Sintering sensitivity of aluminium metal matrix composites developed through powder metallurgy proposed technique- a review

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Abstract. This paper interprets the effect of sintering parameters like sintering time and sintering temperature as well as various sintering methods on distinct properties of the material. The variation of Physical, mechanical, and Tribological behaviour depending on sintering temperature, time and method based on various aluminium metal matrix composites have been investigated. The advantages of aluminium metal matrix composites are high strength to weight ratio, high wear resistance, and erosion resistance, etc. Aluminium Metal matrix composites have vast applications in various fields like structural, automobile, and aviation industries. The optimum value of sintering parameters and choice of sintering methods has a major role in getting these required properties of aluminium metal matrix composites prepared by the powder metallurgy process.

Key words: Sintering Time, Sintering Temperature, Sintering Methods, Aluminium Metal Matrix Composite, Physical Properties, Mechanical Properties and Tribological Properties

1. Introduction
Conventional monolithic materials display a limitation to a decent combination of properties such as strength, durability, density and stiffness. In order to get rid of these limitations and satisfy the ever-increasing demand of today's technology, composites are found to be the most screaming material of current interest. Metal Matrix Composites (MMCs) are advanced materials in which two or more materials are fused to achieve custom-made properties. Among them Aluminium Metal Matrix Composites (AMMCs) have substantially improved properties such as high specific strength, strong wear resistance, and damping ability compared to base alloy properties [1]. The mechanical characteristics of particle reinforced aluminum matrix are quite excellent (modulus, strength and creep resistance at room and higher temperatures) owing to the inclusion of the high strength as well as high modulus reinforcing particles such as Al₂O₃, TiC, SiC, TiB₂ etc. and also have higher wear resistance. Now-a-days these particulate reinforced metal matrix composites (PMMCs) are gaining priority on account of their low cost, isotropic properties and ease of fabrication [2].

The particulate metal matrix composite (PMMCs) can be prepared by means of compacting and sintering the properly mixed powder particles by powder metallurgy(P/M). It is one of the successfully adopted method for MMC preparation [3,4,5,6]. The major benefit of powder metallurgy (P/M) over other techniques is that it involves lower operating temperature and thus, avoid undesirable interfacial reaction products among matrix and particulate reinforcement [7]. Powder metallurgy permits a great degree of freedom in modifying the microstructure (e.g., more volume fraction as well as various size along with morphology of the particulate reinforcement can be used) [3,4,5,8-10,6]. P/M is used for the mass production of precise and intricate parts in low cost and sustainable manner. P/M produces near-net-shape products and thus, eliminates the cost of machining operation. However, it leads to
various metallurgical structures along with porosity which influence the properties of P/M composites [11]. P/M consists of various steps. Among this compaction and sintering are two major steps.

1.1. The Sintering Process

It is the method of consolidating either loose aggregate of powder or green compact of the desired composition under controlled environments and conditions of time and temperature [41]. Sintering process can be classified into majorly two types.

- **a) Solid-state sintering**
- **b) Liquid-state sintering**

1.1.1. Solid-state sintering. This is generally the process of consolidating the metal and the alloy powders. Under this, densification of material happens mostly owing to diffusion of atoms occurring in solid state [41].

1.1.2. Liquid-state Sintering. Densification is improved by adding a small quantity of liquid phase (1 to 10 vol %). At the sintering temperature, the liquid phase predominant within the solid powders seems to have some solubility for such solids. Between the solid particles of the compact sample, a sufficient amount of liquid is created. The liquid phase crystallizes at the grain boundaries during sintering, gluing the grains together. A rapid rearranging of solid particles occurs at this stage, resulting in an increase in density. Solid-phase sintering happens later in the process, resulting in coarse grains and a retardation of the densification rate. This is employed in the sintering of copper-tin and tungsten-copper systems. Silicon carbide and silicon nitride, which are tough to sinter, can be manufactured. [41].

1.2. Sintering Theory

Sintering involves the following steps.

1.2.1. Single-component System. The main material transportation mechanism is self-diffusion and the driving force arises from a chemical potential gradient resulting from capillary forces and surface tension occurring among particles of material [41].

1.2.2. Multi-component System. This involves more than single phase. Here there is inter-diffusion occurring because of concentration gradient which is the main driving force for sintering along with self-diffusion resulting from capillary forces and surface tension. Under such sintering, formation of solid solution and liquid phase occurs along with densification [41].

1.3. Various Sintering techniques

Various commercial Sintering Techniques are conventional technique, hot press sintering, hot isostatic pressing (HIP), spark plasma sintering (SPS) and microwave sintering. Table 1 presents the comparison between various commercial sintering techniques.

| Sintering Method       | Method description                  | Advantages                  | Disadvantages                                                                 | Reference  |
|------------------------|-------------------------------------|----------------------------|------------------------------------------------------------------------------|------------|
| Conventional Sintering | Heating by conduction, convection and radiation | Simple in operation.       | High amount of porosity. Coarse grains due to grain growth and low mechanical performance | [36,38]    |
Sintering in a Hot Press | Electrical resistance, induction heating, or radiations heating are all options for heating. | Better densification due to application of both heat and pressure. | Grain coarsening due to long sintering time and undesirable interfacial reactions. High cost of mold and equipment. | [35] 

Isostatic Pressing in a Hot Environment | Simultaneous heating with consistent pressure applied from all directions | Isotropic properties result from uniform densification. | Long dwell durations | [39] 

Sintering using Spark Plasma | Activation through pulsed current, resistance heating, and applied pressure | Grain growth is inhibited, resulting in microstructures that are dense and fine, with good mechanical properties. | The price is high. Mold and sample have an unfavorable response. | [34] 

Microwave Sintering | Volumetric Heating | It is possible to get a fully dense component with a tiny microstructure. It helps you save time and energy. Reinforcements are distributed evenly. The Microwave Sintering method is less expensive and productive than spark plasma technique. | Complex equipment and limitation in part dimension. | [32-33] 

2. Literature Review

2.1. Effect of Sintering Temperature and Time

2.1.1. Physical and mechanical Properties. Ghasali et al. [30] prepared Al-B₄C composite through microwave sintering of the mixture of B₄C (10wt%, 15wt% and 20wt%) and aluminium powders at 650°C, 750°C, 850°C and 950°C. It was observed that with increasing sintering temperature up to 850°C the hardness and density increases and further it decreases. Compressive strength increases up to 750°C and further it remains constant. But bending strength remains almost constant with varying sintering temperature.

Abdizadeh et al. [12] prepared Aluminium-zircon composite by powder metallurgy method. Sintering is carried out at two temperatures namely 600°C and 650°C for 65 min with a temperature increase rate of 20°C/min. It is found that with increasing temperature sintered density increased for all zircon
content. It was presented by them in Figure 1 and 2 about the variation of sintered and relative density for Al-zircon composite with zircon content sintered at various temperatures respectively.

![Figure 1](image1.png)  
**Figure 1.** Variation of Density with zircon content for Al-zircon composite sintered at various temperatures.

![Figure 2](image2.png)  
**Figure 2.** Variation of Relative Density with zircon content for Al-zircon composite sintered at various temperatures.

Figure 1 and 2 shows that with rising sintering temperature both the sintered and relative density of samples increases. As the sintering temperature rises the atomic diffusion becomes more easier which results in better sinterability of MMCs and density increases. Same trend of Relative Density variation with sintering temperature was found by other researchers [17,19,21,23]. Relative density increases up to 3.5% of zircon, after which there is a decrease in the trend. This happens because of agglomeration of reinforced zircon particles throughout sintering process. Chen et al. [28] prepared AMMC reinforced by Al$_2$O$_3$ and TiB$_2$ particulates synthesized using reactive sintering of Al-B-TiO$_2$ three-component powder mixtures. Relative density was found to increase with sintering temperature.

Asgharzadeh et al. [26] prepared Al6061-SiC composite by powder metallurgy method following supersolidus liquid phase sintering. Sintering was conducted at 580°C-620°C. The sintering density and densification parameter increases from 580°C to 600°C and further it decreases. Same trend is followed by hardness and compressive strength. Topcu et al. [27] prepared Al-B$_4$C composite by powder metallurgy process. Sintering of specimens are conducted at 600°C, 625°C and 650°C. As the sintering temperature increases the sintering density increases. Following results are obtained which is shown in the table 2 below.
Table 2. Various results obtained from Al-B₄C composite

| Materials (%B₄C) | Density (gm/cc) | Hardness (HV) | Impact Energy (KJ/m²) |
|-----------------|-----------------|---------------|-----------------------|
|                 | 600°C | 625°C | 650°C | 600°C | 625°C | 650°C | 600°C | 625°C | 650°C |
| 0               | 2.51  | 2.55  | 2.57  | 38.1  | 36.6  | 25.8  | 80    | 65    | 42    |
| 5               | 2.510 | 2.550 | 2.58  | 40.9  | 39.9  | 45.6  | 59    | 48    | 38    |
| 7.5             | 2.42  | 2.540 | 2.55  | 43.8  | 42.9  | 53.5  | -     | -     | -     |
| 10              | 2.40  | 2.520 | 2.54  | 49    | 52.1  | 56.8  | 58    | 54    | 52    |
| 12.5            | 2.37  | 2.510 | 2.52  | 56.1  | 61.1  | 66.6  | -     | -     | -     |
| 15              | 2.36  | 2.500 | 2.51  | 61.5  | 68.1  | 72    | 26    | 28    | 24    |
| 17.5            | 2.35  | 2.500 | 2.55  | 64.8  | 77.2  | 74.8  | -     | -     | -     |
| 20              | 2.35  | 2.500 | 2.53  | 74.1  | 82    | 82.1  | 12    | 10    | 9     |

Rahimian et al. [13] prepared Aluminium (Al)-Alumina (Al₂O₃) composites through powder metallurgy method. Sintering of green compacts were conducted under inert argon atmosphere at various temperatures namely 500°C, 550°C and 600°C for time duration of 30 min, 45 min, 1 hour and 1.5 hour. They presented the variation of Relative Density, Yield stress, compressive strength and % elongation with Alumina particle size for Al-Al₂O₃ composite sintered at various temperatures in Figures 3, 4, 5 and 6 respectively.

Figure 3. Variation of Relative Density with Alumina particle size for Al-Al₂O₃ composite sintered at various temperatures.

Figure 4. Variation of Yield stress with Alumina particle size for Al-Al₂O₃ composite sintered at various temperatures.

It is presented in Figure 3 about the variation of Relative Density with Alumina particle size for Al-Al₂O₃ composite sintered at different temperatures.

The Relative Density is given by,

\[ \text{Relative Density} = \frac{\text{Experimental Density}}{\text{Theoretical Density}} \times 100 \]  \hspace{1cm} (1)
From Figure 3, it was observed that relative density rises with rising sintering temperature. This can be described by using the following equation.

\[ D = D_0 \exp \left( \frac{-Q}{RT} \right) \]  

(2)

The diffusion coefficient, the Equation constant, the activation energy, Boltzmann's constant, and the temperature are presented by the notation \( D, D_0, Q, R \) and \( T \) respectively. So, more densification occurs and experimental density increases at higher temperatures as diffusion increases with temperature. This enhances the Relative Density.

**Figure 5.** Variation of Compressive Strength with Alumina particle size for Al-Al\(_2\)O\(_3\) composite sintered at various temperatures.

**Figure 6.** Variation of % Elongation with Alumina particle size for Al-Al\(_2\)O\(_3\) composite sintered at various temperatures.

It is presented in Figure 4 and 5 about the variation of Yield stress and Compressive Strength with Alumina particle size for Al-Al\(_2\)O\(_3\) composite sintered at various temperatures respectively. Figure 4 and 5 indicate that because of a stronger bonding among the particles at elevated sintering temperatures, resulted in a higher strength. Same trend of Compressive strength variation with sintering temperature was found by other researchers [16,17,21].

It is presented in Figure 6 about the variation of % Elongation with Alumina particle size for Al-Al\(_2\)O\(_3\) composite sintered at various temperatures. From Figure 6, the increase in elongation is due to an increase in sintering temperature, especially close to the melting point of aluminium, because the bonding strength among the alumina and aluminium is higher under these conditions.

Microwave assisted rapid sintering was carried out by Ghasali et al. [29] to fabricate Al-ZrB\(_2\) composite containing 1wt% cobalt (Co) and 10wt%,15wt%,20wt% ZrB\(_2\) as reinforcements at temperatures of 600°C,700°C and 800°C. For Al-10%ZrB\(_2\)-1% Co and Al-15%ZrB\(_2\)-1% Co composites, as the sintering temperature increases the compressive strength increases up to 700°C and after that it decreases. For Al-20%ZrB\(_2\)-1% Co composite it is strictly decreasing while for Al-10%ZrB\(_2\) composite it is strictly increasing.

Wang et al. [14] prepared Al - SiC/Cu composite through powder metallurgy method. The samples were sintered under inert argon atmosphere at various temperatures namely 650°C,700°C,750°C and 800°C for a time duration of 2h. Figure 7 presents the variation of density with sintering temperature.
for SiC/Cu-Al composite while Figure 8 represents the variation of Micro hardness and Strength with sintering temperature for SiC/Cu-Al composite.

![Figure 7. Variation of Density with Sintering Temperature for SiC/Cu-Al composite.](image1)

![Figure 8. Variation of Micro hardness and Strength with Sintering Temperature for SiC/Cu-Al composite.](image2)

It is presented in Figure 7 about a weak declining trend of density with increase in sintering temperature. This is due to decomposition of the compound Cu$_2$O or due to the occurrence of reaction among Al and Cu that results in lower densification behaviour of the Al-SiC/Cu composite. It is presented in Figure 8 about the dependence of Micro hardness and Strength on Sintering Temperature for SiC/Cu-Al composite. Figure 8 indicates that the micro hardness of the Al-SiC/Cu composite rises with increasing sintering temperature from 650°C to 700°C. The maximum hardness was found to be 80MPa at 700°C. This is due to the change in microstructure with sintering temperature. The relatively uniform microstructure results in this highest hardness. In case of composite sintered at 800°C, though there is development of non-uniform microstructure the hardness of composite increases than that of 750°C because of generation of substantial intra-granular SiC grains which is not found with sintered at 750°C. Figure 8 indicates that strength rises with rising temperature. The strength is only 33MPa at 650°C, but rises to 140MPa at 800°C. The strength at 650°C is lowest because of weak bonding between matrix and reinforcement. At higher temperatures strength increases because of strong interfacial bonding. Gurbuz et al. [25] prepared Aluminium-graphene nanoplatelets composite by powder metallurgy method. The effect of different sintering times (60,120,180,300min) and different sintering temperatures (550°C,600°C,630°C) are investigated. The best sintering time and sintering temperature was found to be 180 min and 630°C respectively at which hardness reaches its best value.

Same trend of Hardness variation with sintering temperature was found by other researchers [17, 18, 21, 22 and 24]. Reddy et al. [31] prepared Al-Cu-Li particles reinforced to Pure Aluminium matrix through Microwave Sintering followed by hot extrusion. They presented the influence of reinforcement amount and sintering temperature on UTS as presented in the table 3 below. Ultimate tensile strength (UTS) of composites were found to be lower at higher temperatures as Al matrix become softer at higher temperatures.
Table 3. Ultimate Tensile Strength (UTS) of Al matrix reinforced by Al-Cu-Li with varying Sintering Temperature

| Composite       | Temperature(°C) | UTS (MPa) |
|-----------------|-----------------|-----------|
| Al-5AlCuLi      | 40              | 127.018   |
| Al-5AlCuLi      | 100             | 114.957   |
| Al-5AlCuLi      | 200             | 85.7834   |
| Al-10AlCuLi     | 40              | 151.971   |
| Al-10AlCuLi     | 100             | 130.081   |
| Al-10AlCuLi     | 200             | 103.929   |
| Al-15AlCuLi     | 40              | 167.472   |
| Al-15AlCuLi     | 100             | 141.802   |
| Al-15AlCuLi     | 200             | 125.293   |

Leszczyńska-Madej et al. [37] prepared Al-SiC composite through spark plasma sintering. They conducted sintering at 580°C and 600°C at varying SiC content of 0,10,20 and 30wt%. The value of Brinell Hardness and bending strength for varying sintering temperature and SiC content is presented in below table 4. The sintering temperature and decomposition of the SiC strengthening phase have major impact on hardness. Higher value of bending strength was obtained at higher value of sintering temperature.

Table 4. Hardness and Bending Strength of Al-SiC composite sintered at temperatures of 580°C and 600°C

| SiC (wt.%) | 580°C | 600°C |
|------------|-------|-------|
|            | Hardness (HB) | Bending Strength (MPa) | Hardness (HB) | Bending Strength (MPa) |
| 0          | 28    | 225   | 28    | 225    |
| 10         | 31    | 146   | 52    | 328    |
| 20         | 31    | 87    | 55    | 331    |
| 30         | 33    | 78    | 35    | 89     |

2.1.2. Tribological Properties. Rahimian et al. [15] prepared Al-Al₂O₃ composite by powder metallurgy route. Green compacts were sintered at various temperatures namely 500°C,550°C and 600°C for the time periods of 30 min,45 min,1 hour and 1.5 hour. They conducted wear test and presented the effect of sliding distance on wear rate of Al-Al₂O₃ composite for various sintering temperature (Figure9). It is found that wear loss is lower at both higher sintering temperatures and higher sintering times. But as the sintering time reaches to 90mins, the specimens are over-sintered and displayed higher wear as hardness get reduced because of grain growth occurring under these conditions. It is also found that wear loss increases with increasing sliding distance. They also presented about the effect of sintering time on wear loss for Al-Al₂O₃ composite at various sintering temperatures (Figure 10). Wear tests were conducted on 10wt.% alumina composite. Except for the composites sintered at 600°C, the all-other composites show reduction of wear loss with increasing sintering time as there is grain refinement leading to higher hardness and thus, wear resistance. Similar thing happens for composite sintered at 600°C from 45 min to 60min.But further as the sintering time increases from 60min to 90min, there is over-sintering leading to grain growth. With increasing grain growth hardness decreases which leads to more wear loss.
In some research work it is found that the composite prepared by PM route shows better wear resistance in comparison to other methods [20,40]. Some other research work also reported that increasing the sintering temperature by 100°C, reduces the wear rate [40].

2.2. Effect of Sintering Methods

Ghasali et al. [36] prepared Al₃V-Al-VC nano composite via conventional sintering, microwave sintering and spark plasma sintering (SPS) separately. Conventional and microwave sintering was done at 600°C while SPS was done at 450°C. They provided a nice comparison between these Processes as provided in the below table 5. The density increases for SPS while for the other two it decreases as there is full densification occurring without formation of any light intermediate product and porosity. SPS samples show best hardness and bending strength than the other two samples because of the previously mentioned cause.

Table 5. Comparison of results obtained from SPS, Microwave and conventional sintering on Al₃V-Al-VC nano composite.

|          | SPS | Microwave | Conventional | Properties          |
|----------|-----|-----------|--------------|---------------------|
|          | 15wt% VC | 5wt% VC | 15wt% VC | 5wt% VC | 15wt% VC | 5wt% VC |               |
| Density (g/cc) | 275   | 243      | 132       | 110      | 75        | 103      | Bending Strength (MPa) |
|           | 260   | 162      | 131       | 95       | 101       | 70       | Hardness (HV)        |
|           | 2.91  | 2.76     | 2.59      | 2.63     | 2.51      | 2.61     | Density (g/cc)       |
Ghasali et al. [39] prepared Al-SiC-TiC composite using pure aluminium and AA1056 aluminium powders by both conventional and microwave sintering methods. They provided a detailed analysis result as presented in the table 6 below. Relative density, bending strength and microhardness decreases with increasing sintering temperature irrespective of material and method of sintering.

Table 6. Comparison of results obtained from Microwave and conventional sintering on Al-SiC-TiC composite

| Matrix Material | Methods of Sintering | Sintering Temperature(°C) | Relative Density (%) | Bending Strength (MPa) | Microhardness (HV) |
|-----------------|----------------------|---------------------------|----------------------|------------------------|-------------------|
| AA1056          | Microwave            | 750                       | 96.32                | 340                    | 192               |
| AA1056          | Microwave            | 650                       | 94.21                | 252                    | 161               |
| AA1056          | conventional         | 750                       | 93.63                | 208                    | 137               |
| AA1056          | conventional         | 650                       | 91.89                | 201                    | 121               |
| Pure Al         | Microwave            | 750                       | 89.71                | 115                    | 86                |
| Pure Al         | Microwave            | 650                       | 89.48                | 81                     | 80                |
| Pure Al         | conventional         | 750                       | 77.14                | 58                     | 65                |
| Pure Al         | conventional         | 650                       | 82.82                | 51                     | 60                |

Ghasali et al. [23] prepared WC-Co particle reinforced to aluminium matrix by both conventional and microwave sintering. Their results about Relative Density and Bending Strength are depicted in the Figures 11 and 12 below.

Figure 11. Variation of relative density with temperature for various composition and various Sintering Methods.

Figure 12. Variation of bending strength with temperature for various composition and various Sintering Methods.

From Figures it is found that Bending strength value of composites prepared by microwave sintering firstly remains below than that of conventional at 650°C but after that increases and passes above the conventionally prepared composites after 850°C. But in case of Relative Density the final value in case of conventionally prepared samples is more than that prepared by microwave sintering method.
3. Conclusion

From the above literature it was found that

1. Sintering time, sintering temperature along with sintering method has major influence on properties of Metal Matrix Composites (MMCs).
2. Optimum value of these parameters and choice of process leads to most improved properties. So, both under-sintering and over-sintering must be avoided.
3. Denser structure is obtained under higher sintering temperatures.
4. Higher sintering time leads to unwanted grain growth and thus, degrades the mechanical properties excluding %Elongation.
5. As the sintering temperature rises the atomic diffusion becomes more easier which results in better sinterability of MMCs and enhances its properties.

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