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Preparation and Sintering of Al–Cu–Mg–Si–SiC Metal Matrix Composites by Powder Metallurgy

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Abstract: The continuing demand for light structural materials that also offer good strength has drawn considerable attention to aluminium based metal matrix composites. In the present work an unreinforced aluminium body and a silicon carbide reinforced aluminium composite were fabricated through the press–and–sinter powder metallurgy route in order to avoid the melting losses and the coarse microstructures that commonly accompany conventional casting of aluminium. A powder blend consisting of 91.5% aluminium, 2.5% copper, 0.5% magnesium, 0.5% silicon and 5% silicon carbide (by weight) was homogenised in a mixer grinder, the magnesium being added in small increments to suppress the risk of ignition. The blend was cold compacted in hardened steel dies at a load of approximately 80 kN and the green compacts were subsequently sintered in a muffle furnace at 630 K, followed by furnace cooling. The sintered specimens were evaluated for dimensional stability and hardness. The Vickers hardness of the composite rose to about 26 kg/mm² from roughly 15 kg/mm² for unreinforced aluminium, while the product retained a low density and improved machinability at a manufacturing cost lower than that of the constituent elements. The results confirm that the chosen composition and processing window yield a sound, light and comparatively hard component suitable for weight–critical applications.

Keywords: Powder metallurgy, Aluminium metal matrix composite, Silicon carbide reinforcement, Cold compaction, Sintering, Vickers hardness.

I. INTRODUCTION

Lightweight alloys that combine low mass with adequate mechanical performance have become central to modern transport and aerospace engineering. Aluminium and its alloys are attractive in this respect because of their low density, ease of machining, corrosion resistance and comparatively modest production cost. A recurring limitation of pure aluminium, however, is its low strength and hardness, together with the melting losses and porosity that arise when components are produced by conventional liquid–metal casting. These shortcomings have encouraged the search for alternative processing routes and for reinforcement strategies that raise strength without sacrificing the weight advantage.

Powder metallurgy (PM) offers one such route. Rather than melting the metal, PM consolidates finely divided powders into a near–net shape by compaction and sintering. Because the material is never fully molten, the process largely avoids the segregation, shrinkage and oxidation losses associated with casting, and it permits close control of composition and porosity. The technique is also economical for medium to high production volumes, gives consistent part–to–part dimensions, and can produce materials, such as cemented carbides, that cannot easily be obtained by melting. For aluminium in particular, PM allows reinforcing ceramic particles to be distributed uniformly through the matrix, producing a metal matrix composite (MMC) whose stiffness and hardness exceed those of the base metal.

Among the ceramic reinforcements available, silicon carbide (SiC) is widely used with aluminium because of its high hardness, thermal stability and chemical compatibility with the matrix [3], [1]. The addition of SiC particles transfers load from the soft matrix to the hard ceramic and obstructs dislocation movement, both of which raise the measured hardness and strength of the composite. Small additions of copper, magnesium and silicon further strengthen the aluminium matrix: copper and silicon promote solid–solution and precipitation effects during sintering, while magnesium assists wetting between the matrix and the reinforcement by disrupting the tenacious oxide film that normally coats aluminium powder particles [7].

In the present study an attempt is made to fabricate both an unreinforced aluminium body and a silicon carbide reinforced aluminium composite through the conventional press–and–sinter PM route. The objective is to obtain a component that is lighter than equivalent ferrous parts, harder than unreinforced aluminium, easy to machine and inexpensive to produce. Each stage of the work – powder selection, blending, die design, compaction and sintering – was monitored closely to maximise the soundness and reproducibility of the final product.

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A. Objective of the Study
The principal aim of the project is to synthesise an aluminium based composite reinforced with silicon carbide using the powder metallurgy method, and to compare it with an unreinforced aluminium specimen prepared by the same route. The specific objectives are to establish a workable powder composition and blending procedure, to design and manufacture suitable dies and punches, to compact the blended powders into green specimens, to sinter the compacts at a controlled temperature, and to assess the resulting change in hardness and dimensional behaviour relative to pure aluminium.

II. LITERATURE REVIEW
A substantial body of work has examined the production of aluminium–SiC composites by powder metallurgy and the factors that govern their mechanical response. Investigations into the effect of sintering temperature have shown that both the density and the hardness of aluminium composites improve as the consolidation temperature is raised toward, and in some cases beyond, the melting point of aluminium, provided the reinforcement content is matched to the temperature used [2], [9]. Studies on sintering duration report a similar trend, with compressive strength, impact resistance and hardness all increasing as the hold time at temperature is extended [13].
The amount of reinforcement is consistently identified as a dominant variable. Several researchers have observed that hardness rises steadily as the weight fraction of SiC is increased, a result generally attributed to efficient stress transfer to the ceramic particles and to dislocation strengthening within the matrix [1], [3]. The size of the reinforcing particles is also important: finer SiC particles tend to give higher hardness because they distribute more uniformly and present a greater obstacle to deformation [2]. Comparative work between powder metallurgy and stir casting has repeatedly found that the PM route yields a more uniform particle distribution and denser products, which translates into more reproducible mechanical properties [6], [4].
The role of the oxide film on aluminium powder has received particular attention, since this film hinders bonding during sintering. High–energy ball milling and the addition of magnesium have both been reported to mitigate the effect of the oxide layer, leading to denser, better alloyed billets after pressureless sintering [5]. Hybrid composites that combine SiC with a second reinforcement, such as boron carbide or graphite, have also been explored, with measurable gains in hardness and wear resistance over the unreinforced matrix [11], [10], [14]. Collectively, these studies establish that composition, particle size, compaction load and the sintering schedule jointly determine the final quality of the composite, and they provide the basis for the processing parameters adopted in the present work.

III. MATERIALS AND METHODS
A. Raw Materials
Commercially available powders of aluminium, magnesium, copper, silicon and silicon carbide were procured from a powder manufacturer. Aluminium served as the matrix, silicon carbide as the ceramic reinforcement, and copper, magnesium and silicon as alloying additions intended to strengthen the matrix and to improve bonding during sintering. Because magnesium powder is highly reactive and can ignite readily, it was handled and blended in small quantities under controlled conditions.

Fig. 1: As–received metal and ceramic powders used in the study

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B. Die and Punch Design

The dies and punches required for compaction were designed with the help of AutoCAD, and the relevant circumferential (hoop) stresses were calculated to ensure that the tooling would withstand the applied compaction load without deformation. Four cylindrical dies were then machined on a lathe, two with an internal diameter of 20 mm and two with an internal diameter of 25 mm. After machining, the bores were polished to a smooth surface finish so that the green compacts could be ejected cleanly, and each empty die was weighed accurately for later reference.

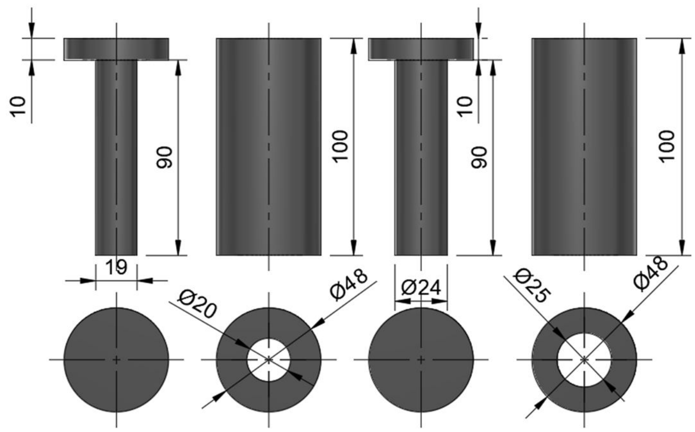

Fig. 2: CAD design and dimension of the die

Fig. 3: Finished dies after machining and polishing

C. Powder Blending

The powders were weighed in the proportions given in Table 1 and blended in a mixer grinder for a total of about 45 minutes. To minimise the risk of explosion associated with magnesium, mixing was carried out in short bursts of roughly three minutes at a time rather than in a single continuous operation. After blending, the homogenised powder mixture was stored in air–tight containers to prevent moisture pick–up and oxidation.

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TABLE 1: NOMINAL COMPOSITION OF THE POWDER BLEND (WEIGHT %)

Aluminium	**Magnesium**	**Copper**	**Silicon**	**Silicon Carbide**
91.5	0.5	2.5	0.5	5

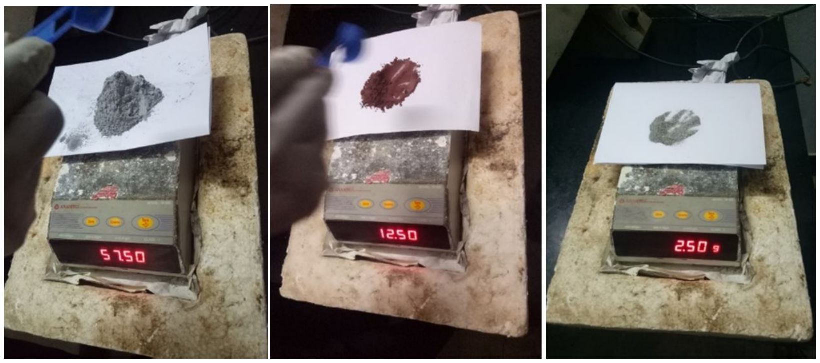

Fig. 4: Weighing and blending of the powders in the required proportions

D. Compaction

Prior to filling, the empty dies were weighed and the bores were lubricated with castor oil to reduce friction during ejection of the specimen. The blended powder was then poured carefully into each die, and the filled dies were re–weighed so that the mass of powder charged could be determined. The recorded masses of the dies before and after filling are listed in Table 2. Each filled die was mounted in turn on a digital power compaction machine of 3000 kN maximum capacity, and compaction was carried out at a load of approximately 80 kN to form the green compacts.

TABLE 2: MASS OF DIES BEFORE AND AFTER POWDER FILLING

Die	**A1**	**A2**	**B1**	**B2**
Without powder (g)	347	382	380	381
With powder (g)	510	516	446	448

fig. 5: Digital power compaction machine (3000 kN capacity)

After compaction the green compacts were removed, weighed and stored in dry, air–tight containers. The length and mass of each specimen were measured against its identification number, and these green values are recorded in Table 3.

TABLE 3: DIMENSIONS AND MASS OF THE GREEN COMPACTS

Specimen	**A1**	**A2**	**A3**	**A4**
Length (mm)	45	44	45.3	44.9
Weight (g)	160	132	66	67

Fig. 6: Green compacts obtained after cold compaction

E. Sintering

The green compacts were sintered in a muffle furnace at a temperature of 630 K. The compacts were held in the furnace through a repeated heating cycle lasting about 45 minutes, after which they were allowed to cool slowly within the furnace (furnace cooling) to limit thermal stresses. During sintering, diffusion bonding between the powder particles consolidates the porous compact into a coherent solid. The mass and length of each specimen were measured again after sintering, and the values are presented in Table 4; the close agreement with the green dimensions indicates that the specimens remained dimensionally stable and undistorted through the thermal cycle.

TABLE 4: DIMENSIONS AND MASS OF THE SPECIMENS AFTER SINTERING

Specimen	A1	A2	B1	B2
Weight (g)	158	131	66	66
Length (mm)	45	44	45.3	44.9

Fig. 7: Muffle furnace used for sintering the compacts

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Fig. 8: Final sintered specimens

IV. RESULTS AND DISCUSSION

The specimens produced by the press–and–sinter route were sound, flat and free of visible distortion, confirming that the selected compaction load and sintering schedule were appropriate for the chosen composition. A comparison of the green dimensions in Table 3 with the sintered dimensions in Table 4 shows that the length and mass of the specimens were essentially unchanged after the thermal cycle, indicating good dimensional stability and the absence of slumping or excessive shrinkage during sintering at 630 K.

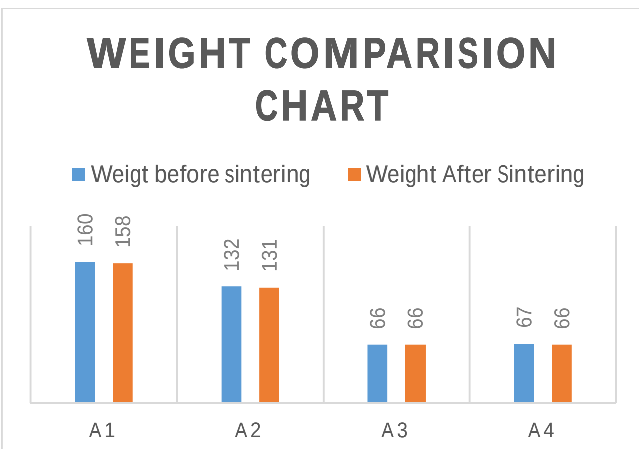

Fig 9: Weight comparison chart

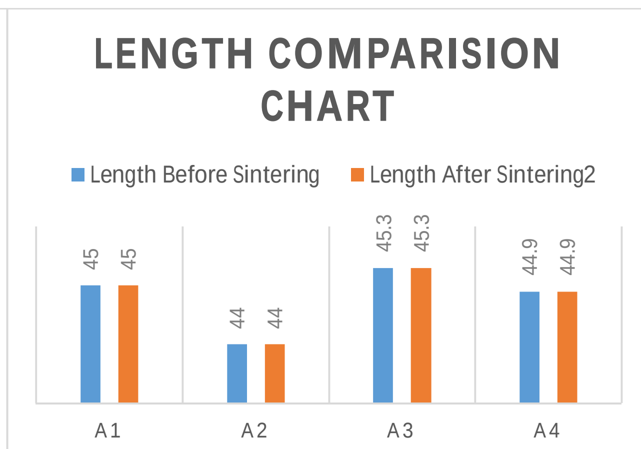

Fig 10: Length comparison chart

The most significant outcome of the work is the increase in hardness brought about by the silicon carbide reinforcement and the alloying additions. Vickers hardness testing of the composite gave a value of approximately 26 kg/mm², compared with about 15 kg/mm² for unreinforced aluminium processed under the same conditions. This represents an increase of roughly 73% in hardness. The improvement is consistent with the strengthening mechanisms reported in the literature: the hard SiC particles carry a share of the applied load that would otherwise be borne by the soft matrix, and they act as obstacles to dislocation motion [1], [3], while the copper, silicon and magnesium additions strengthen the aluminium matrix through solid–solution and precipitation effects and improve bonding by reducing the influence of the surface oxide film [5], [7].

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fig. 11: Vickers hardness indentation on the sintered composite specimen

In addition to the gain in hardness, the sintered composite retained the low density characteristic of aluminium, so that the strength–to–weight ratio of the material is favourable. The product also exhibited better machinability than unreinforced aluminium and was obtained at a manufacturing cost lower than that of the individual parent elements, owing to the efficiency of the near–net–shape powder route and the minimal material wastage involved. Taken together, these observations indicate that the combination of a 5% SiC reinforcement with small additions of copper, magnesium and silicon, consolidated by cold compaction and sintering at 630 K, yields a light, comparatively hard and economical component.

V. CONCLUSION

An aluminium based metal matrix composite reinforced with 5% silicon carbide and strengthened with small additions of copper, magnesium and silicon was successfully fabricated by the conventional press–and–sinter powder metallurgy route. The following conclusions can be drawn from the study:

1) Sound, flat and dimensionally stable specimens were obtained, with the sintered length and mass remaining essentially unchanged from the green state, confirming that a compaction load of about 80 kN and sintering at 630 K are suitable for the chosen composition.
2) The Vickers hardness of the composite increased to approximately 26 kg/mm² from about 15 kg/mm² for unreinforced aluminium, an improvement of roughly 73%, attributable to load transfer to the SiC particles, dislocation strengthening and matrix alloying.
3) The composite combined this higher hardness with the low density of aluminium, giving a good strength–to–weight ratio together with improved machinability.
4) The powder metallurgy route produced the component at a manufacturing cost lower than that of the parent elements, with little material wastage, making it an economical alternative to conventional casting for weight–critical parts.

VI. SCOPE FOR FUTURE WORK

In the present study silicon carbide was used as the reinforcing phase. Future work could examine the substitution of, or combination with, harder reinforcements such as tungsten carbide, which may yield still greater strength and durability. Systematic variation of the reinforcement content, particle size, compaction load and sintering schedule would help to optimise the composite further, and the addition of microstructural characterisation, density and porosity measurement, and wear and tensile testing would give a more complete picture of the material's behaviour. Composites of this type, being light and strong, are promising candidates for lightweight, high–strength components in the automotive and aerospace industries.

VII. ACKNOWLEDGMENT

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