared to producing primary aluminum, promoting environmental sustainability and resource conservation.
The synthesized duralumin is reinforced with Titanium Carbide (TiC) and Graphite (Gr) powders, forming an aluminum matrix composite (AMC). The incorporation of these reinforcements enhances the material's properties, including wear resistance, hardness, and thermal stability, making the composite suitable for high-performance applications. Friction Stir Processing (FSP) technique is applied to ensure uniform distribution and proper interfacial bonding of the reinforcements within the duralumin matrix. This process refines the microstructure, promoting grain refinement and enhancing mechanical properties such as strength and ductility.
Through this research, a sustainable method for producing high-strength duralumin composites is demonstrated. The outcomes include significant waste reduction, energy savings, reduced production cost and the synthesis of an environmentally friendly material that can be widely applied in industries requiring lightweight and durable materials. This research contributes to advancing the field of metal matrix composites while supporting circular economy principles.

***Keywords*: Duralumin, Reinforcement, Metal Matrix Composites, Recovery of Scrap Materials.**

INTRODUCTION:

1.1 Duralumin:

Duralumin is an aluminum-based alloy primarily composed of aluminum (about 90 – 95 wt %) and copper (around 4 – 5 wt %). This was first developed in the early 20th century and is known for its excellent combination of lightweight properties and strength, making it highly suitable for aerospace and automotive applications. One of the standout characteristics of duralumin is its high strength-to-weight ratio, which allows for reduced weight without compromising on structural integrity. This is especially important in industries where weight reduction plays a critical role, such as in aerospace, automobile manufacturing, and marine engineering. For instance, in the aviation industry, duralumin is used in aircraft fuselage, wings, and other structural components to enhance fuel efficiency while ensuring durability. The key advantage of duralumin is its workability. It can be easily formed, machined, and welded into different shapes, allowing for versatile design and manufacturing processes. However, duralumin is typically aged or heat-treated to enhance its strength, a process that precipitates copper and other alloying elements, increasing its mechanical properties. In terms of strength, duralumin, after aging or proper treatment, achieves tensile strengths up to 450 MPa, making it significantly stronger than pure aluminum [2].

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1.2 Recycling of Components from Automobile Scraps:

Automobile scrap serves as a major source of aluminum. Vehicles, particularly cars and trucks, contain significant amounts of aluminum in various components, including engine blocks, wheels, body panels, and frames (Refer Fig 1). As vehicles reach the end of their life cycle, these aluminum-rich parts can be recycled and repurposed instead of being discarded in landfills. Aluminum from automotive scrap is typically separated during the scrap metal recycling process, where old vehicles are crushed and shredded. The aluminum is then recovered, melted, and purified, making it an ideal raw material for the synthesis of duralumin. Recycling aluminum requires only about 5% of the energy used in producing primary aluminum from bauxite, making this method highly energy-efficient and environmentally friendly. On the other hand, copper can be obtained from waste wires, which are commonly found in discarded electronic devices, electrical systems, and wiring infrastructure (Refer Fig 2). Waste wires are stripped of their insulation and subjected to a recycling process where the copper is recovered, refined, and melted. This copper can then be used in the synthesis of duralumin. By using copper from waste wires, the need for mining new copper is reduced, further supporting sustainable resource management.

Fig 1: Alloy Wheel from Automobile Scrap

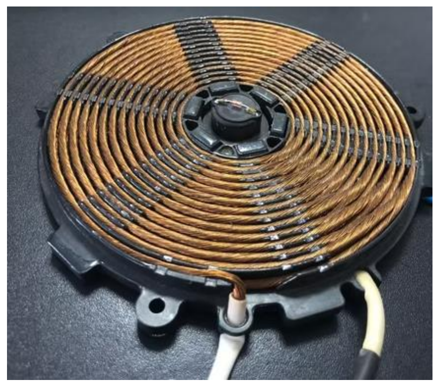

Fig 2: Waste Wires from Scrap Induction Stove

1.3 Metal Matrix Composites (MMCs):

Metal Matrix Composites (MMCs) are advanced materials that consist of a metal or alloy as the matrix phase, embedded with the reinforcements like ceramics or fibers. These reinforcements provide enhanced properties such as increased strength, stiffness, wear resistance, and thermal stability compared to the base metal. The combination of metal matrices with strong, high-performance reinforcements creates composites that are different from the properties of base metals, including capable of withstanding extreme conditions and finds applications in wide range of sectors.

1.4 Aluminum Matrix Composites (AMCs):

Among various MMCs, Aluminum Matrix Composites (AMCs) have gained significant attention due to aluminum’s lightweight and corrosion-resistant properties. In AMCs, aluminum or its alloy serves as the base matrix, and materials like ceramics (e.g., silicon carbide, titanium carbide, aluminum oxide) or carbon-based reinforcements (e.g., graphite, carbon nanotubes) are added to improve mechanical and physical characteristics of aluminum. AMCs exhibit enhanced properties such as higher specific strength, hardness, wear resistance, and thermal stability while maintaining aluminum's lightweight nature. The key advantage of AMCs is their ability to provide superior strength-to-weight ratios compared to conventional aluminum alloys, making them ideal for weight-sensitive applications like aircraft structures and automotive components. For instance, aluminum composites reinforced with ceramics (like TiC or SiC) demonstrate exceptional wear and abrasion resistance, while the inclusion of graphite enhances self-lubricating properties, reducing friction in moving parts.

1.5 Friction Stir Processing (FSP):

Friction Stir Processing (FSP) is a solid-state processing technique that plays a crucial role in enhancing the properties of materials, particularly in the synthesis of advanced composites. FSP involves a rotating tool that is plunged into the material surface, generating frictional heat and mechanical stirring without melting the base material. This unique approach allows for the effective distribution of the reinforcements within the base matrix.

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One of the primary advantages of FSP is its ability to refine the microstructure of the composite. This microstructural refinement is essential for achieving higher strength and improved ductility, as smaller grain sizes often correlate with superior mechanical performance. Additionally, FSP enhances the homogeneity of the composite by ensuring a uniform distribution of reinforcement particles throughout the matrix material. This uniformity is critical for optimizing the mechanical properties, including hardness and tensile strength. The schematic representation of FSP is shown in Fig 3.

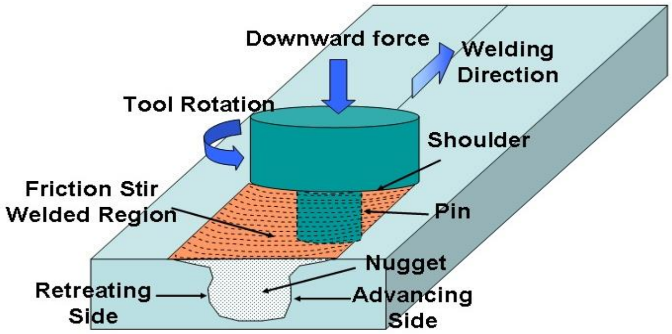

Fig 3: Schematic Representation of Friction Stir Processing

In this research, Duralumin is synthesized by extracting its primary components: aluminum and copper from automobile scrap and waste wires respectively. This approach not only promotes the recycling of valuable materials but also aligns with sustainable engineering practices aimed at minimizing environmental impact. By synthesizing duralumin from these recycled sources, this project contributes to waste minimization and the circular economy. This process not only diverts significant amounts of waste from landfills but also reduces the demand for virgin raw materials, leading to significant energy savings and carbon emission reductions.

RESULTS AND DISCUSSIONS:

Methodology:
Automobile wheel scrap is collected and is washed thoroughly to remove the adhering sand and dirt. This cleaned wheel is subsequently cut into small pieces to facilitate melting process. Copper wire is taken from the scrap induction stove components. Aluminium and copper are taken in the weight percentages of 95.5 and 4.5 respectively for the synthesis of Duralumin. To compensate the shrinkage during the melting process, additional 1wt% of aluminium and copper are taken. Now, the cut aluminium pieces are melted in a furnace at 560°C, followed by the melting of copper wires at 1080°C (Refer Fig 4). The molten aluminium and copper are poured into a mold of required dimensions. This molten duralumin is grinded with a grinding machine to polish the duralumin surface. Three holes are drilled on one face of the grinded duralumin at a uniform diameter and distance (Refer Fig 5).
Two different proportions of titanium carbide and graphite are taken. In the first trial, 90 wt% of TiC and 10 wt% Gr and in the second trial, 70 wt% TiC and 30 wt% Gr are taken. For the blending of TiC and Gr nanopowders, these nanopowders are taken in the respective trial proportions and are blended with the help of ethanol as a binder, which is taken in the powder: binder ratio of 1:2 [1]. These blended nanopowders are dried in a muffle oven at 100°C to remove the ethanol and moisture content. These nanopowders are then inserted into a die of required dimension with respect to the holes size on the duralumin surface. This is compressed at a pressure of 250 MPa for strong binding of nanopowders. This compacted powder is then sintered at a temperature of 3000°C for the fusion of nanopowders and finally inserted into the holes on the duralumin surface. FSP is carried out for the uniform distribution of reinforcement powders on the duralumin surface (Refer Fig 6). Both the trials of duralumin are subjected to rotational speed of 500 rpm and a traverse speed of 20 mm/min.
Characterization test such as SEM and EDX are done for analyzing the distribution and the composition of reinforcement powders on the surface. Mechanical tests such as thermal conductivity, electrical conductivity, impact strength and hardness test and are carried out.

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Fig 4: Melting of Al & Cu

Fig 5: Drilled Specimen

Fig 6: Reinforced Specimen

CHARACTERIZATION ANALYSIS:

Scanning Electron Microscopy (SEM) analysis is carried out to evaluate the distribution, bonding, and microstructural changes introduced by the reinforcement of TiC and Graphite nanopowders. The SEM image of the Duralumin revealed a relatively smooth matrix with visible grain boundaries and few casting defects. Furthermore, the microstructure appeared significantly densified, with reduced porosity and enhanced particle-matrix interfacial bonding. Fig 7 shows the SEM analysis of Duralumin at a magnification of 400 µm.

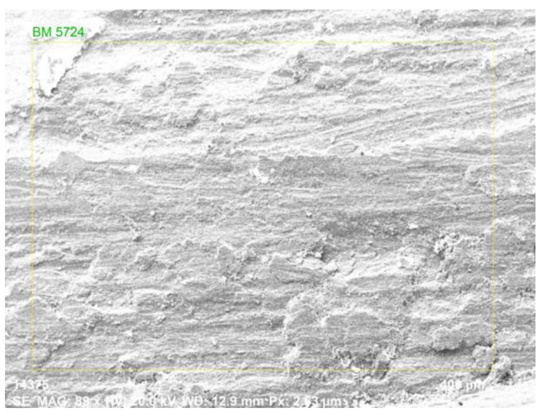

Fig 7: SEM Analysis of Duralumin

Energy Dispersive X-ray Spectroscopy (EDX) analysis is carried out to confirm the elemental composition and successful incorporation of base matrix and reinforcement particles. The spectra collected from various regions of the composite consistently showed the presence of aluminium (Al), Graphite (C), and Titanium Carbide (Ti), validating the integration of both Graphite and Titanium Carbide nanopowders. In all scanned zones, aluminium remained the dominant element, confirming the continuity of the Duralumin matrix. The presence of carbon, with normalized weight percentages exceeding 30% indicates a significant contribution as a soft lubricant. Titanium Carbide is also consistently detected across all regions, although in smaller quantities due to its relatively lower proportion in the TiC/Gr reinforcement blend (70 wt% TiC).

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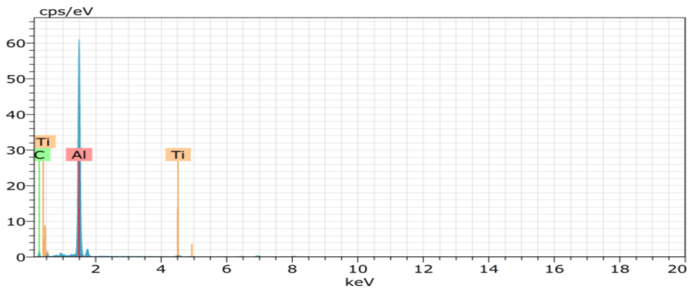

Fig 8: EDX Analysis of Duralumin + 70%TiC + 30% Gr

The elemental consistency across multiple scan points suggests a uniform distribution of reinforcement particles due to FSP. The detection of both reinforcement elements in the matrix and without excessive clustering – supports the effectiveness of the powder compaction and FSP stages. Overall, the EDX analysis confirms the successful embedding and homogeneity of TiC and Graphite within the Duralumin composite.

MECHANICAL TESTS:

The variation in density is measured by the conventional formula, which is the ratio of mass to volume of specimen. The measurement of density is carried out at room temperature conditions. It is observed that the increase in density is very small due to the addition of nanopowders. This satisfies the original property of duralumin, i.e less weight but more strength.

Porosity is a measure of void spaces present and can be measured by Archimedes' method which is the ratio of difference between theoretical density and measured density to the theoretical density of the specimen. During the process of sintering, voids may be formed within the composite and evaluating these void spaces help to determine how the reinforcements are integrated. It is observed that the porosity increases with an increase in the weight percentage of the TiC nanoparticles and this is in accordance with the literature [5]. High levels of porosity can significantly weaken the composite, leading to reduced tensile strength, ductility, and overall durability.

Hardness test is carried out to both duralumin and reinforced duralumin. This value is measured by compaction of hard indenter onto the specimen surface and observing the resistance to deformation. Rockwell test (HRC) is done on the specimen with the diamond shaped indenter. This indenter applies a force of 150 kgf on the specimen surface and measures the specimen's hardness. It is observed that the increase in graphite content significantly reduces the hardness value. Since graphite is a soft solid lubricant and it has weak Vander Waals force, graphite could not bear the hardness. It is also observed that the increase in TiC content increases the hardness of the specimen. According to a literature, it is evident that the increase in TiC is responsible for the increase in hardness value [3]. The hardness value for duralumin ranges between 70-76 HRB.

Thermal conductivity represents the ability of the specimen to conduct heat and is measured by heating the specimen with a known amount of heat source and measuring the input and output temperature of the specimen. The thermal conductivity of duralumin and reinforced duralumin are measured to be 140, 128 and 120 W/m°C respectively. This test is carried out at room temperature condition and the temperature difference is observed to be 0.8°C. According to a literature, the thermal conductivity of duralumin ranges between 130-190 W/m°C [4]. Thermal conductivity of material used in aerospace industry should be moderate. This is because increased thermal conductivity may affect the flight electronics system. This is important for better heat dissipation and prevents hot spots.

Electrical conductivity of the specimen is measured by passing a known amount of current and measuring the voltage drop across the specimen. The electrical conductivity of duralumin and reinforced duralumin are measured to be 27.25, 36.7 and 41.57 MS/m respectively. This test is carried out at room temperature condition and the voltage drop is observed to be 0.28V. The electrical conductivity should be high especially for materials used in aerospace industry. Airplanes often encounter lightning strike on the fuselage and the increased electrical conductivity represents the distribution of electrons on the surface. According to literature, the electrical conductivity of duralumin ranges between 34 – 50% IACS [4].

Compressive strength is measured by compressing the specimen at a high pressure and is a measure of maximum stress that the specimen can bear before the point of breaking. According to literature, the compressive strength of duralumin ranges between 190 – 480 MPa [4]. The consolidated mechanical test results of the specimens are given below:

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Tests	**Duralumin**	**Duralumin + 90% TiC + 10% Gr**	**Duralumin + 70%TiC + 30% Gr**
Density (g/cm^3)	2.67	2.95	2.9
Porosity	0.011	0.0167	0.017
Hardness (HRB)	77	91	83
Thermal conductivity (W/(m°C))	140	128	120
Electrical conductivity (MS/m)	27.25	36.736	41.57
Compressive strength (MPa)	450	650	550

CONCLUSION:

This project is focused on the improvement in mechanical properties with the reinforcement of titanium carbide and graphite nanopowders. Notable improvement is observed in the reinforced duralumin when compared with duralumin. As this project is also focused on the recycling of scrap automobiles and electronic components, the purchase cost of reinforced duralumin is compensated. With the reinforcement of duralumin, improved strength, reduced weight, and increased wear and tear resistance can be achieved. The purchase cost of titanium carbide and graphite can be compensated by the recycling of scrap automobiles and electronic components. As discussed earlier, graphite acts as a soft lubricant and TiC provides the hardness and improves wear resistance. From the mechanical tests, it is cleared that the use of graphite should be reduced due to its reduced hardness and the use of TiC should be promoted due to its excellent strength and wear resistance. Depending on the area of application, different proportions of TiC and Gr can be used.

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