

Review

Microwave Rapid Sintering of Al-Metal Matrix Composites: A Review on the Effect of Reinforcements, Microstructure and Mechanical Properties

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Abstract: Aluminum metal matrix composites (AMMCs) are light-weight materials having wide-spread use in the automobile and aerospace industries due to their attractive physical and mechanical properties. The promising mechanical properties of AMMCs are ascribed to the size and distribution of the reinforcement, as well as to the grain size of the matrix. Microwave rapid sintering involves internal heating of aluminum compacts by passing microwave energy through them. The main features of the microwave sintering technique are a short processing time and a low energy consumption. The aim of this review article is to briefly present the microwave rapid sintering process and to summarize the recent published work on the sintering and properties of pure Al and Al-based matrix composites containing different reinforcements.

Keywords: aluminum; metal matrix; reinforcement; microwave sintering; microstructure; mechanical properties

1. Introduction

Metal matrix composites (MMCs) can be categorized under advanced materials, as they can be tailored using fundamental principles to cater to end engineering applications. In MMCs, different metals or alloys, such as aluminum, magnesium, copper or nickel, are generally used as the matrix. Among these, Al alloys are widely used in engineering structure and applications [1] due to their better properties, such as lightweight, high strength, high specific strength and modulus, wear resistance and low coefficient of thermal expansion [2–6]. Depending on final desired properties of the composites, different reinforcement types, such as amorphous, metallic and ceramic particles, are used in aluminum matrix composites.

In fact, the Al-based matrix composites (AMMCs) reinforced by amorphous alloy/metallic glass/ceramic particles produce a high performance composite compared to Al-based alloys. The Al-MMCs have the potential to exhibit superior mechanical properties, like high tensile strength, good ductility, good wear, fatigue, fracture toughness, etc., as compared to the un-reinforced Al alloys [2–8].

Although conventional powder metallurgy (PM) can produce products close to the final shape, reducing the cost of surface finishing, it faces problems in the strength and toughness of the final product. There is a high probability of an oxide film formation on the Al particles,

preventing strong metallic bonding [9,10]. Oxide layer formation can be avoided by adopting time-consuming complex and costly methods, such as canning, degassing, passing inert gas during sintering or in a vacuum [10,11]. Over conventional materials, Al alloys have advantages of being economically inexpensive, mechanically strong and lightweight. These are the most desirable features in selecting Al for automobile industry keeping in view the present days' demand for higher efficiency and sky-scraping fuel cost. Thus, it has become inevitable to streamline Al and Al component processing, innovatively incorporating energy efficiency and cost-effective techniques compared to the existing ones.

In contrast to traditional heating methods, microwave sintering of composites can offer certain advantages, such as energy efficiency, environmental friendliness, enhanced densification and a fine grain size due to the faster heating rates and the lower sintering temperature [12,13]. Additionally, uniform volumetric heating and smaller and equiaxed pores in the sintered green compacts and fine microstructure are added advantages of microwave sintering [13–15]. Hence, microwave sintering should result in improved mechanical properties and better product performance [13]. Therefore, after the success of microwave sintering of metallic materials in 1999 [16], many researchers paid significant attention to the processing of metals and their composites through microwave heating. Up till now, most research has been carried out on ferrous, copper, tungsten and magnesium with limited studies on aluminum and its composites [17].

Most of the literature on microwave processing of materials presents fundamental concepts of materials processing and concentrates on the physical, morphological and microstructural characteristics of materials. The literature review presents limited studies on the applications of microwave processing of materials, as well as particle-reinforced Al-metal matrix composites. Therefore, the objectives of this review article are (i) to briefly present the microwave sintering technique; (ii) to review the effect of the microwave sintering; (iii) to highlight the role of reinforcement size and the effect of the volume fraction of reinforcement and (iv) to show the influence of microwave heating behavior and the extrusion process on the microstructure, physical, thermal and mechanical characteristics of pure Al and Al-based metal matrix composites.

2. The Microwave Rapid Sintering Process

Material processing using microwaves is a promising research field with enormous potential for discovering new materials and unique microstructures [18,19]. Lately, microwave material processing technology has gained much interest due to the relatively low manufacturing costs, both energy and time saving, the fast sintering process, short soaking time, higher energy efficiency, improved product uniformity and high yields.

The microwave sintering process has unique advantages (shown in Figure 1) over the conventional sintering processes [20]. The basic difference between the traditional and microwave sintering process lies in the heating mechanism [21], as shown in Figures 2 and 3. In conventional heating, the specimen is heated using heating elements like silicon rods. The heat is then transferred to the specimen either by conduction, convection or radiation. This poses the serious problem of non-uniform heating, creating thermal gradients, which in turn results in internal stresses in the specimen.

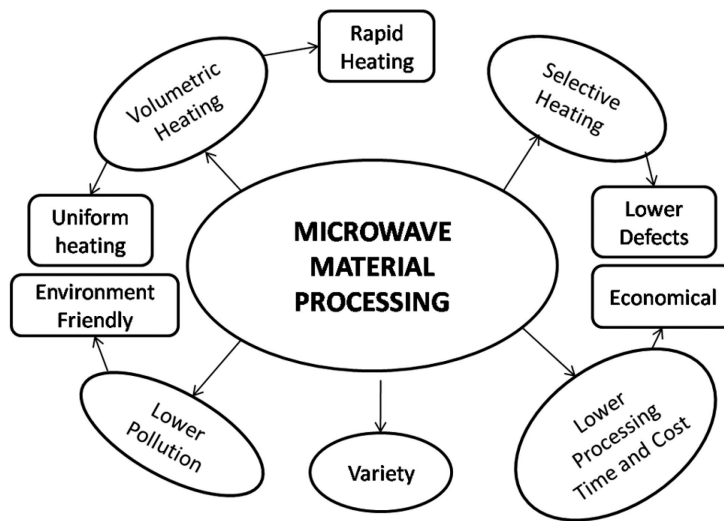


Figure 1. Favorable characteristics of microwave materials processing [20].

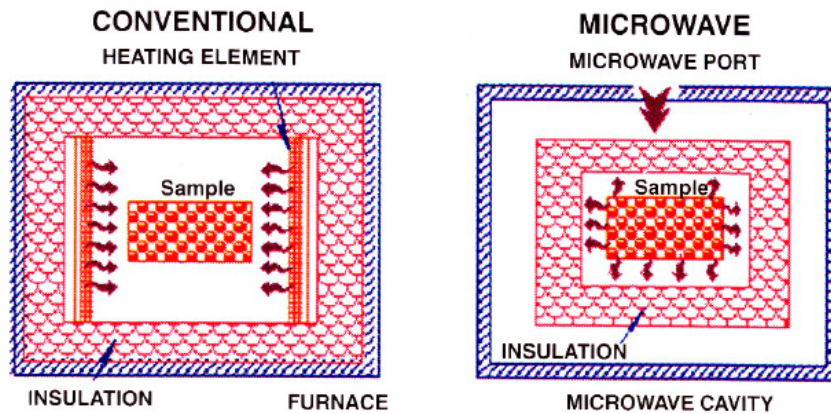


Figure 2. Comparison of the heating procedure between conventional and microwave methods [21].

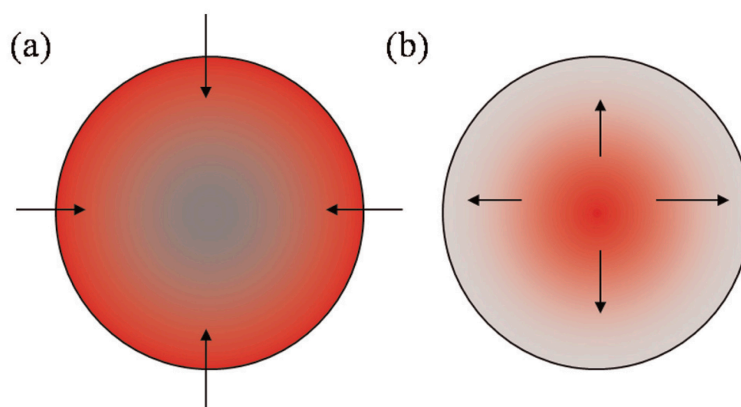


Figure 3. Heating mechanism for (a) conventional heating from the outer to the inner surface and (b) microwave heating from the inner to the outer surface [20].

2.1. Principle and Problems Associated with Microwave Heating of Metals

Microwave heating characteristics of metal-based materials are different from dielectric materials, as no internal electrical field is induced in metals due to the high conductivity [22]. Microwave heating of metal-based materials depends on the depth of penetration, i.e., skin depth (d). The penetration

depth or skin depth of the field is defined as the distance from the surface of the material at which the magnitude of the field strength drops by a factor of $1/e$. Mathematically, it can be expressed as [23]:

$$\delta = 1/\sqrt{(\pi f \mu \sigma)} = 0.029 (\rho_e \lambda_0)^{0.5} \quad (1)$$

where f is the microwave frequency (2.45 GHz), μ is the magnetic permeability of material ($\text{H} \cdot \text{m}^{-1}$), σ is the electrical conductivity of material ($\text{S} \cdot \text{m}^{-1}$), ρ_e is the electrical resistivity of material ($\text{V} \cdot \text{m}$) and λ_0 is the incident wavelength of the microwave (m). It is evident from the Equation 1 that the materials with higher electrical conductivity have lower skin depths. Accordingly, the skin depth is very small for metal-based materials, owing to the facts that they are good electrical conductors.

Microwave heating is dependent on many factors, like the material's properties, physical characteristics, boundary conditions and the application fields to which the material is being exposed [24]. The use of microwaves in ceramic processing is a relatively recent development. They can be applied effectively and efficiently to heat and sinter ceramic objects. The most recent development in microwave applications is in sintering of metal powders, a surprising application, in view of the fact that bulk metals reflect microwaves. However, reflection by a metal occurs only if it is in a solid, nonporous form and is exposed to microwaves at room temperature. Metals in the form of powder will absorb microwaves at room temperature and will be heated very effectively and rapidly. The implications of microwave sintering of metals are obvious in the field of powder technology. Metal powders are used in a diverse range of products and applications in various industries, including the automotive industry, aerospace and heavy machinery. The challenging demands for new and improved processes and materials of high integrity for advanced engineering applications require innovation and new technologies. Finer microstructures and near theoretical densities in special powder metal components are still elusive and widely desired. Increasing cost is also a concern of the industry. Microwave processing offers a new method to meet these demands of producing fine microstructures and better properties, potentially at lower cost.

Walkiewicz et al. [25] studied the behavior of different metals at various heating rates when exposed to microwave radiation and showed that metal powder coupled well with microwaves, better than some dielectric metal oxides. Agrawal and his colleagues [26] reported that a sheet of metal was reflected by microwaves, but in powder form, it seems that metals are no longer so reflective. The researchers were able to make dense sintered bodies from powders of just about every metal they tried, including iron, steel, copper and aluminum. In several cases, the microwave-sintered metals were denser and harder than those sintered by conventional heating.

2.2. Microwave Furnace

Microwave processing is a volumetric cooking of the material involving instantaneous transfer of electromagnetic energy into thermal energy rapidly and with high efficiency. In the electromagnetic spectrum, the region between infrared and radio waves represents the microwave region. These waves have wavelengths between 0.01 m and 1 m, corresponding to the frequency of 30 GHz (or 3×10^4 MHz) to 0.3 GHz (or 3×10^2 MHz).

However, 2.45 GHz and 915 MHz are the commonly-used microwave frequencies for research and industrial activities. The specimens are usually housed in an insulated alumina chamber or tube. The insulation of the chamber ensures that the heat generated within the specimen does not escape and is effectively utilized. The temperature generated in the specimen is measured using IR sensors, optical pyrometers and/or sheathed thermocouples, which are placed close enough to the surface specimen. The sintering chamber is appropriately equipped to provide the desired inert atmosphere by passing Ar or N_2 and is capable of achieving temperatures up to 1600 °C. The microwave sintering machine normally consists of four parts namely: (a) microwave generator or magnetron; (b) susceptor; (c) heating system and (d) programmable controller.

(a) Microwaves Generator

A microwave furnace utilizes one or two magnetrons lying on either side of the cooking chamber for the generation of microwaves. A typical furnace is pictorially represented in Figure 4 [27]. As mentioned earlier, the frequency of the microwave beam is normally 2.45 GHz, capable of delivering a power output of 900 W–1.1 kW, which accelerates the heating rate, and the specimens can reach 1600 °C without any difficulty.



Figure 4. Microwave sintering furnace [27].

(b) Susceptor

The susceptor is one of the vital components of the microwave furnace. A microwave-active material should have a moderate value of the dielectric constant and a high value of dielectric loss ($\tan\delta$). Most of the white ceramics are not susceptors to microwaves at or near room temperature. However, they begin to couple with the field once heated beyond ~ 800 °C. With the further increase in temperature, the susceptibility increases exponentially, resulting in a “thermal runaway” condition. Effective hot zone conditions are obtained usually by a hybrid heating system composed of SiC or high loss ferrite powders in the cavity [21].

The susceptor is a part of the hybrid microwave heating system in which the sample can be loaded for sintering. For example, a cubical chamber made of dense alumina tiles is lined inside with silicon carbide plates on the four side walls and at the base. Silicon carbide is a high loss material, to facilitate rapid heating of the crucible and its contents and the maintenance of high temperatures therein. Typically, the chamber can accommodate a batch loading in a 5×5 cm area. The top of the chamber acts as a lid with a 2-cm diameter hole at the center. The circular aperture facilitates temperature sensing and the maintenance of an inert atmosphere. The four sides of the chamber are externally insulated using glass wool to prevent temperature gradients during microwave sintering [28]. Figure 5a,b represents a typical susceptor cavity chamber [27].



Figure 5. (a) Susceptor cavity inside the furnace; (b) Susceptor showing SiC lining [27].

(c) Heating System

Special magnetron (1100 watts) \times 2 is used to heat the furnace electrically. A suitable susceptor will be provided, and it reacts with the electromagnetic waves and creates the instant heat in the system. Adequate numbers of susceptor pieces are supplied along with the furnace. The specimen may be placed inside the cavity of the susceptor and carefully placed in the furnace box. The temperature sensor is fixed at the top and carefully provides the sample center to the sensor manually.

(d) Programmable Controller

The Eurotherm (Model 3216) digital programmable temperature indicator/programmer is used to take care of the full operation of the furnace. The rate of heating and dwell with respect to time are pre-programmed, and the entire operation will be automatically controlled by the programmer. The temperature sensor output lead will be directly connected to the programmer as the input.

2.3. Loading Process

Moisture content in the pressed sample may lead to sample cracking during the sintering process in the microwave furnace. Hence, the sample may be heated on a hot plate for allowing any moisture retained in the sample to be evaporated before loading into the crucible in the susceptor. The entire susceptor assembly (susceptor + ceramic padding) is usually placed at the center of the microwave furnace and adjusted so as to align the thermocouple position, as will be mentioned in the next section. At the same time, the height of the ceramic padding was arranged in such a way that the sample placed inside the crucible lies exactly at the center of the path of the microwave beam.

2.4. Temperature Sensor

Generally, temperature sensing in microwave furnaces is done by Impac imported non-contact probes, like IR sensors. Some studies use R-type and K-type thermocouples shielded by crystallized alumina tubing as a sensor for the detection and control of temperature, which is economical and comparable to the function of IR sensors [21]. An IR temperature sensor is placed on top of the furnace in such a way that the infrared rays fall on the specimen uninterrupted. The sensor is connected to the display unit for temperature readings. Another probe is taken as a feedback from the sensor to the program controller for controlling the specified program.

2.5. Susceptor and Sample Heating

During the sintering process, initially, the microwave energy is absorbed by the SiC lining and produces a large amount of heat, which in turn thermally activates the alumina block for further

heating. Simultaneously, as the microwave beam passes through the sample, all of the dipoles oscillate with a very high frequency (microwaves frequency). The friction generated due to the rapid oscillations of the dipoles produces large amounts of heat. This heat in turn is utilized by the sample for sintering. This provides uniform heating, microstructure formation and the densification or compactness of the sample.

2.6. Mechanism of Microwave Sintering

Microwave sintering of the metals involved is little known to the scientific community. Electromagnetic energy when passing through material, as discussed earlier, will interact with molecular dipoles and generate thermal energy, thus converting electromagnetic energy to thermal energy. The heat energy is generated throughout the volume of the material consistently and quickly. Part of the volumetric heat energy is lost by dissipation from surfaces, leaving the center of the specimen slightly hotter than the surfaces.

Microwave interactions with metals are found to be more complex than expected by researchers in the field. Factors that play a vital role in microwave heating of metals are specimen size, shape, mass, electromagnetic energy distribution in the cavity and the magnetic field strength of microwaves. The research is at its beginning stage, and it has to go a long way to exactly propose a theory on metal-microwave interactions.

3. Properties of Microwave Sintered Al-Metal Matrix Composites

The literature reports are limited mainly to the incorporation of amorphous/ceramic alloy reinforcements in pure Al metal matrix. The compressive strength of Ni-Nb-Ta amorphous alloy-reinforced Al-MMC synthesized by the squeeze infiltration technique is reported by Lee et al. [29]. Zheng et al. [30] investigated the microstructure and mechanical properties of Al-2024 and Al-2024-Fe composites synthesized by mechanical milling and hot extrusion. They observed a significant increase in the mechanical properties due to the grain refinement and the uniform distribution of the Fe-based metallic glass particles. Scudino et al. [31] and Kim et al. [32] have observed a 60%–90% increase in the compressive strength of high volume fraction of Zr- and Ni-base glassy metal particles in Al and brass matrices produced by microwave sintering compared to the powder metallurgy technique. Others have also reported the enhancement of compressive strength in Mg and Al-matrices reinforced with Zr-, Cu- and Fe-based glassy ribbons processed by powder metallurgy-based hot compaction through the induction heating method [32–35]. The processing techniques involved in these reports limit the particle dimension of the composites (4–10 mm in diameter), which has a greater impact on the compressive strength of the composites.

As mentioned earlier, microwave-assisted sintering has several advantages compared to many powder metallurgy-based techniques [36]. Microwave processing involves sintering of specimens by passing a microwave through them along with an external heating source coupled with the microwaves. Additionally, microwave processing has the advantage of reaching the metal melting point temperatures in a short interval of time, resulting in uniform and dense microstructures [36,37].

3.1. Interfacial Reactions in AMMCs

Jayalakshi et al. [38] fabricated Al-MMC reinforced with Ni₆₀Nb₄₀ amorphous particles using two-directional microwave rapid sintering with 5%, 10% and 25% particulate weight fractions. The microstructure and mechanical properties of matrix alloy and the developed composites have been evaluated. Their microstructure results showed that the reinforcements retain the amorphous structure and the consistent distribution without any interfacial reaction products (Figures 6 and 7). Structural dilatation in the amorphous reinforcement in 25% V_p composite is due to the local atomic rearrangement. The authors also reported that microhardness and compressive strength properties were increased tremendously with increasing of the volume fraction of Ni₆₀Nb₄₀. The highest V_p (25%) exhibited a prominent increase in strength of about 60%, is attributed to efficient load transfer

and matrix growth. They also reported that the $\text{Ni}_{60}\text{Nb}_{40}$ amorphous reinforcements could act as competent candidates compared to conventional ceramic alloy reinforcements at the same length scale.

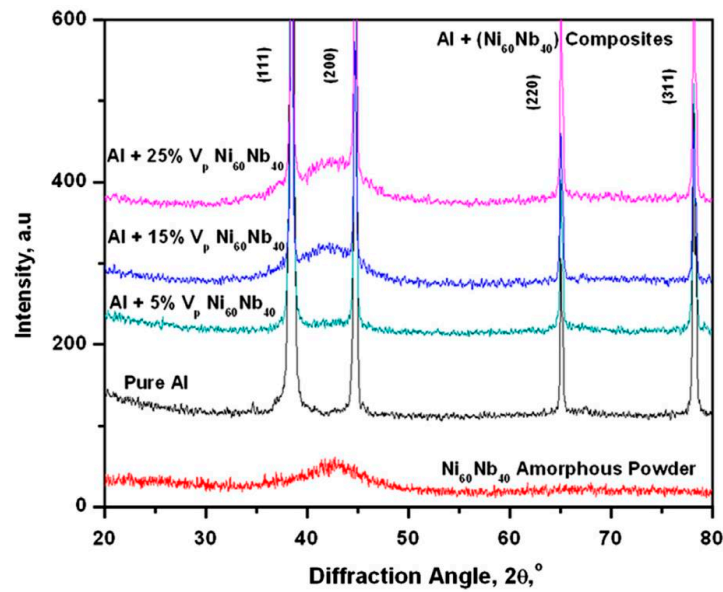


Figure 6. XRD pattern of the developed Al-composites compared with those of pure Al and as-received $\text{Ni}_{60}\text{Nb}_{40}$ amorphous powder [38].

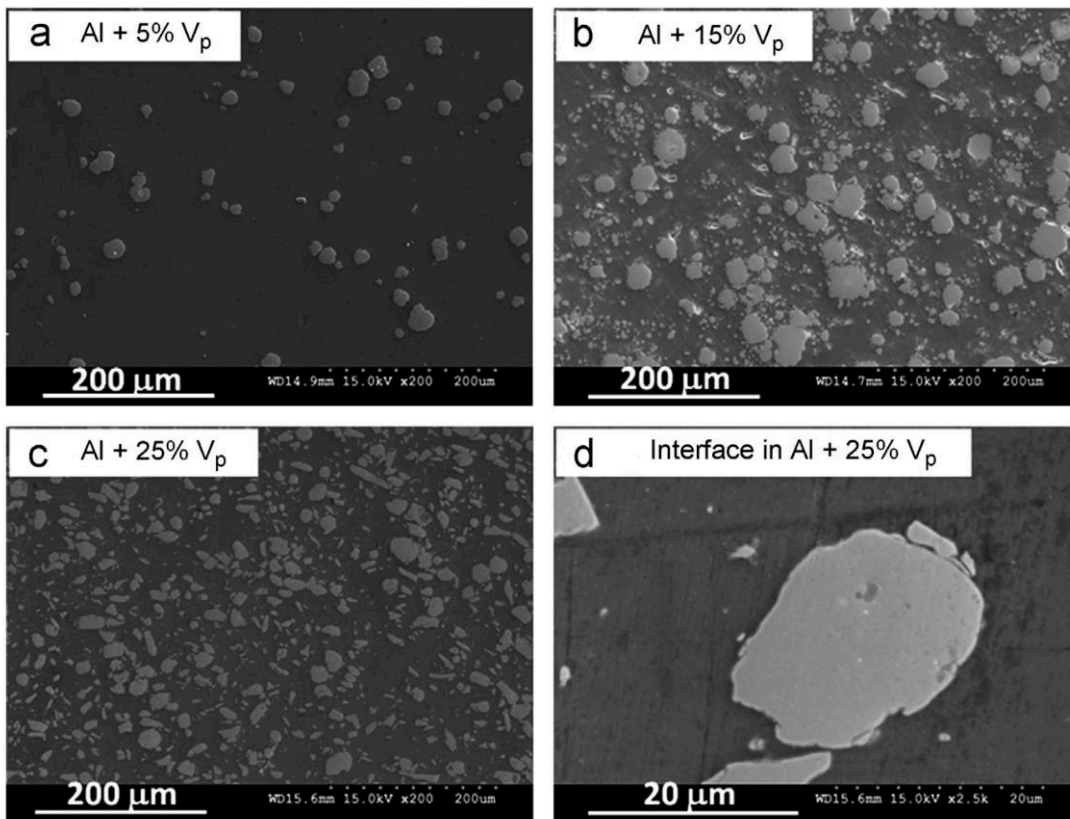


Figure 7. Field emission scanning electron microscopy images showing uniform distribution of amorphous reinforcement particles in Al-composite with, (a) 5% V_p ; (b) 15% V_p and (c) 25% V_p . Note the deformation of amorphous reinforcement particles at 25% V_p . (d) Representative image showing particle/matrix interface free of any interfacial products [38].

Zhu et al. [39] prepared and characterized Al-matrix composites containing α -Al₂O₃, Al₃Ni and Al₃Ni₂ particulates, which were synthesized from Al and Ni₂O₃ powders by the microwave technique. Al-based alloy was initially mixed with reinforcement of 20% (volume fraction); the weight ratio of Al and Ni₂O₃ powders was 87.11%:12.89% (in wt. %), respectively, and milled in a stainless steel jar under a sealed vacuum atmosphere for 2 h. The blended powder was then pressed into cylindrical specimens of a diameter of 30 mm and a length of 5 mm. The cylindrical specimens were sintered by the microwave heating method. Their results showed that an optimum microwave sintering temperature of 695 °C was essential for the synthesis of the Al-Ni₂O₃ system, which is lower than that in the conventional heating (735 °C). The SEM observations (Figure 8) indicated that the microwave-heated samples exhibited a finer and homogeneous microstructure when compared to samples prepared by other conventional sintering methods.

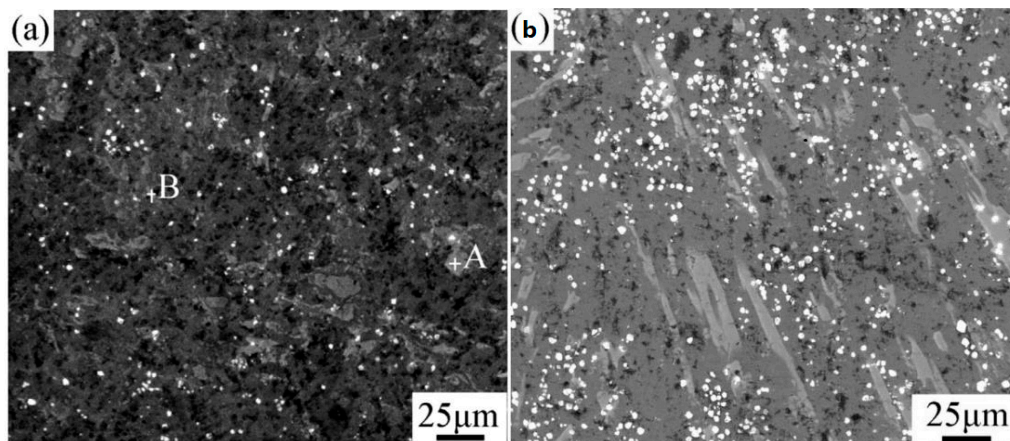


Figure 8. Scanning electron microscopy micrograph of the composites (Al-Ni₂O₃) obtained by Microwave (a) and conventional heating (b) method [39].

Pure Al and metastable Al/Cu nanocomposites reinforced with varying volume fractions of Cu nanoparticles were synthesized by Nawathe et al. [40] through the microwave hybrid sintering method. In the first step, Cu reinforcement nanoparticles were prepared by the powder metallurgy technique. In this process, certain amounts of Cu were blended with pure and a Al/Cu composite mixture in a RETSCH PM-40 (Retsch Solutions in Milling & Sieving, Hann, Germany) mechanical alloying machine for 1 h with a speed of 200 rpm. Milling balls or milling medium were not used during the milling step. The mixed Al and Cu powders were then uniaxially pressed at a pressure of 97 MPa into billets with a diameter and height of 35 mm and 40 mm, respectively. Billets of pure Al were compacted in the above dimensions without blending. In the next stage, the billets were sintered at a temperature near the melting point of Al using a multi-mode microwave oven (Sharp, Singapore) capable of delivering 900 W of power at a 2.45-GHz frequency at various microwave power levels of 30%, 50% and 100% for 50, 24 and 11 min, respectively. The microstructural properties of the prepared Al/Cu nano-composites were characterized by scanning electron microscopy. The SEM results revealed a uniform distribution of Cu reinforcement, except for some amount of clustering. The Cu phase was identified and confirmed by energy dispersive spectroscopy analysis (EDX) (JEOL USA Inc., Peabody, MA, USA), as shown in Figure 9. Clustering of Cu nanoparticles may be expected because of the large atomic size difference between Al and Cu powders and the high surface energy involved.

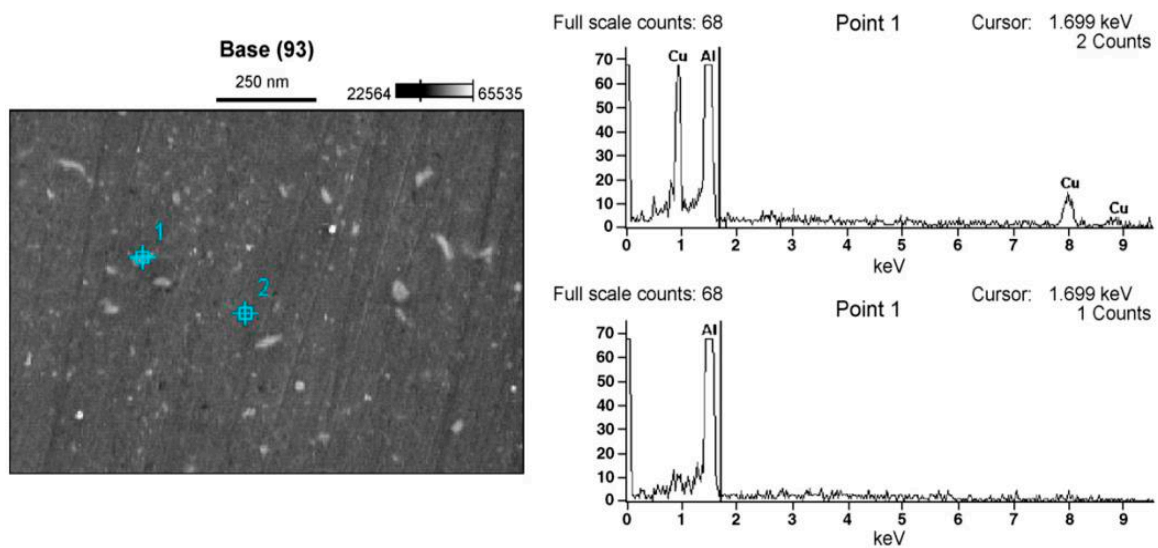


Figure 9. Energy dispersive spectroscopy analysis showing the presence of Cu phase in Al/Cu nanocomposites (Point 1 taken on Cu phase and Point 2 taken on matrix) [40].

The tensile fractured microscopic analysis of pure Al and Al-Cu composite formulations showed dimples (Figure 10), indicative of a ductile mode of fracture. The authors also reported that no other significant difference was seen in the fracture surface. Their observation may be attributed to the presence of Cu nanoparticles or microwave power variations during sintering [40].

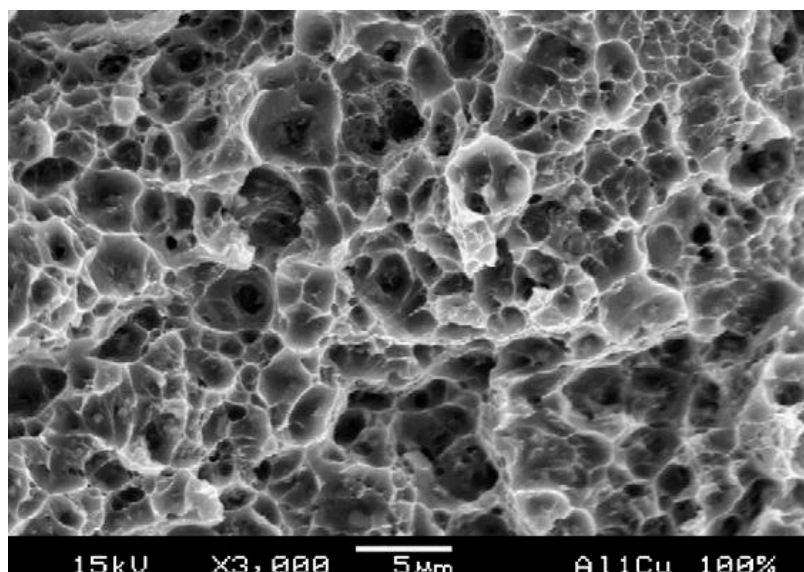


Figure 10. Representative Scanning electron microscopy micrograph showing the fracture morphology in Al/Cu Nanocomposites [40].

The fabrication and characterization of 6061 Al alloy reinforced with different content of reinforcements (i.e., 10, 20 and 30 wt. % (Ti,W)C) were studied by Zheng and his co-workers [41]. The 6061 Al alloy powder and (Ti,W)C powder were prepared by mechanical alloying using a two-station planetary ball mill for 1 h with a ball-to-powder ratio of 5:1 and a milling speed of 200 rpm. Then, the stoichiometric amount of 10, 20, 30 vol. % of (Ti,W)C amorphous reinforcement powder was mixed with pure aluminum in a planetary high-energy ball mill with a rotation speed of 200 rotations per minute (rpm). No balls were used in this stage. The blended carbide green

composites were compacted into rectangular billets ($23 \times 7 \times 7$ mm) at a pressure of 400 MPa for 2 min. The compacted billets were then sintered by microwaves at four different temperatures (500, 520, 540 and 560 °C) with a constant soaking time of 45 min. The authors reported that the porosity increased with an increase in the amount of (Ti,W)C particulates. At the same time, the porosity initially increased with an increase in sintering temperature. Furthermore, the grain growth trend has been significantly restrained by introducing the (Ti,W)C phase, while increasing the temperature facilitates grain growth. The XRD results showed that there was no significant interfacial product between 6061 Al alloy and (Ti,W)C particulate. The SEM micrographs showed a uniform distribution throughout the matrix, and a few agglomerations could be found even at the highest reinforcement content (30 wt. %). High resolution TEM analysis revealed defect-free interfaces between Al alloy grains and Al/(Ti,W)C in the composites, as shown in Figure 11.

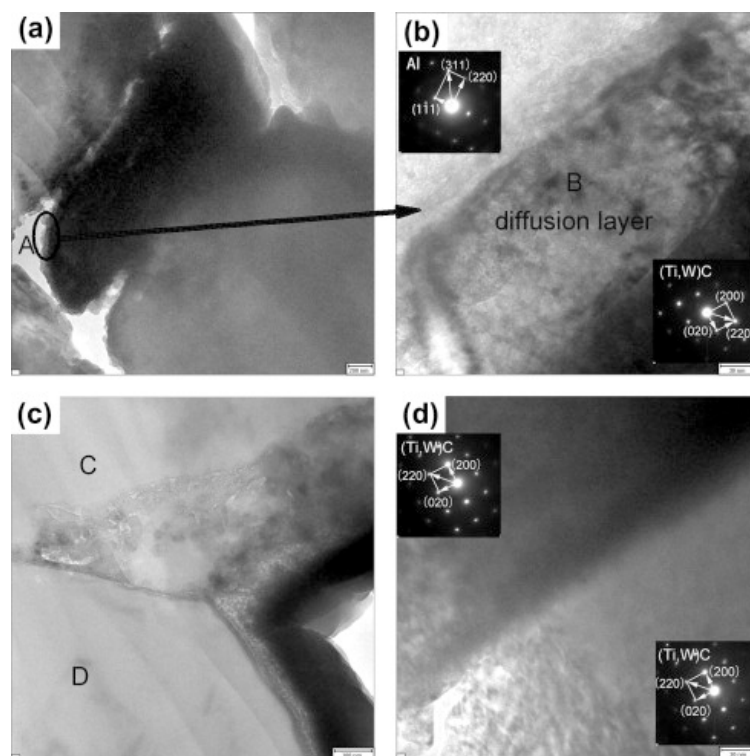


Figure 11. High-resolution transmission electron microscopy images of the interfaces: (a) the interface between (Ti,W)C and liquid Al phase; (b) micrograph at high magnification; (c) the Al/Al interface; (d) the (Ti,W)C/(Ti,W)C interface [41].

Bayraktar et al. [42] reported a uniform distribution of Fe_3O_4 reinforcing particles in new aluminum matrix composites and Al composites processed through the microwave heating process. The experimental results showed that the density after sintering increased regularly with the compact pressure and percentage of iron oxide.

Recently Zhu et al. [43] investigated the fabrication and characterization of in situ Al_2O_3 - and Al_3Zr -reinforced aluminum matrix composites by microwave combustion synthesis. Their results demonstrated that the obtained microstructure was found finer than that prepared by the conventional methods, and no cracks could be seen in the Al_3Zr reinforcements. As such, the newly-developed composites have potential for safety-critical applications where catastrophic failure is not tolerated. The reported mechanical properties of the pure Al and various reinforced Al metal matrix composites' data are given in Table 1. However, more efforts are still needed to better understand the effect of reinforcement and different experimental conditions, such as: microwave power levels, heating rate, sintering time and sintering temperature.

Table 1. Mechanical properties of the pure Al and Al based metal matrix composites by microwave sintering.

Matrix	Reinforcement Alloy/glassy Particles	Fraction of Amounts	Processing Circumstances	Microhardness (Hv)	Compressive Yield Strength (MPa)	Ultimate Compressive Strength (MPa)	Strain at Fracture (%)	Ref
Pure Al	-	-	Powder Metallurgy Technique + Hybrid Microwave Sintering + Hot Extrusion	45 ± 1	133 ± 43	160 ± 44	14.5 ± 0.8	[44]
Pure Al	B ₄ C particles	10 wt. %	Mixture Mill Technique + Microwave Sintering Method + Hot Extrusion	83	280	-	-	[37]
		15 wt. %		108	315	-		
		20 wt. %		112	325	-		
Pure Al	Ni ₆₀ Nb ₄₀ amorphous alloy	5 vol. %	Mechanical Alloying Method + Microwave Assisted Rapid Sintering + Hot Extrusion	74.5 ± 4.15	114 ± 6	300 ± 5	>50	[38]
		15 vol. %		103.3 ± 4.4	125 ± 2	333 ± 6	>50	
		20 vol. %		125.2 ± 4.4	155 ± 8	375 ± 10	>50	
Pure Al	Cu nanoparticles	1 wt. %	Mechanical Alloying + Microwave Synthesis + Hot Extrusion	66 ± 1	157 ± 4	251 ± 5	16.4 ± 10.7	[40]
6061 Al Alloy	(Ti,W)C particulate	10 wt. %	Powder Metallurgy Technique + Microwave Sintering method + Hot Extrusion	59 ± 4	118 ± 1	346 ± 6	39.56 ± 1.72	[41]
		20 wt. %		69 ± 5	151 ± 4	415 ± 6	37.58 ± 18.1	
		30 wt. %		90 ± 4	236 ± 3	474 ± 14	33.48 ± 1	

3.2. Influence of Reinforcement Volume Fractions on the Mechanical Properties

Jayalakshmi et al. [38] reported that the amorphous reinforcement contributes toward the significant improvement in the yield strength of the composites. The representative stress-strain curves under compression and tension are shown in Figure 12a,b. The strength of Ni₆₀Nb₄₀ amorphous particle-reinforced aluminum composites increased with increasing the volume fraction of reinforcements. Furthermore, they compared the mechanical properties (ultimate tensile strength and ductility) of their composite with those of traditional ceramic-reinforced MMCs [40,41], as shown in Figure 13.

The compressive engineering stress-strain curves are shown in Figure 14. Mechanical studies revealed that the maximum strength and minimum failure strain were achieved for the Al/Cu composite sintered at 50% microwave power level compared to the other two microwave power levels for the sintered Al/Cu composites [40]. The microstructure of the fractured samples was investigated using scanning electron microscopy and showed dimples in the reinforcing particles, which indicates the ductile mode of fracture.

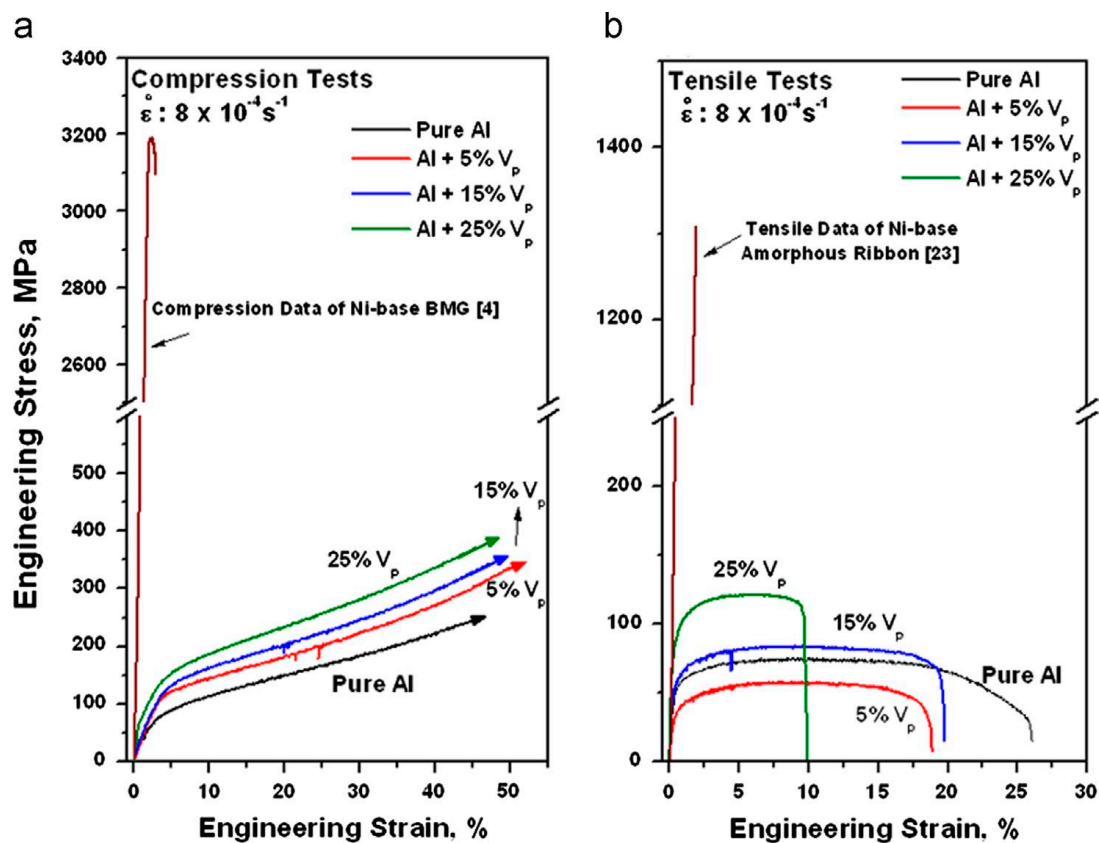


Figure 12. Engineering stress-strain curve of pure Al and Al-Ni₆₀Nb₄₀ amorphous particle reinforced composites under: (a) compression and (b) tensile loading conditions. Stress-strain curve of a Ni-base BMG/amorphous alloy ribbon is also presented [38].

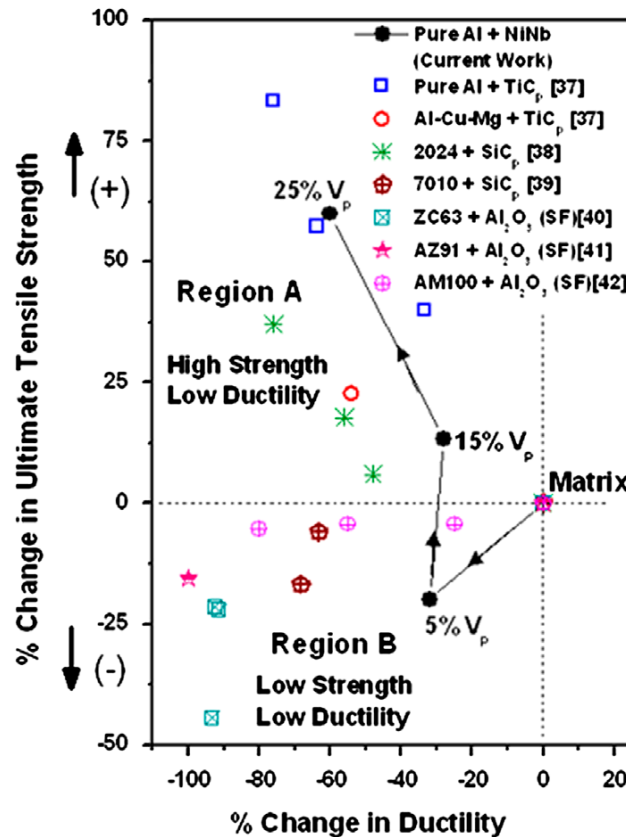


Figure 13. Percentage change in ultimate tensile strength with the percentage change in ductility in the developed composites, compared to those of conventional ceramic-reinforced metal matrix composites (MMCs) [38].

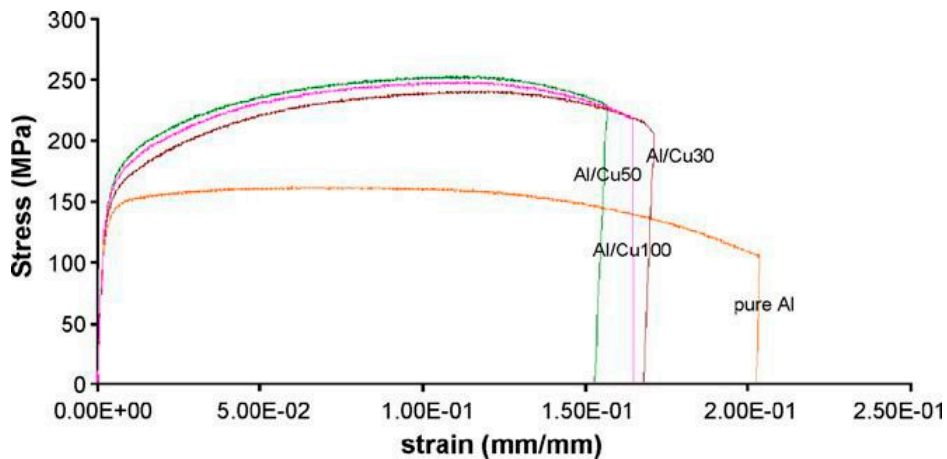


Figure 14. Representative stress-strain graphs for pure Al and Al/Cu nanocomposites [40].

3.3. Effect of Sintering Temperature on AMMCs

Recently, Ghasali et al. [44] reported the synthesis, microstructural and mechanical properties of B₄C-reinforced aluminum composites using the microwave sintering method. In the first stage, mechanical mixing was used for the synthesis of 10, 15 and 20 wt. % B₄C-Al composites. Then, the mixed powders were compacted to prepare the bar-shaped samples with the dimension of 25 × 5 × 5 mm at 250 MPa using a uniaxial press. The sintering of samples was carried out using

a microwave furnace (900 W and 2.45 GHz), in which the temperature was monitored using an optical pyrometer at 650 °C, 750 °C, 850 °C and 950 °C without soaking time in a graphite bed. The authors observed that there were no sharp changes in the density of different composites sintered at the same temperature (Figure 15). The results of structural characterizations, such as X-ray diffraction and scanning electron microscopy, revealed the achievement of grain refinement, a homogeneous distribution of the low volume fraction of reinforcement and the lower sintering temperature of 850 °C in the Al-B₄C composites. The effect of different amounts of B₄C on the microstructure and mechanical properties of Al matrix was also examined. It was observed that the Al-10wt. % B₄C-1wt. % Co composite exhibited some porosity around the B₄C reinforcement particles. They [44] reported that the microhardness was increased with the increasing amount of reinforcement (Figure 16), since B₄C is inherently harder than Al matrix, and the fairly good distribution of the reinforcements improves the ability of the soft matrix to resist deformation. Sintering temperature is another important parameter that influenced the microhardness of the composite. They concluded that microwave sintering has the capability to produce Al/B₄C composites in a short time and with the saving of energy.

A continuous and tight interface without voids and debonding area could also be found, and the inserted electron diffraction indicated that the two phases aside the interface are (Ti,W)C particulates. Nawathe et al. [41] also reported that the average microhardness, compressive yield strength, as well as compression strength were enhanced with an increase of both (Ti,W)C reinforcement level and sintering temperature, as shown in Figure 17. An interesting point noticed here was that a small amount of the liquid Al phase appeared around the (Ti,W)C due to the better absorbing ability of (Ti,W)C to microwave and heat concretion due to the angular initial powder. The appearance of liquid might have promoted interfacial adhesion.

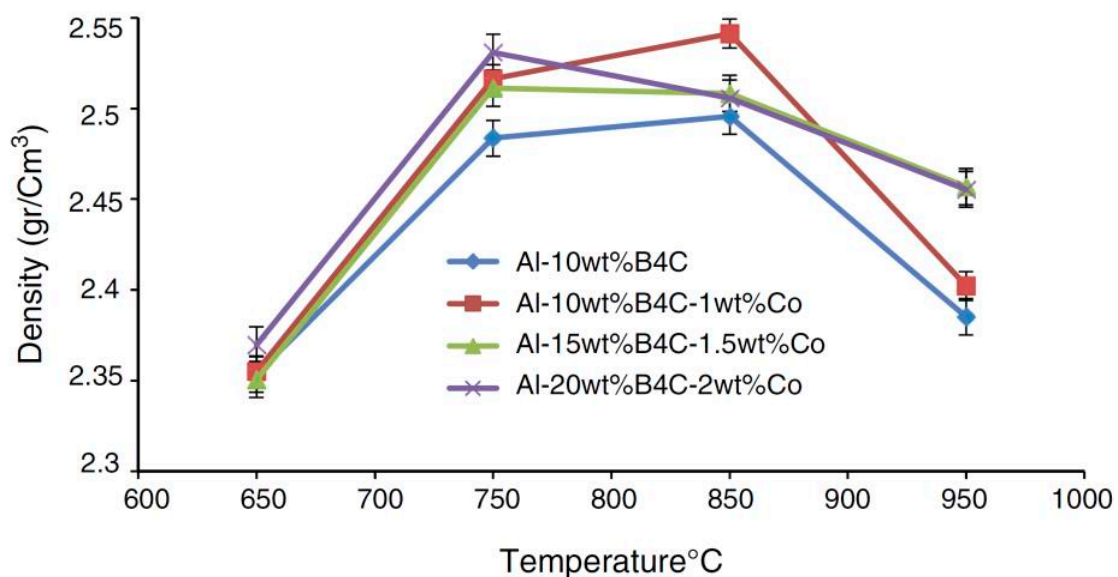


Figure 15. Density versus sintering temperature [44].

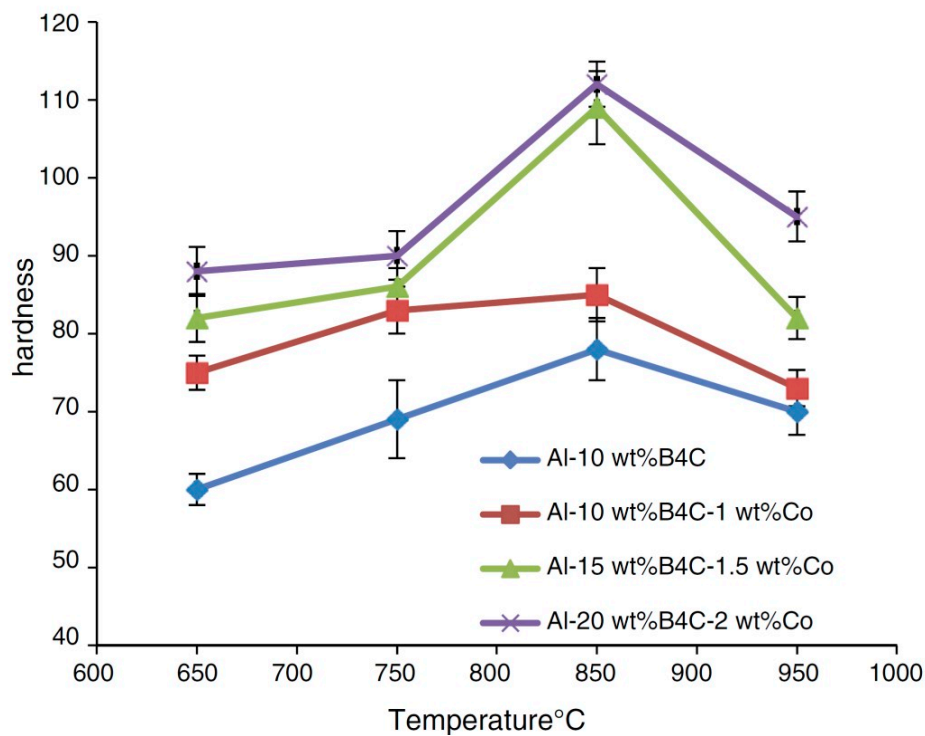


Figure 16. The effect of sintering temperature on microhardness on microwave sintered B_4C -Al composites samples [44].

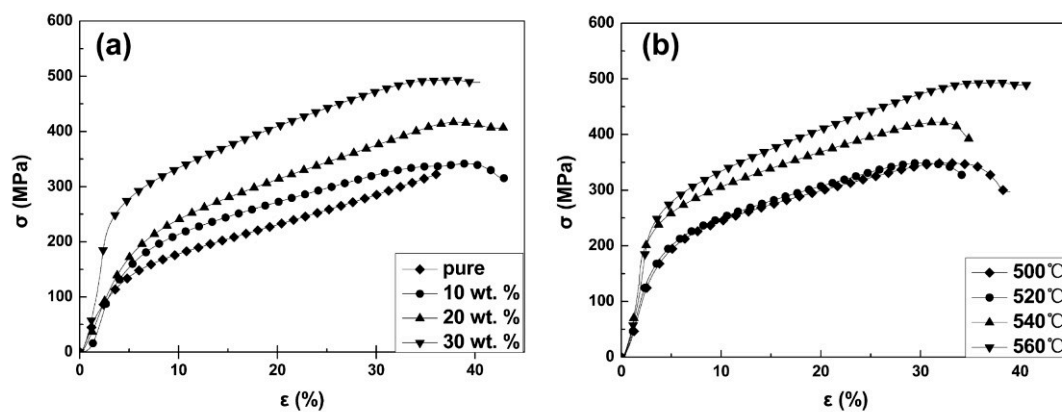


Figure 17. The effect of (a) (Ti,W)C content and (b) sintering temperature on stress-strain behavior of the composites [41].

4. Conclusions

In this review article, the microwave rapid sintering technique was presented, and the recent published work on microwave-rapid sintered pure aluminum and aluminum metal matrix composites was reviewed. A significant quantity of interest in AMMCs by researchers among academics and industry has helped in the investigations of various studies and has enriched our knowledge about the microwave sintering of Al metal matrix composites, their structural, physical, thermal and mechanical properties. The major conclusions are summarized as below:

The cost-effective and innovative microwave rapid sintering process followed by secondary processing, such as hot extrusion, can be successfully utilized to synthesize pure Al and Al-metal matrix composites.

The advantages of microwave rapid sintering, such as shortened processing time and reduced energy consumption, as well as rapid heating rate improve the homogeneity of the microstructure and the mechanical properties of the composite materials.

Aluminum composites containing amorphous reinforcement can be prepared using the microwave sintering route. The amorphous nature of the reinforcements can be retained in the composites with no interfacial reaction products.

It was observed that the hardness and compressive properties of the aluminum metal matrix composites increased remarkably with varying volume fractions of reinforcements. The hardness of amorphous-reinforced composites could also be improved by sintering time and sintering temperature.

The tensile properties of microwave-sintered Al-metal matrix composites were predominantly superior to those produced with tradition sintering techniques.

More research work is needed to better understand the effect of reinforcement and different experimental conditions: microwave power levels, heating rate, sintering time and sintering temperature to fine-tune the microwave processing method for different materials.

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