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Article

Development and Characterization of Sustainable Al6061–Bone Ash Bio-Composites for Metal Additive Manufacturing

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Abstract: Metal matrix composites (MMCs) have attracted increasing interest in advanced manufacturing because of their high specific strength, lightweight characteristics, and potential for engineering applications. The development of sustainable reinforcement materials has become an important research direction for improving the performance of aluminium-based composites while reducing dependence on conventional reinforcement materials. In this study, Al6061 alloy reinforced with bone powder was developed using the powder metallurgy technique to investigate the influence of bio-derived reinforcement on the mechanical and wear-related properties of the composite. Composite specimens containing different weight percentages of bone powder were prepared through controlled powder mixing, compaction, and sintering processes. The fabricated specimens were experimentally evaluated through hardness, compressive strength, and wear tests to establish the relationship between reinforcement content, processing conditions, and material performance. The obtained experimental results were analysed to identify the influence of bone-powder reinforcement on the measured properties and to determine the most suitable reinforcement condition. The generated experimental dataset also provides a foundation for the application of artificial intelligence and machine-learning techniques for predicting material behaviour and identifying suitable processing conditions in future studies. The developed bio-reinforced Al6061 composite therefore demonstrates potential as a sustainable material for advanced engineering applications and provides a basis for future data-driven material development and optimization. Key words: Al6061 Alloy, Bone Powder, Powder Metallurgy, Metal Matrix Composite, Mechanical Characterization, Sustainable Materials, artificial intelligence; Machine learning; Material optimization Powder Feedstock, Metal Additive Manufacturing.
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1. INTRODUCTION:

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The increasing demand for lightweight, high-strength, and environmentally sustainable materials has encouraged researchers to develop advanced metal matrix composites (MMCs) for engineering applications. Among the available aluminium alloys, Al6061 has gained considerable attention because of its excellent strength-to-weight ratio, corrosion resistance, good machinability, and weldability. Owing to these characteristics, Al6061 is extensively used in aerospace, automotive, marine, and structural applications where weight reduction and mechanical performance are equally important.

The properties of Al6061 can be further improved by incorporating suitable reinforcement materials. Conventional ceramic reinforcements such as silicon carbide (SiC), aluminium oxide (Al_2O_3), and boron carbide (B_4C) have been widely investigated because they significantly improve hardness, wear resistance, and strength. However, the high cost of these materials and the growing emphasis on sustainable manufacturing have motivated researchers to explore alternative bio-based reinforcements. Agricultural waste, industrial by-products, and naturally available materials have attracted considerable interest due to their low cost, environmental benefits, and availability.

Bone powder is one such bio-derived reinforcement material that contains calcium phosphate compounds and possesses good hardness and wear-resistant characteristics. In addition to providing an effective utilisation route for biological waste, bone powder offers the possibility of improving the mechanical behaviour of aluminium matrix composites while supporting sustainable material development. Therefore, the use of bone powder as a reinforcement material has emerged as an attractive research area for developing lightweight and environmentally friendly engineering materials.

Powder metallurgy is a well-established manufacturing process for producing aluminium matrix composites with uniform reinforcement distribution and improved microstructural control. Compared with conventional casting techniques, powder metallurgy minimises material wastage, improves dimensional accuracy, and reduces segregation of reinforcement particles. These advantages make it suitable for developing advanced composite materials with enhanced mechanical properties.

Recently, powder-based manufacturing technologies have gained significant attention with the rapid growth of Metal Additive Manufacturing (MAM). Processes such as Laser Powder Bed Fusion (LPBF), Selective Laser Melting (SLM), Directed Energy Deposition (DED), and Binder Jetting rely on high-quality powder feedstock materials with consistent physical and mechanical characteristics. Consequently, there is increasing interest in developing sustainable composite powders that can satisfy future requirements of advanced manufacturing technologies.

Although several studies have investigated Al6061 composites reinforced with ceramic and natural materials, limited research has focused on the mechanical performance of Al6061 reinforced with bone powder produced through powder metallurgy. Furthermore, the potential of such sustainable composites for future powder-based additive manufacturing applications has received relatively little attention.

Therefore, the present study investigates the development of Al6061–bone powder metal matrix composites using the powder metallurgy technique. The fabricated composites were evaluated through hardness, compression, and wear tests to examine the influence of bone powder reinforcement on mechanical performance. In addition, the study discusses the potential of the developed composite as a sustainable material for future powder-based Metal Additive Manufacturing applications. The findings are expected to contribute to the development of lightweight, sustainable, and high-performance engineering materials for next-generation manufacturing industries.

Improvement in AI 6061 Composite Because of the huge difference in area and volume, these nanoparticles may be huge in influencing mechanical and physical characteristics of composites even at low concentrations.

However, challenges remain for dispersion/agglomeration of nanoparticles and scalability of production processes. Indeed, while the field is developing fast, only a regular integration of computational modeling and simulation tools into experimental studies will be able to bring acceleration in the development of next-generation AMMCs with property profiles optimized for particular industrial applications.

Table 1. Physical Properties of Bone Powder

Compound Formula	AI6061
Appearance	Grey
Melting Point	482-660 °C
Density g/cm3	2.5 to 2.9
Particular Size	30-45 Microns

The Al6061 alloy-based bio composite is fabricated and three samples were successfully obtained. The sample preparation process involves the powder mixing with suitable ratio of Al6061 alloy and the bone powder, once the powder mixing is done then the mixed powder is poured into the die and tightly fixed with the C- clamps, then powder compaction takes place with the certain load. Once the sample is removed from the die, the sample has given for heat treatment with suitable temperature and required period of time.

Table 2 Composition details of AI6061 Powder and Bone Powder Mixing and Compaction

No Of SAMPLES	QUANTITY (gm)		PERCENTAGE (%)	
	Al6061	Bone Powder	Al6061	Bone Powder
Sample 1	50	0	100	0
Sample 2	46	4	92	8
Sample 3	42	8	84	16

The pure AI6061 Powder was mixed with a known percentage of ingredients from the AI6061 alloy-based bio composite in a high-energy planetary ball mill[13]. The mixed powder the mixed powder was poured into a jar containing 25 steel balls, each 10 mm in diameter, and then rotated in a planetary ball mill for approximately 3 hours at 250rpm to ensure homogeneousmixing.

The Al6061 powder was mixed with bone powder at weight percentages of 8% and 16% using a planetary ball mill continuously for 3hr at 250rpm in order to get homogenous mixing. The mixture of each proportion was compacted in a die parts and assembly using a hydraulic press of 1000KN capacity as depicted, and the mixture was then pressed at a load

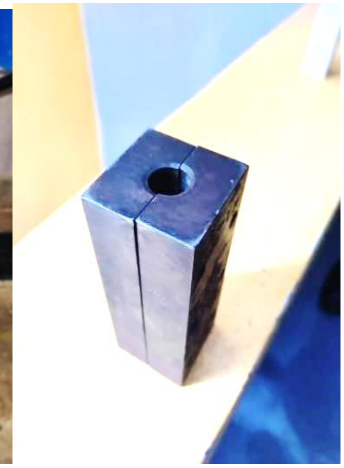
The prepared powder mixture was compacted under a load of 30 tons to produce billets measuring 20 mm in diameter and 70 mm in length. The compacted billets were then sintered in a vacuum tube furnace at 580 °C for 2 h under a nitrogen atmosphere and subsequently cooled in air to room temperature.

The billet was carefully removed from the die by first disassembling the die components. Once the die was separated, particular attention was given to the bottom part where the billet remained attached.This part of the die was securely clamped in the vise, ensuring that it was held firmly in place to avoid any damage during the removal process. With the billet clamped, a plunger was aligned parallel to the billet, and gentle taps were applied using a hammer. This gradual and controlled application of force allowed the billet to be released without causing deformation or affecting the integrity of the material.

To ensure the removal process did not compromise the billet's structural properties, the use of a gradual approach was essential. The controlled hammering, coupled with the use of a plunger, minimized the risk of introducing stress concentrations or micro-cracks that could adversely affect the billet's performance in subsequent processes. Moreover, clamping the die in the vise provided stability, preventing any undesired movement that could lead to uneven force distribution during billet extraction.

Additionally, the careful removal process ensured that the billet's surface finish remained intact, which is critical for subsequent machining or processing steps. Any imperfections introduced during removal could necessitate additional finishing operations, increasing both time and cost. By adhering to this meticulous procedure, the integrity of the billet was maintained, ensuring that it met the required specifications for further use in the production process.





PLANETARY BALL MILL DIE ASSEMBLING HYDRAULLIC PRESS


SAMPLES FURANCE PROCESS

SAMPLES:

This method highlights the importance of precision in the handling of billets during the manufacturing process, particularly in scenarios where the quality of the final product is paramount. The procedure also underscores the need for proper tooling and technique to avoid any damage that could affect the mechanical properties or surface finish of the billet.

2. RESULT AND ANALYSIS

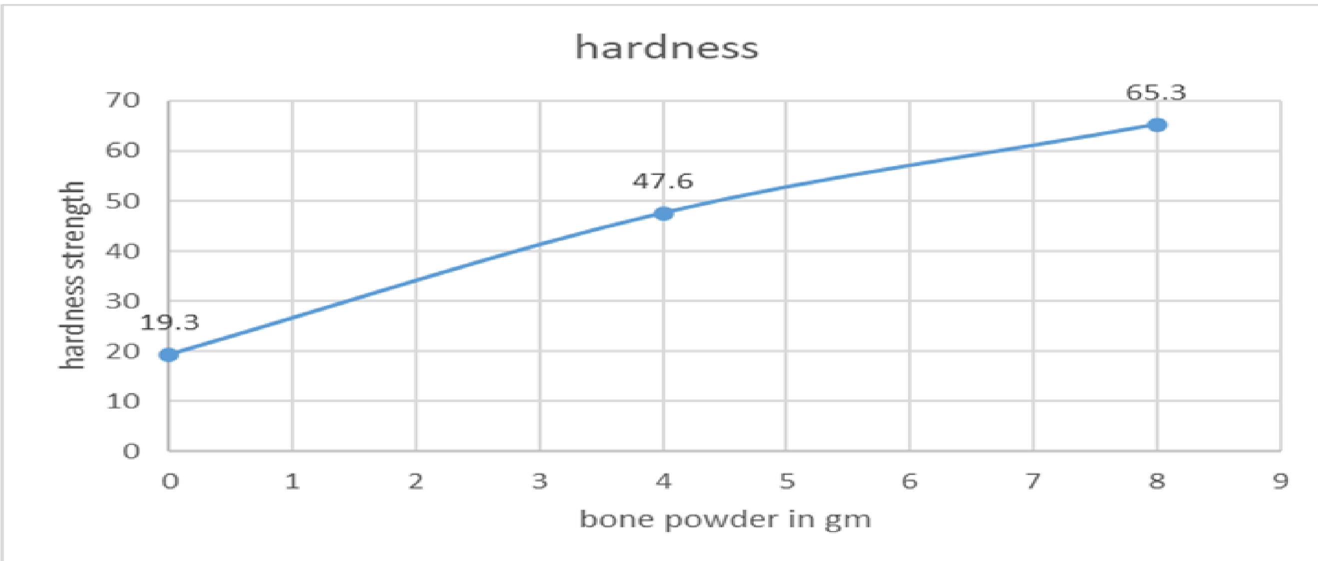
HARDNESS TEST

TABLE 3

Samples	**Rockwell Hardness No**			**Average**
	T1	**T2**	**T3**	

Sample 1	20	13	25	19.3
Sample 2	50	45	48	47.6
Sample 3	55	67	74	65.3

GRAPH REPRESENTAION:

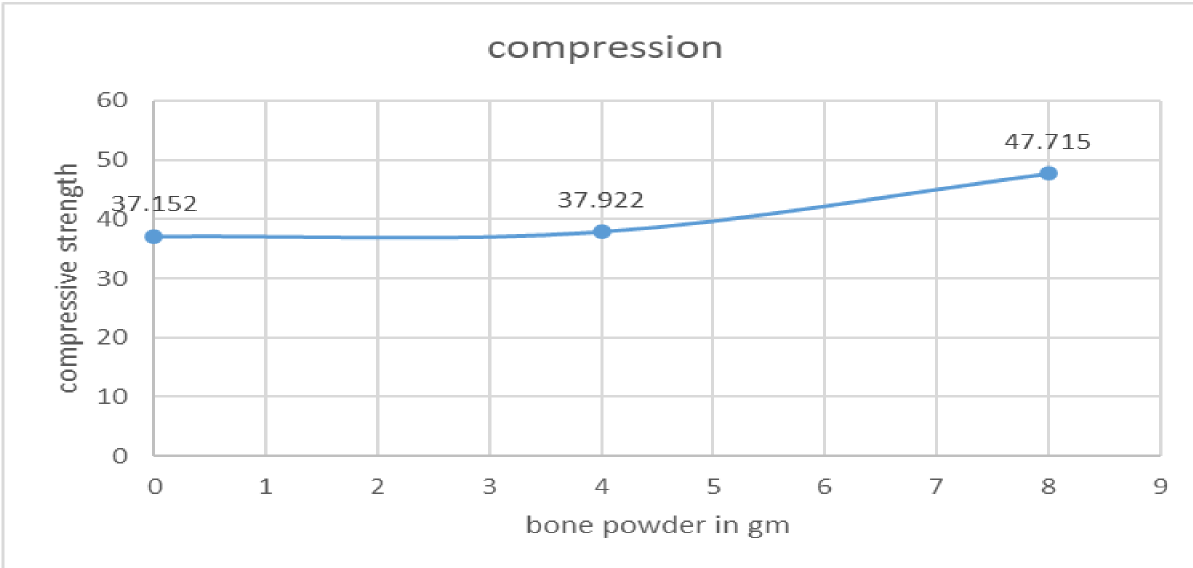


COMPRESSION TEST:

TABLE 4

SAMPLES	**WEAR (MICROMETER)**	**FRICTIONAL FORCE(N)**
Sample 1	297	166.3
Sample 1	291	171.2
Sample 1	256	198.2

GRAPH REPRESENTAION:



WEAR TEST:

SAMPLES	WEAR (MICROMETER)	FRICTIONAL FORCE(N)
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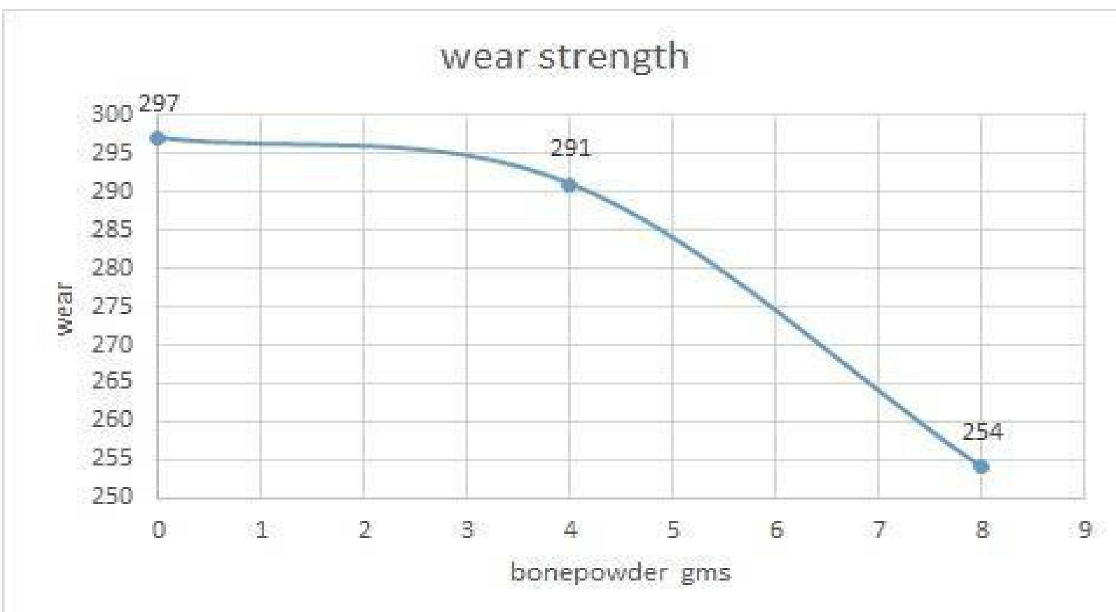

Analysis of Hardness, Compression, and Wear Test Results

This Analysis the findings from hardness, compression, and wear tests conducted on different material samples to evaluate their performance under varied conditions.

Hardness Test: The Rockwell hardness values were obtained for three samples, with the following results: Sample 1 had values of 20, 13, and 25, resulting in an average Rockwell hardness of 19.3. Sample 2 recorded hardness values of 50, 45, and 48, with an average of 47.6. Sample 3 exhibited values of 55, 67, and 74, yielding an average hardness of 65.3. The significant variation in hardness across the samples indicates marked differences in their material properties. Sample 3, with the highest average hardness, suggests superior resistance to deformation compared to the other samples, particularly Sample 1, which had the lowest average hardness.

Compression Test: The results of the compression tests, illustrated in the accompanying graphs, provide insights into the mechanical strength of each sample under compressive stress. These results are critical for understanding how the materials behave under load and their structural integrity. The graphical representation, including stress-strain curves or bar charts, reveals the performance characteristics of the materials, highlighting their capacity to withstand compressive forces.

Wear Test: The wear resistance of the samples was assessed through wear tests, with results depicted in the provided graphs. Wear resistance is essential for evaluating the durability and longevity of materials in practical applications. The graphs detail the performance of each sample over time or distance, showcasing any variations in wear rates. This information is crucial for determining the suitability of materials for applications where wear resistance is a critical factor.

Summary: The hardness test results demonstrate that Sample 3 possesses the highest hardness, indicating a greater resistance to deformation and potentially enhanced wear resistance. The compression test results further elucidate the structural strength of the materials, while the wear test results provide insights into their durability over time. Collectively, these analyses offer a comprehensive evaluation of the materials' performance, guiding informed decisions for material selection and application.

3. Conclusion:

Differing investigation were conducted on the use of bone powder as reinforcement in Al6061 through powder metallurgy. These have indeed been very promising, while significant enhancement in mechanical and tribological properties has been documented. Based on extensive tests and characterizations carried out in this work, the addition of bone powder increased the hardness and improved the wear resistance of Al6061 composites over pure aluminum alloy.

The observed improvements may be attributed to the bone powder's unique microstructure and composition, which enable it not only to share the loads effectively but also to reduce wear under a variety of service conditions, mainly as a consequence of the dispersion-strengthening effect afforded by the bone powder particles . The homogeneous distribution of these particles within the aluminum matrix delays the dislocation motion, which in turn gives rise to an increase in general strengthening and overall hardness of the composite. In addition, bone powders also act as solid lubricants in tribological interactions through the formation of a protective tribolayer on the surface of the material .

This tribolayer helps substantially in reducing the wear rate, therefore prolonging the service life of the composite under sliding conditions. These results suggest a potential use for bone powder as an effective eco-friendly reinforcement material in MMCs. It is fitting to the emphasis of modern manufacturing on sustainability and environmental stewardship that the source of the bone powder is biological and this resource is abundant and low-cost. Furthermore, the research opens new perspectives in the creation of lightweight and strong materials, which is so important in automotive and aerospace industries, where material performance stands in close relation with efficiency and safety.

The effects of such research are considerable because it might show that composites with bone powder reinforcement would be worth using instead of traditional reinforcement material composites, such as ceramics or man-made fibers. This may lead to the design and manufacture of components that need a balance between lightweight characteristics and high wear resistance. Future work shall, therefore, be directed toward the optimization of bone powder content, particle size, and distribution within the aluminum matrix for maximum mechanical and tribological performance. Besides that, other biologically derived reinforcements may further present some opportunities to develop novel MMCs with superior performance. Implications such as these will help the greater goal of engineering material development sustainably, meeting the demands of modern industrial requirements.

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