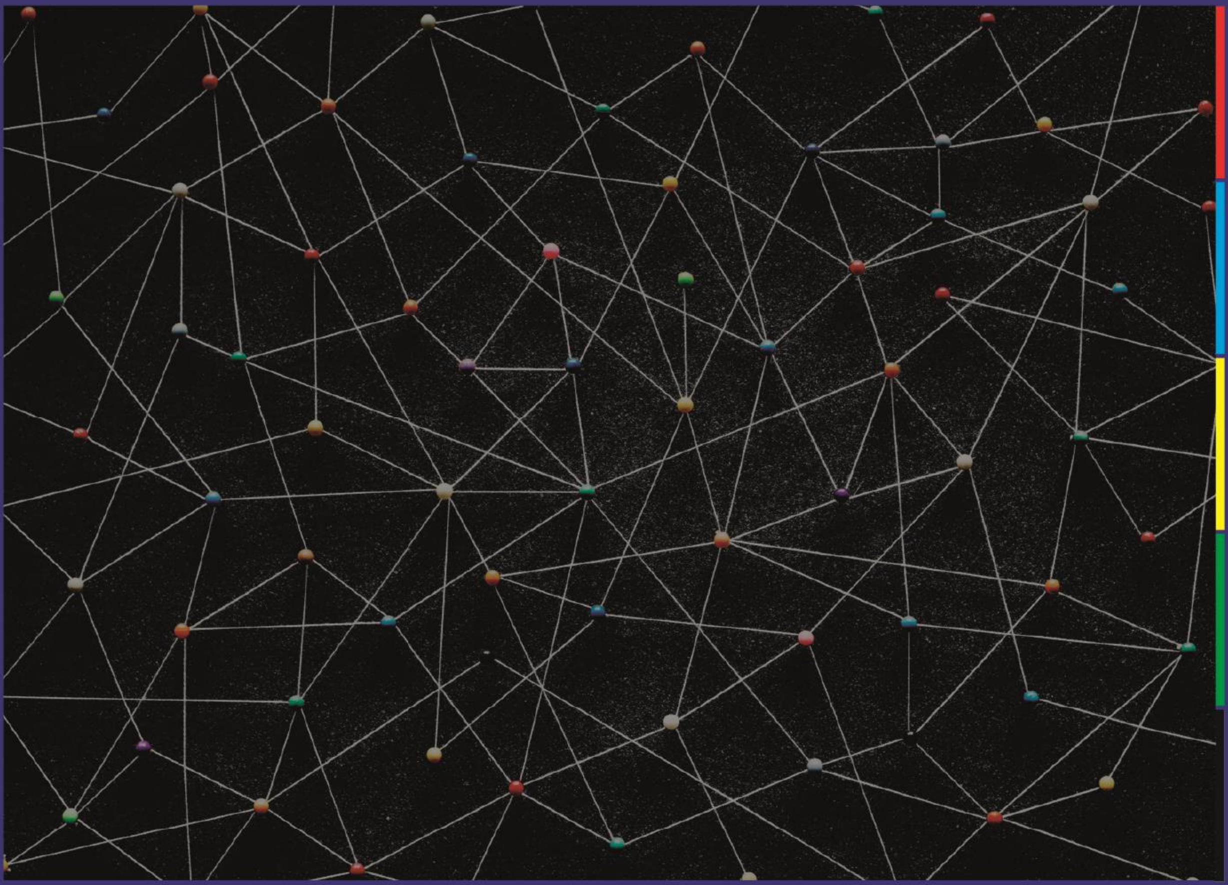
Examination of Mechanical Properties of B4C Particulate Reinforced Aluminum MMC Under Different Loading Conditions



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Examination of Mechanical Properties of B4C Particulate Reinforced Aluminum MMC Under Different Loading Conditions

By

İsmail TOPCU

2023

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INTRODUCTION

Powder Metallurgy is a highly evolved method of manufacturing reliable net shaped components by blending elemental or pre-alloyed powders together, compacting this blend in a die and sintering or heating the pressed part in a controlled atmosphere furnace to bond the particles metallurgically. The P/M process is a unique part fabrication method that is highly cost effective in producing simple or complex parts at final dimensions (Koczak, M. J. 1989).

MMC consist of at least one metal and a reinforcement material as continuous fiber, intermetallics particles, compounds, oxide, carbide or nitride in order to achieve requirements and expected properties which can not be met by single compound materials (Huda at all 1995). Nowadays production of metal matrix composites by liquid phase process is convenient in the production of MMC reinforced with particles. The driving force behind the development of MMC has been the attractive mechanical and physical properties and enhanced elevated temperature capabilities (Topcu at all 2020, Lee at all 2001). In addition, AMC reinforced with ceramic particles or whiskers have received considerable attention because they can be formed by standard metalworking practices. Apart from improved mechanical properties, other controlling attributes, such as coefficient of thermal expansion and wear resistance, are greatly improved by the addition of ceramic particles (Chapman at all 1999).

With good properties, such as high hardness, high melting point, good thermal conductivity and good electrical conductivity, boron carbide ceramics are excellent candidates for neutron absorption materials, wear resistant materials, electrode materials and cutting tools (Schwartz, M.M..(1984) , Topcu at all 2020). Among the outstanding physical and mechanical properties of boron carbide is its hardness, which is second after diamond and c-BN. This specific property comes along with other attractive properties such as high impact and wear resistance, low density, high melting point, and excellent resistance to chemical agents as well as high capability for neutron absorption.

Aluminum MMC are being considered as a group of new advanced materials for its light weight, high strength, high specific modulus, low coefficient of thermal expansion and good wear resistance properties. Combination of these properties is not available in a conventional material (Huda at all 1995). The use of Aluminum MMC has been limited in very specific applications such as aerospace and military weapon due to high processing cost. For applications at low temperatures, aluminum or aluminum alloys is a material of choice. Suggested applications for B4C-Al composites include its use as a structural neutron absorber, arm our plate materials, and as a substrate material for computer hard disks(Du, W .F,1997).

The term composite is used for describing materials which are semi-homogenous and have higher mechanical and physical properties than the properties of their components. Although there is no well known description for composite materials, by the broadest definition, composite materials can be described as materials which have at least two chemically distinct metal or non-metal components with a distinct interface separating the constituents (Ahlatçı, H. 2003). Figure 1. shows the materials used for producing composites.

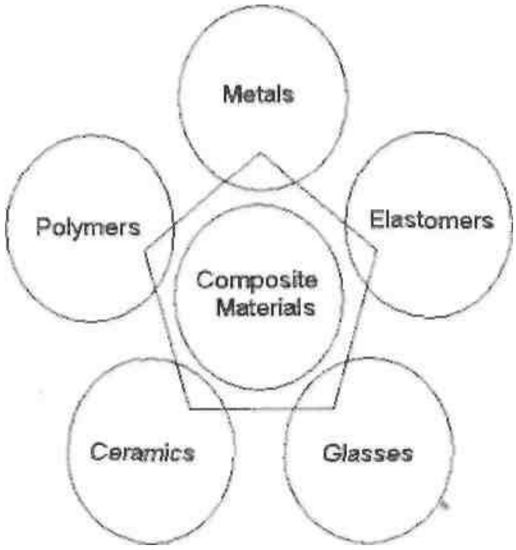


*Figure 1: Material classes used in composite materials (*Ahlatçı, H. 2003*)*

In order to shorten the range of description given above, composite materials must have the following properties (Akbulut, H. 2001).

In the production of composite materials, many different types of reinforcements are used. According to their structural shapes, reinforcement materials are basically classified as continuous or discontinuous. Reinforcement materials are found in the following forms (Yörükler E.C. 2006)):

Depending on the type and shape of the constituent, composites can be classified as

Continuous fiber reinforced composites

Particulate reinforced composites

Whisker or discontinuous fiber reinforced composites

Plate like composites

Filled composites

Laminate composites

If matrix materials are considered, classification can be made as follows (Mary T. Spohn, 1994) :

Ceramic matrix composites

Polymeric matrix composites

Metal matrix composites

Aluminum (Al) alloys and Al alloy based MMC are all widely used as engineering and construction materials. The important characteristics of Al alloys are their light weight and high strength-weight ratio. The mechanical properties of Al alloys can be greatly enhanced by incorporating reinforcing particles to form composites. Possible applications include air-frame components, automotive engines, transmission and brake disc components and bicycle frames. Boron carbide (B4C) belongs to light ceramic material group, melts at high temperatures and exhibits high mechanical properties, chemical resistance as well as neutron absorbing (Dieter, G.M.1989, German 2005, Topcu at all 2019). Despite all its advantages, low fracture toughness is the most important disadvantage of boron carbide. B4C is the third hardest materials after diamond and cubic boron nitride, but the most produced and used hard materials(Dieter, G.M.1989).

Powder metallurgy (P/M) technology provides a useful means of fabricating net shape components that enables machining to be minimized, there by reducing costs. In addition, P/M technology can be used to refine microstructures compared with those made by conventional ingot metallurgy, which often results in improved mechanical and corrosion properties. Consequently, the usefulness of aluminum alloys for high technology applications, such as those in aircraft and aerospace structures, is extended. Aluminum alloys have numerous technical advantages that have enabled them to be one of the dominant structural material families of the 20th century. Aluminum has low density (2.71 g/cm3) compared with competitive metallic alloy systems. It also has good inherent corrosion resistance because of the continuous, protective oxide film that forms very quickly in the air, and good workability that enables aluminum and its alloys to be economically rolled, extruded, or forged into useful shapes (Koczak, M. J. 1989).

GENERAL BACKGROUND

1.Powder Technologies

Powder technologies are provocative to engineers, not only because of the replication capabilities, but because design options allow for the selective placement of phases or pores to tailor the product to the application. The powder metallurgy and particulate materials processes, commonly abbreviated as P/M2 enable many kind to form net shaping bodies, similar to castings. But unlike casting, which is only applied to metals with a lower melting temperature, powder techniques are applicable to almost all materials. Thus, many of the products created via P/M2 technologies are not available as castings, such as composites, high temperature ceramics, certain polymers, copper, steels, refractory metals, and a wide variety of intermetallics, cermets, and mixed phase compositions. For large volume production, powder technologies rely on a die cavity which is replicated over and over. Freeform fabrication extends the technology to the fabrication of single objects. Cost is always an important factor, so the ability to fabricate complex shapes to final size and shape has significant economic benefit. Further economic gains come from the fact that powder processes use automation with relatively low energy consumption, while exhibiting high material utilization (German 2005).

The P/M2 processes derive from a synthesis of many technologies powder metals, ceramics, particulate composites, and even plastic molding and metal forging. One widely employed option is to mix combinations of insoluble powders to form composites. Significant property customization is achieved in these materials by controlling the microstructure in terms of the relative sizes, shapes, and amounts of the phases. Further, P/M2 routes allow for the production of porous structures that are useful in filtration, lubrication, and energy dissipation. Often there is no competing technology for these products (Koczak, M. J. 1989).

A few terms are defined to start the discussion. First, particles are discrete, small divisions of solids. Particles come in many sizes, ranging from the size of a virus to sand. The convenient unit for particle size is the micrometer (μm), which is 10-6 m or about 0.00004 inch. Most engineering particles used in P/M2 range from 0.1 to 200 μm in size, with ceramic particles tending toward the smaller sizes and plastic particles tending toward the larger sizes. For reference, human hair is typically in the 100 μm range and the pigment in paint is typically in the 1 μm range. A powder is a collection of particles. Powders often consist of mixtures of different particles, including polymer phases. Powders covered in this book are metals, ceramics, intermetallics, and various composites or cermets. However, in recent years there have been significant developments in the use of powdered polymers. To achieve the customized properties desired in many engineering applications, the powders used in P/M2 are mixtures of particles where the amount, size, and placement of phases are selected to attain the desired properties. As a simple example, a powder mixture used to form automobile connecting rods is composed of iron, copper, graphite, and zinc stearate particles. Accordingly, many of the P/M2 systems are inherently composites and powders used in production are usually mixtures of different particles. After processing, the powder is bonded into a solid and the character of the initial particles is often lost. At that point the discrete crystal regions are termed grains. So particles are mixed to form powders. Powders usually flow under the action of gravity. After sintering the structure consists of grains that are bonded to form a solid component.

An important characteristic of a powder is the high ratio of surface area to volume. Particles exhibit behavior that is between that of a solid and a liquid. Powders will flow under gravity to fill containers or die cavities; in this sense they behave like liquids. All powders exhibit some compressibility like a gas, but after deformation they become rigid like a solid. The harder the particles, the higher the pressure needed for compression. Often a polymer is added, most powders are easily shaped, but not necessarily deformed, so shaping technologies and compression technologies are the two major routes to forming green bodies. Prior to heat treatment to sinter the particles, the compact is termed "green." Thus, a powder is easily shaped, especially with polymer processing aids, and the sintered product behaves like a solid (German 2005).

Powder consolidation activities include compaction and sintering. The core technologies change the shape, properties, and structure of a powder to produce the desired product. Softer powders can be pressed to nearly full density, but hard powders resist pressing they are bonded into the desired shape using polymers. Sintering is a thermal treatment applied to a powder that induces bonding or brazing of the particles, leading to very strong and useful solid bodies. After the forming and sintering stages, attention turns to the properties, with emphasis on microstructure. Indeed, microstructure control is a significant advantage of powder processing. Phases can be mixed or even placed in layers to tailor function in a device. Other material forming techniques cannot compete with this ability to customize the microstructure to the application Turan E.(2003), Topcu at all 2020).

2.Powder product Techniques

2.1 Basic Approaches

Knowing how a powder is made provides a first means to estimate its characteristics such as size and shape. Almost all materials can be made into powder, but the method selected for fabricating a specific powder depends on a mixture of factors costs, reactions, and desired characteristics. The main categories for fabricating powders are based on mechanical comminution, chemical reactions, electrolytic deposition, liquid atomization, and vapor condensation. In addition to these main approaches, several specialty techniques are used for selected materials.

In all of the powder fabrication techniques, energy is delivered to create surface area. Unfortunately, the processes are low in efficiency, so the energy required to form a powder is many times larger than the newly created surface energy. In terms of energy, consider the reduction of one cubic meter of a material into 1 pm particles. For spherical particles this gives nearly 2x1018 particles with a net surface area of approximately 6x106 m2. Most engineering materials have surface energies from 1 to 2 J/m2, so this corresponds to an energy of 6 to 12 MJ/m3 of energy. This actually is not that much energy, just 1.7 to 3.4 kW/h which would cost typically $0.15 to $0.30 in electricity. However, with a low process efficiency the input energy can be much larger, often 30 times more than the newly created surface energy. The selection of one fabrication method over another depends on understanding the process, its economics, the resulting powder characteristics, and how those characteristics match with the intended application (German 2005).

2.2 Mechanical Fabrication Techniques

There are four fundamental mechanical comminution processes: impaction, attritioning, shearing, and compression. Impaction involves the rapid, instantaneous delivery of a blow to a material, cracking the material into smaller pieces, such as by hammering. Attritioning applies to the reduction in particle size by a rubbing motion usually caused by grinding media rubbing against each other. Shearing fractures the material by a cutting process, such as occurs in machining. Indeed, many early metallic powders such as silver for dental amalgams (fillings) were created using lathe turning. Powders formed by shearing tend to be large. Impaction, attritioning, shearing and compression are usually combined during mechanical powder fabrication. For powders in the millimeter size range, hammer mills are efficient, but for powders in the 1 to 100 pm size range, stirred ball mills and other intense attritioning devices are more appropriate. Powders produced by mechanical techniques are typically irregular in shape as shown in Figure 2 for both a milled boride and machined aluminum. The following subdivisions show how basic comminution techniques are manifested in fabricating powders (German 2005).

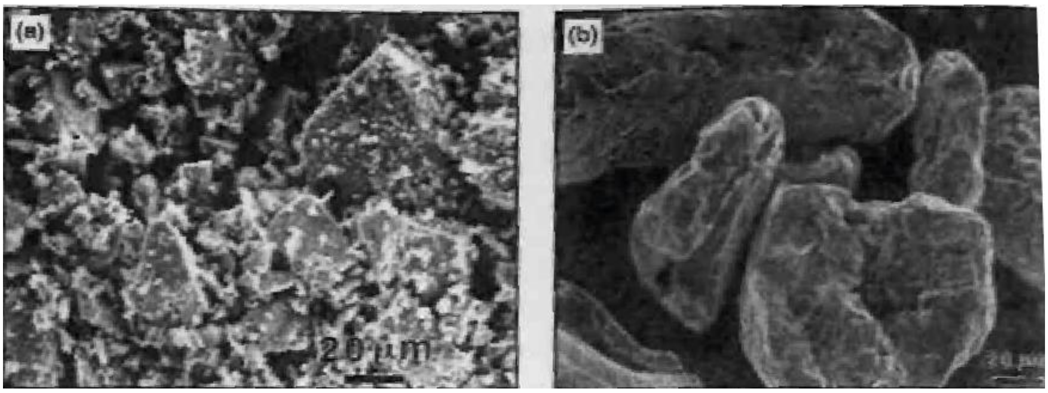
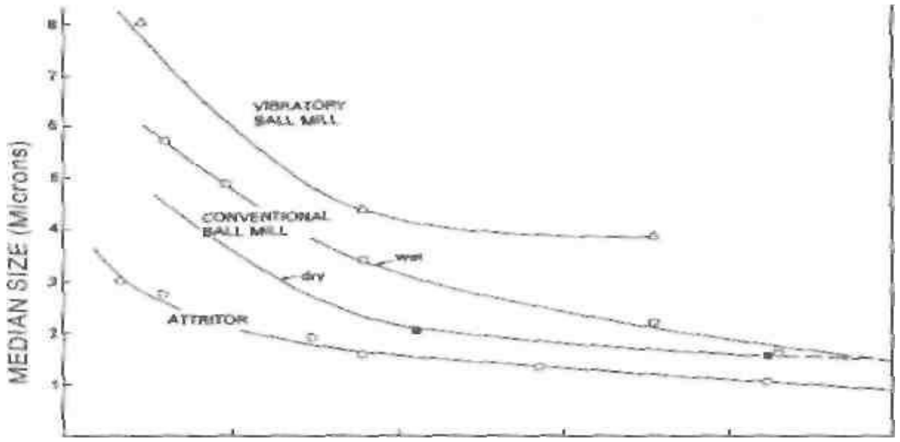


Figure 2. Scanning electron micrographs of powders produced by mechanical techniques: a) Milled iron boride b) machined aluminum powder prepared by mechanical cutting [12].

2.2.1 Attritioning and Mechanical Alloying

Particulate composites such as oxidedispersion strengthened materials have been used for their high-tempreture creep resistance for many years. Obtaining a homogeneous distribution of hard phase throughout the matrix is an inherent difficulty in fabricating dispersion strengthened materials. Milling techniques have evolved to generate these composites. A successful technique is mechanical alloying which employs the attritioning motion between agitated balls to create an alloyed composite particle (Suryanarayana, C. 2004).

Conventional ball mills use large media, normally in or larger, and run at a low speed (10-50 rpm). Attritions, on the other hand, use grinding medium of about 1/8 to 3/8 in. size and run typically at moderate speeds of about 60 rpm in the largest production size units, but at about 250 rpm for the laboratory size units. The most important concept in the attrition is that the power input is used directly for agitating the media to achieve grinding and is not used for rotating or vibrating a large, heavy tank in addition to the media. Figure 3 shows a comparison of the effectiveness of the various grinding devices in ultra fine grinding of chalcopyrite concentrate. It may be noted that the attritor is much more effective than a conventional ball mill or a vibratory ball mill. For the specific energy input of around 100 kWh/ton, the median particle size achieved through the attritor is nearly half smaller than that obtained from conventional ball mills, and is about one-third smaller than that obtained from vibratory mills. Furthermore, for specific energy input exceeding 200kWh/ton, attritions continue to grind into the sub micrometer range, while other grinding machines can no longer effectively produce any smaller particles Turan E.(2003).



Specific energy input, (kwh/t)

Figure 3. Comparison of the effectiveness of various grinding devices for ultrafine grinding of chalcopyrite concentrate.

2.2.2 Milling

Milling implies mechanical impaction using hard balls, rods, or hammers and is a classic approach to fabricating powders from brittle materials. The simplest device is a jar mill, such as diagramed in Figure.4, that consists of a cylindrical jar filled with balls and the material to be milled. As the jar rotates, the balls continuously collide with the powdered material, further crushing it into smaller particles. The impact stress required to fracture a brittle material via milling relates to the materials defect strucrute and sensitivity to crack propagation. Larger require less impact stress to fracture. As the particle size decreases during milling, the required stress Increase (Suryanarayana, C. 2004).

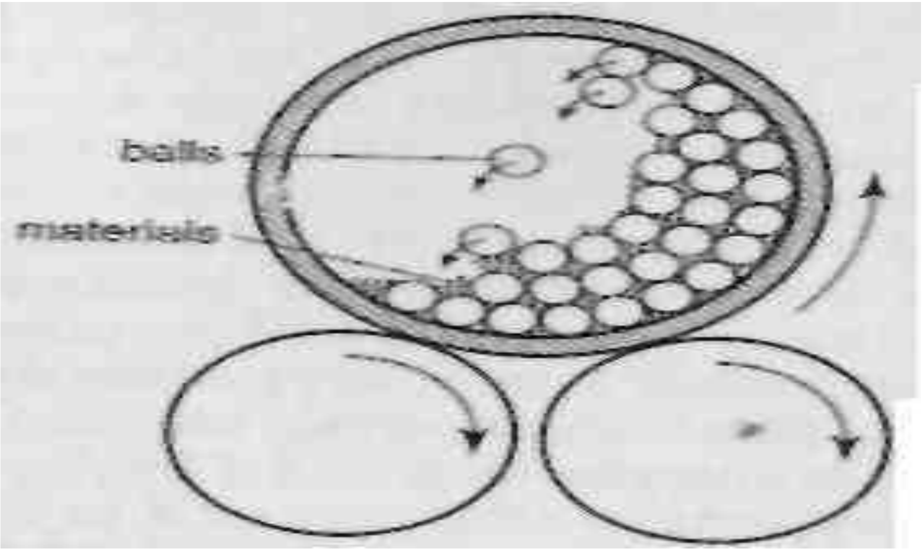


Figure.4 A view of the action in ajar mill. The jar is rotated on its side and the impact of the falling balls grinds the material into a powder [(Suryanarayana, C. 2004).

2.2.3 Machining

Large powder with an irregular shape results from the shear associated with machining wrought material. The large amount of machining scrap produced in metalworking operations provides an abundant source of powder. Such scrap is cleaned by chemical techniques and often is further milled to reduce the parti cle size. Indeed, it is common to change either the particle size or particle shape via milling (German, R,M. 2005).

2.2.4 Other Impaction Techniques

Powder fabrication techniques based on high strain rate impacts are useful for brittle materials. Compressive crushing a jaw crusher works well with weak materials to bring the particle size down to 1 mm or so. Beyond that size, high velocity impact mills with hard blades can be used to further reduce the particle size. Production rates are slow. In the cold stream approach the particles are launched at supersonic velocities to collide with a cold, hard target. The input powder is accelerated in a feed gas using pressures of approximately 7 MPa (1ksi). The product is generally above 10 um in size with a rounded but irregular shape. A cold operating temperature tends to make the material more brittle and aids impact attritioning. The technique is used in fabricating flame spray powders (powders for protective coatings) and stainless steel powders for filters (Suryanarayana, C. 2004).

2.2.4.1 Electrolytic Fabrication Techniques

Elemental powders can be deposited at the cathode of an electrolytic cell under certain operating conditions; example metals include palladium, chromium, copper, iron, zinc, manganese, and silver. The main benefit of an electrolytic method is the high product purity [13].

2.2.4.2 Chemical Fabrication Techniques

Most materials can be fabricated into powders by chemical techniques. Typically the particle size and shape are adjusted by controlling the reaction variables. There are several variants to chemical synthesis: powders are formed by solid, liquid, or vapor phase reactions (Turan E. 2003).

2.2.4.3 Gas Atomization

The use of air, nitrogen, helium, or argon as a gas for breaking up a molten stream is termed gas atomization. The liquid material is disintegrated by rapid gas expansion out of a nozzle, just as a perfume is misted. Equipment designs vary with respect to the molten material feed mechanism and the sophistication of the melting and collection chambers; however, the main idea is to deliver energy (from a rapidly expanding gas) to the molten stream to form droplets which immediately solidify into particles (Suryanarayana, C. 2004).

3. Composite Materials

A composite, in general, is defined as a combination of two or more components differing in form or composition on a macroscale, with two or more distinct phases having recognisable interfaces between them (Jain, S. 2005).

Proper combination of materials into composites give rise to properties with transcends those of the constituents, as a result of the principle combined action. Materials of biological origin are generally composites -(Akovali, G.2001). Bone, for instance, achieves its combination of lightness and strength by combining crystals of apatite (a compound of calcium) with fibres of the protein collagen, whereas wood contains cellulose fibres surrounded by lignin and hemicellulose. Crushed rock aggregate used in concrete produces a composite structure, which reduces the cost and helps to improve the compressive strength. Structural weight savings (while retaining the reliability and strength), are achieved for aerospace, rocket applications etc. by the use of composite materials (Table 1) -(Berthelot at all, 1999).

Composites are produced to optimise material properties, mechanical (mainly strength), chemical and/or physical properties. In the latter, optimisation of thermal (thermal expansion, thermal conduction, specific heat, softening and melting points) as well as electrical (electrical conductivity, dielectric loss), as well as optical and acoustical properties can be noted. Since the early 1960s, there has been an increasing demand for materials that are stiffer and stronger, yet lighter in aeronautic, energy, civil engineering and in various structural applications (Schwartz, M.M..1984).

Composites usually consist of a reinforcing material embedded in a matrix. The effective method to increase the strength and to improve overall properties is to incorporate dispersed phases into the matrix, which can be an engineering material such as ceramic, metal or polymer (Huda at all 1995, Vasiliev, V.V.and Evgeny, V,2001). Hence, ceramic matrix composites, metal matrix composites or polymer matrix composites or carbon matrix composites or even hybrid composites are obtained.

In a composite, matrices, in general, are of low modulus, while reinforcing elements are typically 50 times stronger and 20-150 times stiffer. Metal matrix composites and ceramic matrix composites structures are developed to provide rather high temperature applications (>316 °C), where polymer matrix composites are usually inadequate (Akovali, G.2001). Furthermore, since metals are more conductive (electrically and thermally) metal matrix composites are also used in heat dissipation and electronic transmission applications. Each matrix type has different impact on the processing technique. Composites are usually used for their structural properties where the most commonly employed reinforcing component is in particulate or fibrous form and hence the definition above can be restricted to such systems that contain continuous/discontinuous fiber or particle reinforcement, all in a continuous supporting core phase, the matrix (Vasiliev, V.V.and Evgeny, V,2001).

Table 1. Example of Composite Materials (Berthelot at all, 1999).

Matrix	**Constituents**	**Areas of Application**
1. Organic Matrix Comp. Paper, cardboard Particle panels Fiber panels Coated canvas Impervious materials Tires Laminates Reinforced plastics	Resin/fillers/cellulose Resin/wood shavings Resin/wood fibers Pliant resins/cloth Elastomers/bitumen Rubber/canvas/steel Resin/glass fibers Resins/Micro-spheres	Printing, packaging Woodwork Building Sports/building Roofing, earthworks Automobiles Multiple areas
2. Mineral Matrix Comp. Concrete Carbon - carbon comp. Ceramic Comp.	Cement/sand/gravel Carbon/carbon fibres Ceramic/ceramic fibers	Civil Engineering, Aviation, space, sports, biomedicine, Thermomechanical
3. Metal matrix Comp.	Aluminum / boron fibres Aluminum / carbon fibres	Space
4. Sandwiches Skins Cores	Metals, laminates, etc. Foam, Honeycombs, etc	Multiple Areas

A reinforcement phase usually exists with substantial volume fractions (10% or more). Generally, three types of composites can be described as: (a) particle strenghtened, (b) discontinuous fibre reinforced and (c) continuous fibre reinforced composites; depending on the size and aspect ratio and volume fractions of reinforcing phases (Chung, D.L.2003).

In these, the function of each component can be different: in particle strengthened composites, the matrix bears the load and small dispersed particles obstruct the motion of dislocations in the matrix; and the load is distributed between matrix and particles (Vasiliev, V.V.and Evgeny,2001, Topcu at all, 2021). In addition to these types of composites, one should also note the existence of another group of composite system, laminar composites (or simply laminates); where reinforcing agents are in the form of sheets bonded together and are often impregnated with more than one continuous phase in the system. The classification of composites mentioned above can be narrowed into two groups: macrocomposites and microcomposites. This classification depends on whether there are one or more dispersed distinguishable phases and on whether there is more than one continuous phase present (for macrocomposites), or whether all dispersed phases are between 10-1000 nm in size and there is only one continuous phase (for micro composites) (Topcu at all, 2019).

If the size of reinforcing component of a microcomposite is in the form of 'quantum dots' (i.e., being much smaller than 25 nm) then a new specific term is assigned to it by calling it a nanocomposite. The term flexible composite is used to identify composites based on elastomeric polymers where the usable range of deformation is much larger than the conventional thermoplastic or thermoset composites (Hoa, S.V and Tsai, S.W.2003).

High tensile and high modulus fibres (such as carbon, boron, silicon carbide and alumina) emerged in the 1970s, and were used to reinforce high performance polymer, metal or ceramic matrices. A new group of advanced composite materials were than developed which were, in general, extremely strong and stiff. The matrix is one of the key factors reach to proper advanced composite materials structures, In order to have advanced material properties, firstly densities of matrices should be as small as possible with as high as application temperatures for the material. There usually exist a relationship between density and service temperature for different materials, as presented in Figure 5. As the figure shows, titanium and steel are not considered as advanced because of their relatively high densities. The arrow in the figure indicates the trend for advanced materials which has its peak at high application temperatures and low densities (two important criteria for the next generation spacecrafts being lighter and faster); hence silicone carbide ceramics and carbon-carbon composites are expected to be examples of such advanced materials. The unique properties of advanced composite materials make them special for different applications. For example, advanced polymer composites are not only lightweight, but also offer excellent strength, stiffness and design versatility, which are particularly important in aerospace applications (Akovali, G.2001). Some specialty polymers also have good chemical resistance and dielectric strength, like aramids, which gave rise to their use as electrical insulators in generators and transformers.

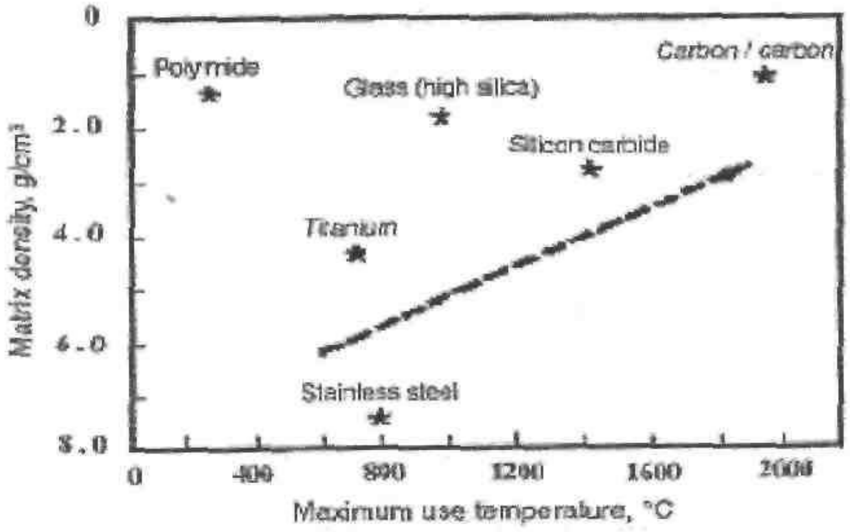


Figure 5.Densities versus Maximum Use Temperature for Some Materials (Akovali, G.2001)

Advanced ceramic materials provide a unique combination of high-temperature resistances, in addition to excellent wear and corrosion resistance and dimensional stability which are particularly important for parts which will be subjected to wear and cutting tools. Advanced metal composites and alloys obtained by rapid cooling of the melt have better strength and better electrical properties as well as improved corrosion resistance and enhanced magnetic properties (Schwartz, M. 1996).

The interfaces and interphases between different components in the composites, which is the boundary surface with a discontinuity, have a vital importance in determining the structural properties of the composite. The interfaces and interphases are expected to be proper, i.e., the interaction and adhesion between the components should be at the optimum level in order to distribute the load that is borne by the composite evenly (Jain, S. 2005).

Finally one should mention the three main forces that may affect the competition between composites and traditional engineering materials, both with similar mechanical properties: they are the cost, reliability and degree of complexities involved. The cost barrier in these is usually overcome by mass production and the degree of complexity is certainly more critical for composites which is due to the unisotropy existing (at least at microscale) for these structures. It is known that, in composites, thermoelastic properties as well as strength and failure modes have strong directional dependencies - (Akovali, G.2001).

3.1. Metal Matrix Composites

MMCs are a group of advanced materials designed for use mainly at elevated temperatures where existing materials are not suitable for use (Schwartz, M. 1996). As the name implies, the matrix is a ductile metal. Reinforcements such as intermetallic compounds, oxides, carbides and nitrides improve specific stiffness and specific strength, wear resistance, creep resistance and dimensional stability [8]. While chemical composition, morphology, microstructure, physical/mechanical properties and cost are important parameters for the reinforcement selection, oxidation resistance, corrosion resistance, density, strength and ductility/toughness are important parameters for the matrix selection [4]. AI, Ti, Mg, Ni, Cu, Pb, Fe, Ag, Zn, Sn and superalloys are widely employed as matrix materials, Al, Ti and Mg alloys have wide application areas when compared to others (Schwartz, M. 1996).

Table 2. Some typical properties of some metals and their alloys .(Mary T and Spohn,1994).

Pure Metals	**Density (gr/cm3)**	**Young's Modulus (GPa)**	**Yield Strength (MPa)**	**Tensile Strength (MPa)**
Aluminum	2.7	70	40	200
Copper	8.9	120	60	400
Nickel	8.9	210	70	400
Ti-6A1-4V		110	900	1000
Stainless Steel (304)		195	240	365
Plain Carbon Steel	7.9	210	250	420

Each year, hundreds of new applications of composites are tried in different disciplines such as sports, aeronautical and automotive industries. Composite materials offer designers an increasing array of material and system solution. Reducing the weight of the vehicle therefore reducing the consumption of fuel is very important for high technological applications. Since MMCs are more expensive than matrix alloys, they are used in the fields where material's properties are more important than the cost (Koczak, M. J. 1989). The most important property of MMCs is wear resistance. They are used in high wear applications (Akbulut, H.2001).

On the other hand, like ceramic composites the reason for low use of MMCs is that they have low fracture toughness and there is a difference in thermal expansion coefficients of constituents. The key parameter for MMCs at elevated temperatures is the specific strength (strength/density). MMCs are more reliable than the conventional materials at high temperatures (Schwartz, M. 1996).

Although MMCs have been well known over the last forty years, the application of MMC has been increasing for the last twenty years because of problems related with manufacturing processes and finding fibers that are compatible with matrix. There are many advantages of MMC when compared with metals.

Advantages of MMCs over conventional metals are:

High elastic modulus

High strength (tensile, compressive, wear, creep and slip)

Stability at elevated temperatures

MMCs posses ductility and toughness of metals and high elastic modulus and strength of ceramics.

Low density

Low sensitivity to temperature differences and thermal shocks

High electrical and thermal conductivity (Schwartz, M. 1996).

Disadvantages of MMCs are:

Low ductility

Low fatigue resistance

Complex and expensive production techniques (Schwartz, M. 1996).

Since discontinuous reinforcement materials can be produced and obtained easily, in recent years, they are preferred in the manufacturing of MMCs. After production they may be subjected to a secondary process such as forging, rolling and/or extrusion. Easy productions techniques lead to the use of MMCs in many fields such as sports equipment and automotive industry.

Many different metals are used as a matrix material in MMCs. Matrix acts like a binder to hold reinforcement particles together and the main function of matrix is to transfer and distribute the stress to the reinforcement material. The transfer of stress depends on bonding interface between matrix and reinforcement, which depends on the type of matrix and the reinforcement as well as the fabrication technique. The major problem for attaining good load transfer is the achievement of proper bonding between the matrix and the reinforcement. Not all combinations of reinforcement and matrix are compatible and many combinations cannot be processed into commercially useful composites. In some composites, the coupling between the reinforcement and the matrix is poor and adhesion promoters are needed. In others excessive interfacial reactivity can lead to a brittle layer around the reinforcement. The most important parameter for the MMCs is the compatibility between matrix and reinforcement material. In order to enhance wettability therefore the interface bond between matrix and reinforcement, matrix should be alloyed. Researches show that aluminum and aluminum alloys are the best matrix materials when wettability, cost and density are to be taken into consideration. Particle reinforced MMCs are a class of materials that exhibit a blending of properties of the reinforcement and the matrix. According to their chemical compositions reinforcement materials are classified into three groups; nitrides, oxides and carbides (Mary T. Spohn,1994).

In the selection of reinforcement material, the factors listed below must be taken into consideration (Schwartz, M. 1996, İ Topcu at all,2021).

If the composite material will be used in structural applications, reinforcement material must have high strength, elastic modulus and low density. Since cornered particles cause stress concentration and decreases the ductility, the particle shape of the particle has strong influence on mechanical properties (Ahlatçı, H. 2003, Morgan, P 2005).

Their relatively higher costs to the other prevalent abrasive powders (SiC and AI2O3), not too many works has been done on boron carbide (B4C) reinforced metal matrix composites. B4C seems to be a better reinforcement material with its lower density and higher hardness according to SiC and AI2O3. Boron carbide is an outstanding reinforcement material for aluminum and its alloys meeting many of the mechanical and physical properties required of an effective reinforcement -(Langman at all, 1985).

Table.3 Characteristics of Ceramic Particles (Huda at all 1995).

Particle	**Size (inch)**	**Density (g/ cm3)**	**UTS (GPa)**	**E (GPa)**
Graphite	40-250	1.6-2.2	20	910
SiC	15-340	3.2	3	480
Si02	53	2.3	4.7	70
MgO	40	2.7-3.6		
Si3N4	46	3.2	3-6	360
TiC	46	4.9		320
BN	46	2.25	0.8	100-500
ZrO2	75-180	5.65	0.14	210
B4C	40-340	2.5	6.5	480
TiO2	20	3.9-4.3		
Al2O3	40-340	3.97	8	460
K Glass	30-120	2,55	3.5	110

3.2. Aluminum Matrix Composites

Aluminum is the most significant matrix material for the metal matrix composites. The Al alloys are quite attractive due to their low density, their capability to be strengthened by precipitation, their good corrosion resistance, high thermal and electrical conductivity, and their high damping capacity, Aluminum matrix composites are one of the advanced engineering materials that have been developed for weight critical applications in the aerospace, and more recently in the automotive industries due their excellent combination of high specific strength and better wear resistance. Aluminum matrix composites have been widely studied since the 1920s and are now used in sporting goods, electronic packaging, amours and automotive industries. In table 3.4 markets for some metal matrix composites are given. They offer a large variety of mechanical properties depending on the chemical composition of the Al-matrix. They are usually reinforced by AI2O3, SiC, and C, however, Si02, B, BN, B4C, A1N may also be considered. The aluminum matrices are in general Al-Si, Al-Cu, 2xxx or 6xxx alloys (Morgan, P 2005).

In the 1980s, transportation industries began to develop discontinuously reinforced aluminum matrix composites. These materials are significant for their mechanical properties and low costs (Schwartz, M. 1996).

Table.4 Markets for Some Metal Matrix Composites (in millions of $ US) (Topcu at all, 2020).

Type	**1988**	**1993**	**2000**
Aluminum	12.0	35.0	78.3
Magnesium	2.0	8.9	20.0
Titanium	1.0	2.6	14.1
Copper	1.4	5.5	28.3

AMC can be categorized into three types respect to its reinforcement; particulates, whiskers or discontinuous fibers, and continuous fibers. The AMCs with particulate reinforcement provide high stiffness with low cost. The properties are isotropic:

The whisker reinforced composites are more expensive the particulate reinforced ones, however, they provide mainly high strength. Respect to discontinuous based composites, and particulates, single crystal whiskers usually have a much greater tensile strength. Although the continuous fiber based composites give the best combination of stiffness and strength, they cost very high due to the expensive continuous fibers and the production system (Du, W.F. and Watanebe, T.1997).

MMCs have been attracting the attentions recently due to its outstanding mechanical and physical properties and increased elevated temperatures capabilities. In addition, AMC reinforced with the ceramic particles or whiskers have received significant attention since they can be formed by metalworking practices. Not only the improved mechanical properties, also other controlling behaviors, like coefficient of thermal expansion and wear resistance, can be gained by the ceramic particles. The incorporation of reinforcement into aluminum alloys has reportedly led to both strengthening and accelerated aging effects (Vasiliev, V.V.and Evgeny, V.2001).

Among the ceramic reinforcement materials, boron carbide (B4C) ceramics have been attracting the attentions due to its high hardness, high melting point, good thermal conductivity and good electrical conductivity. These properties make this material a great choice for neutron adsorption materials, wear resistance materials, electrode materials and cutting tools [6], Boron carbide is used for a wide range of engineering applications because of its exceptional hardness just below that of diamond (9.5 + in Mohs' scale), outstanding elastic modulus, and low density (2.52 g/cm3). These hardness and density values are much better than that of SiC and AI2O3, therefore boron carbide has become a better reinforcement material. However, due to the higher cost of boron carbide powder respect to common abrasive powders such as SiC and AI2O3, limited research has been done on B4C reinforced metal matrix composites (Topcu at all, 2021).

Although boron carbide has some outstanding physical and mechanical properties, its extreme sensitivity to brittle fracture (KIC = 3.7 MPa m1/2) and the difficulties involve in fabricating dense B4C materials have limited its use in industrial applications (Lee at all 2001). These problems can be reduced considerably by the production of B4C-based composites, essentially B4C-metal composites.For applications at low temperatures, aluminum or aluminum alloys is a material of choice. Suggested applications for B4C AI composites include its use in as a structural neutron absorber, armour plate materials, and a substrate material for computer hard disks 8Du, W .F. and Watanebe, T.1997).

Particle reinforced AMC produced by powder metallurgy or liquid phase techniques exhibit excellent mechanical properties.

Table.5. Reinforcement materials used in Al matrix composites (Berthelot J.M.and Cole, J.M. 1999).

Reinforcement	**Particle size (µm)**
A12O3	3-200
SiC, particle	6-120
SiC, whisker	5-10
Graphite, lamellar	20-60
Zirconium	40
Silica sand	75-120
Zirconium oxide	5-80
TiC	46
Mg	40
Boron nitride	46
Mica	40-180
B4C	50-80

Table.6 Mechanical properties of pure Al alloys (Du, W .F. and Watanebe, T.1997).

Alloy	**Yield Strength (MPa)**	**Tensile Strength**	**Elongation**	**Elastic Modulus (GPa)**
6061 Al T6	275	310	20	69
2014 A1T6	414-476	483-524	13	73
2021 Al	414	483	13	73
2124 A1T6	325	470	12	72
2618 A1T6	370	470	9	74
7075 Al T6	505	570	10	72
8090 Al T6	415	485	7	80

Table7. Mechanical properties of some Al matrix composites (Vasiliev, V.V.and Evgeny, V.2001)

Matrix	**Reinforcement and Content (vol %)**	**Yield Strength**	**Tensile Strength**	**Elongation %**
Al	SiC, 20	117	200	10
2014-T6	SiC, 10	457	508	1,8
2014-T6	A1203,20	495	515	1,2
6061-T6	SiC, 15	290	340	5,5
6061-T6	SiC, 20	345	410	4,9
6061-T6	SiC, 30	380	435	1.8
6061-T6	A1203, 20	307	349	5,3
7091-T6	SiC, 20	500	560	1,8

3.3. Important Metal Matrix Composites

3.3.1. Aluminum Alloys

Due to their low density and gorgeous strength, toughness, and corrosion resistance, aluminum and its alloys are used in many applications in the field of aerospace. Table 3.8 shows the elastic modulus of some lightweight materials. In this respect of mention the alloys Al-Cu-Mg and Al-Zn-Mg-Cu alloys are very important precipitation hardenable alloys. Also aluminum-lithium alloys generate one of the most outstanding precipitation hardenable alloys. When lithium added to aluminum as a primary alloying element, it yields with an enhancement in the elastic modulus and decreasing in the density of the alloy. Naturally the aerospace technology is the main target for this kind of alloys (Langman at all. 1985).

3.3.2. Magnesium Alloys

Recently a considerable progress has been achieved in magnesium alloy metal matrix composites. Some silicon carbide particles-reinforced magnesium alloy compositions have been used. Most significant benefit of magnesium alloys usage in composite materials is the increasing in the modulus (around 40% respect to unreinforced). These metal matrix composites also show good wear properties and they also have lower coefficient of thermal expansion. These properties make these materials an ideal choice for aerospace, automotive, bicycle and engineering industries (Topcu at all,2020 and Lavemia at all, 1991).

3.3.3 Titanium Alloys

Titanium is one of the most intriguing aerospace materials. The density of the titanium is 4.5 g cm"3 and the Young's modulus of 115 Gpa. However, the density of titanium can be in the range of 4.3 and 5.1 g. cm"3 and the modulus varies between 80-180 Gpa (Meydancıoğlu , O.2006 and German, R,M. 1985). High strength/weight and modulus/weight ratios are important. Titanium has high melting point (1672 °C) respect to other matrix materials and stands strength at high temperatures with good oxidation and corrosion resistance. Consequently all these properties render titanium an important material for aerospace applications. Mainly the turbine parts and compressor blades in the jet engines are made of titanium alloys (Langman at all. 1985).

3.3.4 Copper

Copper has a face centred cubic structure. Its use as an electrical conductor is quite ubiquitous. It has good thermal conductivity. It can be cast and worked easily. One of the major applications of copper in a composite as a matrix material is in niobium based superconductors (Langman at all. 1985).

3.3.5 Intermetallic Compounds

There are many other intermetallics, not necessarily ordered, available. Ordered intermetallic alloys possess structures characterized by long range ordering, in an example, different atoms occupy specific positions in the lattice. Because of their ordered structure, dislocations in intermetallics are much more restricted than disordered alloys. This results in retention of strength at elevated temperatures, a very desirable feature (Langman at all. 1985).

Table 8 Elastic Modulus of Common Lightweight Metallic Alloys (Langman at all. 1985).

Alloy	**Density (g /cm3)**	**Elastic Modulus (GPa)**
Aluminum Alloys	2.7	65
Magnesium Alloys	1.8	45
Ti Alloys	4.5	103
Steel	8.3	200

4. Production Techniques

MMCs are produced using conventional fabrication techniques and many fabrication techniques were developed for optimization of composite's structure and properties. Fabrication techniques of MMCs can be classified into three groups according to the temperature of metal matrix (Betteridge W and Helsop J.1974).

4.1 Powder Metallurgy Prosesing

Consistently improved properties composites have been obtained from composites produced by powder metallurgy. Consolidation in powder metallurgy refers to the production of coherent metal structures using metal powders as the major raw material. Production of metal powders and consolidation are the first and second vital steps, respectively. For industrial applications, attainment of final product accompanied by required material properties is of great importance in the consolidation process. Since powder metallurgy is capable of meeting industrial demands and provides high facility in the consolidation, powder metallurgy is a convenient production technique (Akın, G.(2006).

Powder metallurgy is a culmination of processes used for turning the compactable metal powders into strong and high performance pieces. Powder metallurgy is the most commonly used method for the preparation of composites filled by discontinuous particles and the first advanced technique due to the low wettability of reinforcement materials by liquid alloy.

When compared to other techniques relatively low consumption of energy and low cost are the driving forces for the powder metallurgy to become widespread. Powder metallurgy allows producing metals with a high melting point. The problems like oxidation, segregation, gas absorption and un alloying due to the density differences can be eliminated in powder metallurgy (Tugba at all , 2022).

4.1.1.Atrittion Milling

A conventional ball mill consists of a rotating horizontal drum half filled with small steel balls. As the drum rotates the balls drop on the metal powder that is being ground; the rate of grinding increases with the speed of rotation. At high speeds, however, the centrifugal force acting on the steel balls exceeds the force of gravity, and the balls are pinned to the wall of the drum. At this point the grinding action stops. An attritor (a ball mill capable of generating higher energies) consists of a vertical drum containing a series of impellers. A powerful motor rotates the impellers, which in turn agitate the steel balls in the drum. Set progressively at right angles to each other, the impellers energize the ball charge. The dry particles are subjected to various forces such as impact, rotation, tumbling, and shear. This causes powder size reduction because of collisions between balls, between balls and container wall, and between balls, agitator shaft, and impellers. Therefore, micrometer-range fine powders can be easily produced. Some size reduction, though small in proportion, appears to take place by interparticle collisions and by ball sliding. In addition, combination of these forces creates a more spherical particle than other impact type milling equipment. Particulate composites such as oxidedispersion – strengthened materials, have been used for their high tempreture creep resistance for many years. Obtaining a homogeneous distribution of hard phase throughout the matrix is an inherent difficulty in fabricating dispersion strengthened materials. Milling techniques have evolved to generate these composites. A successful technique is mechanical alloying which employs the attritioning motion between agitated balls to create an alloyed composite, particle (Topcu, at all 2019).

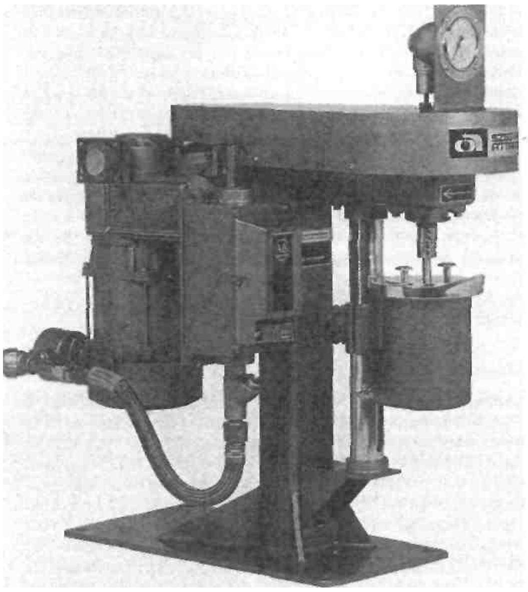


Figure 6.Model 01-HD Attritor. (Courtesy of Union Process, Akron, OH)

4.1.2. Pressing

4.1.2.1 Isostatic Pressing

Isostatic pressing utilizes omnidirectional pressure resulting in a uniform density distribution. This technique can be performed at room temperature (Cold Isostatic Pressing-CIP) or at high temperatures (Hot Isostatic Pressing-HIP) (Lavemia at all, 1991).

4.1.2.1.1 CIP-Cold Isostatic Pressing

In Figure4.2 an isostatic tube compaction cycle is sketched. The tools for this forming process normally consist of steel and elastomeric components, e.g. a steel core and an outer mantle of polyurethane. After filling the space between core and mantle with powder and sealing of the tool, it is inserted in a pressure vessel which may be pressurized up to 6000 bar. This pressure is isostatically transmitted through the elastomeric wall to the powder mass which is thereby compacted. After depressurization and spring-back of the elastomeric tool components, the green compact is removed from the tool and sintered in the conventional way. In Figure 7 thin walled filter tubes are shown as an example for the application of this technique. Core rods in CIP can be threaded (Lavemia at all, 1991).

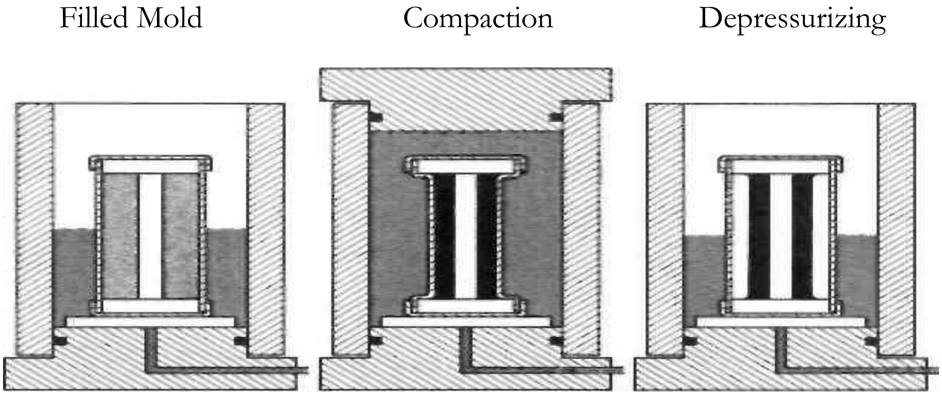


Figure. 7. Cold Isostatic TubeCompaction (Lavemia at all, 1991).

4.1.2.1.2 HIP-Hot Isostatic Pressing

In hot isostatic pressing, isostatic pressure and heat are applied simultaneously. The powder is filled into metallic cans or capsules usually made from mild or austenitic stainless steel and closed with a lid containing a tube for evacuation during heat up. Figure 8 shows schematically the HIP processing cycle. Typical pressures and temperatures are in the range up to 2000 bars and 800 - 2000 °C, respectively. Apart from billets which are subsequently hot worked near-net shape components can also be manufactured.

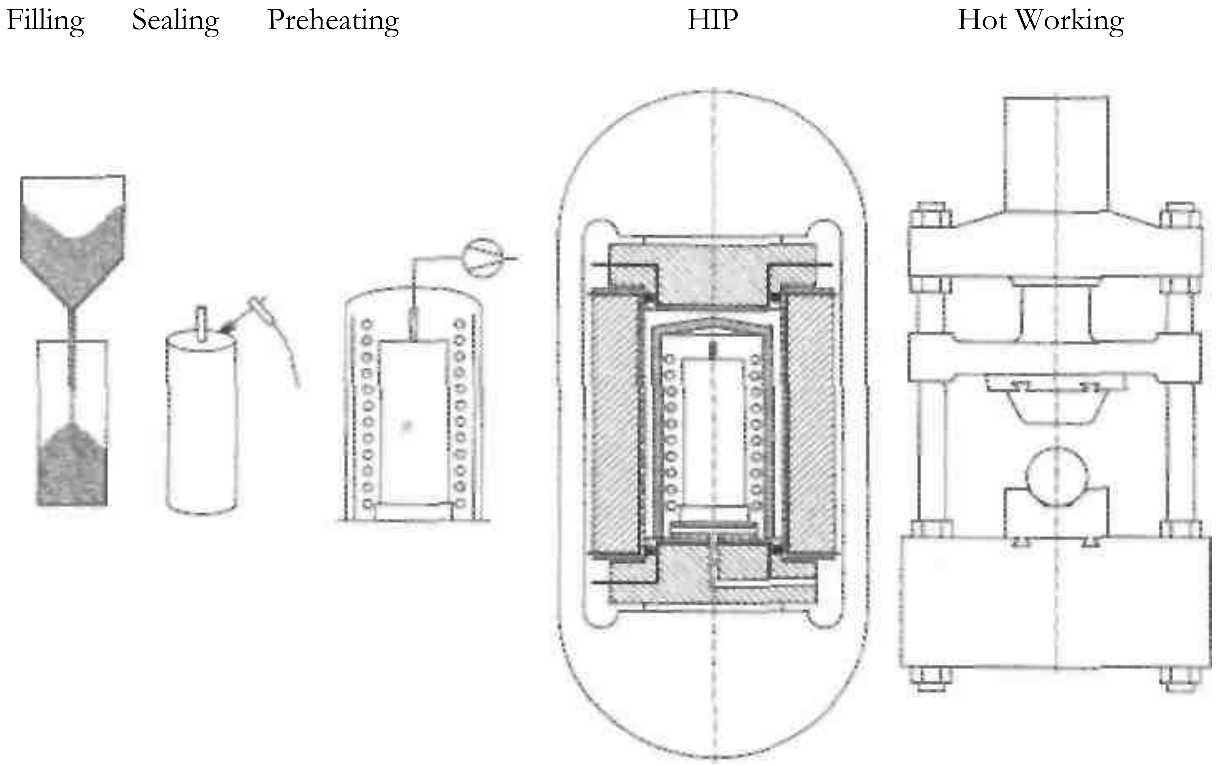


Figure .8 Shows the flow chart for composite fabrication by powder metallurgy. The classical powder metallurgy technique consists of three stages which are blending, gathering powders together (pressing) and sintering, respectively (Mary T. Spohn,1994).

In this process powders of composite's components are first blended and fed into a mould of the desired shape. Since distribution of reinforcement in metal matrix depends on mixing, mixing process is an important process [6]. Pressure is then applied to compact the powder. In order to facilitate the bonding among the powder particles, compact is heated to a temperature which is below the melting points of composite components. Up to 85-90% theoretical density can be achieved after sintering (Lee at all 2001).

Table 9 shows pressing pressure of some materials. Pressing pressure can be performed in a high wear resistance and hard enough mould. The pressing pressures are chosen between 300 and 800MPa according to metal powder. Complex pieces can be produced utilizing either single acting or double acting presses with an average rate of 25 parts per minute (Turan E. 2003).

Table 9. Typical pressure values for powders (Turan E. 2003).

Material	**Pressure (MPa)**
Aluminum	69-276
Brass	414-687
Bronze	207-276
Graphite	138-165
Carbides	138-414
Alumina	110-138
Ferrite (low density)	345-414
Ferrite (medium density)	414-552
Ferrite (high density)	483-827
Tungsten	69-138
Tantalum	69-138

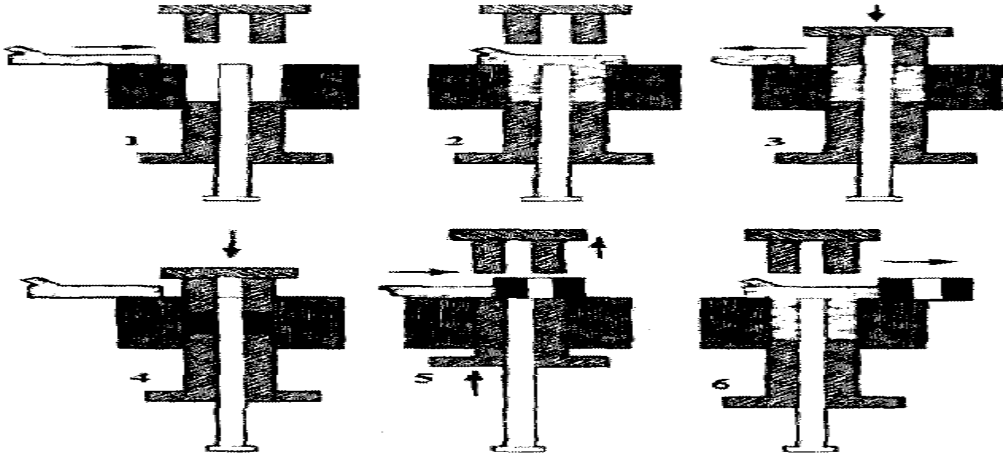


Figure 9. Operation sequence in powder metallurgy, single acting press (Meydancıoğlu , 2006).

Compacted metal powders are called green packed bodies. Only physical bonds occur between metal powders during pressing. Green packed bodies contain a lot of porosities. In order to decrease the number of porosities, green packed bodies are heated in a furnace to a temperature that is usually below the melting point of the major constituent.

Hot press can be used instead of cold press. Denser composites can be obtained by using hot isostatic press as compared to cold press. Extrusion, rolling or forging can be applied to the semi finished products produced by cold and/or hot pressing in order to get the theoretical density and increase mechanical strength.

Powder used in these techniques can be pre-alloyed atomized powders with a particle size of 20-40 μm or wires obtained by fast solidification. Optimum reinforcement particle size is described in terms of ratio of reinforcement particle size and metal powder size (Lee at all 2001 and Mary T. Spohn,1994).

Vacuum must be applied in order to prevent the formation of porosity in hot and cold pressing. Temperature in hot press under vacuum conditions is determined according to the solidus temperature of the alloy. Temperature, under the solidus temperature or at which solid-liquid phases are found together, is selected as pressing temperature. Lower temperatures restrict the reactions between matrix and reinforcement particles therefore higher mechanical properties are obtained (Lee at all 2001).

The schematic view of a hot press is given in Figure 9. Hot pressing is the simultaneous application of elevated temperature and compressive stress to consolidate partially or rally sintered components. The hot press technique was developed for the powder metallurgy industry and has successfully been applied to ceramic components over last several decades. Pressure increases the driving force for densification, in effect, reducing the process temperature required for a sintering process. Also hot pressing results in smaller over grain size, more precise controlover the microstructure and the flexibility of functionally grading the ceramic layers (German, R,M. 81985).

4.1.3. Sintering

During sintering metal powders are chemically bonded. Compacted metal powders can be sintered in an atmosphere controlled furnace. The most important parameters for sintering are time, temperature and atmosphere. The driving force for sintering is decreasing in surface energy occurred at elevated temperatures. As the surface energy decreases, diffusion rate increases therefore necking area between powders occurs and powders diffuse to each other. Diffusion occurs in many ways, such as surface diffusion, vapor transportation, contact point diffusion (Berthelot J.Mand Cole, J.M. 1999).

Sintering induces contacting particles to bond together at high temperatures. It can occur at temperatures below the melting point by solid-state atomic transport events, but in many instances jnvolves the formation of a liquid phase. On a microstructural scale the bonding becomes evident as necks grow between touching particles. Figure 10 shows a scanning electron micrograph of the solid-state neck formation between sintering spheres. Such neck growth increases the strength over the green strength and causes many beneficial property changes.

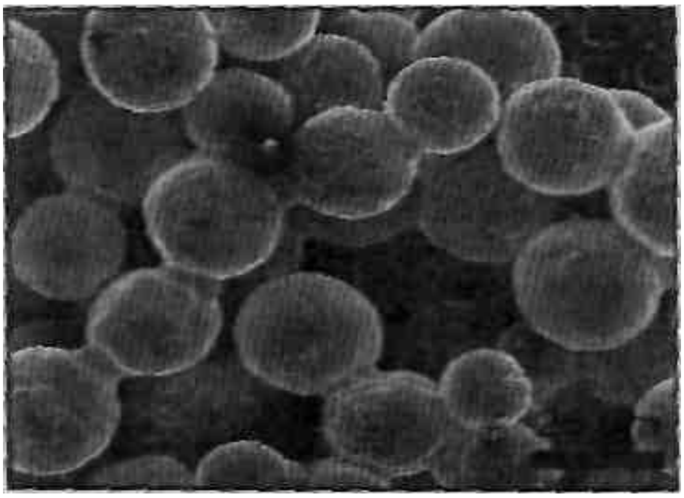


Figure 10. Scanning electron micrograph of the neck formation due to sintering in a collection of loose bronze spherical particles [13].

Inherently, sintering is due to the motion of atoms that occurs at high temperatures and the reduction in the surface energy associated with small particles. Remember that powder fabrication is largely related to putting energy into the material to create surface area or surface energy. Now in sintering, that energy is eliminated. Surface energy per unit volume depends on the inverse of the particle size. Thus, smaller particles with high specific surface areas have more energy and sinter more quickly. However, not all surface energy is available for sintering. For a crystalline solid, nearly every particle contact will evolve a grain boundary with an associated grain boundary energy. So as neck growth removes surface energy, it adds grain-boundary energy. Obviously, this only occurs when the decrease in surface energy is greater than the increase in grain boundary energy (Du, W .F. and Watanebe, T.1997, Meydancıoğlu , O.2006).

From a fundamental view, sintering is treated in terms of'driving forces, mechanisms, and stages:

- sintering driving forces describe the microscopic curvatures that cause bonding
- sintering mechanisms describe the path of atomic motion in response to the driving forces
- sintering stages describe the geometric progress resulting from the atomic motion; those stages in turn change the driving forces.

The driving forces or sintering stresses come from the curvatures in the microstructure. Sintering mechanisms are usually diffusion processes over the surfaces, along the grain boundaries, or through the crystalline lattice. The stages of sintering help describe the driving force and kinetics, and are used to mathematically model the process.

Figure 11 provides a sequence of optical micrographs showing progressive particle bonding, pore elimination, and microstructure coarsening during sintering. The geometric changes in sintering result from the heating that induces atomic movement. At high temperatures more atoms have an energy equal to or above that required to break free of their neighbors and move to a new site. The minimum energy that an atom must have to move is called an activation energy energy (Du, W .F. and Watanebe, T.1997)

At high temperatures, the jumping atoms do not have any knowledge of where to go, so they simply wander. This random walking process occasionally results in the atom landing at the bond between particles where it helps annihilate surface area and surface energy. Once that occurs, then it is unfavorable for the atom to move away, since it will increase energy. Thus, sintering is a collection of an enormous number of atomic jumps, with a small fraction of those jumps leading to growth of the sinter bond and reduction of the surface energy. Each atom is tiny, with a volume of just 1029 ra3, so growth of measurable sinter bonds requires many successful atomic jumps. The role of heating is to increase the number of total atomic jumps, realizing that only a small fraction will be successful. This is like playing the lottery, the more tickets you buy the better the odds of winning. Sintering is a statistical process involving large numbers of very small atoms that vibrate 1014 times per second. At the sintering temperature this results in each atom changing position many times per second (Topcu , 2020).

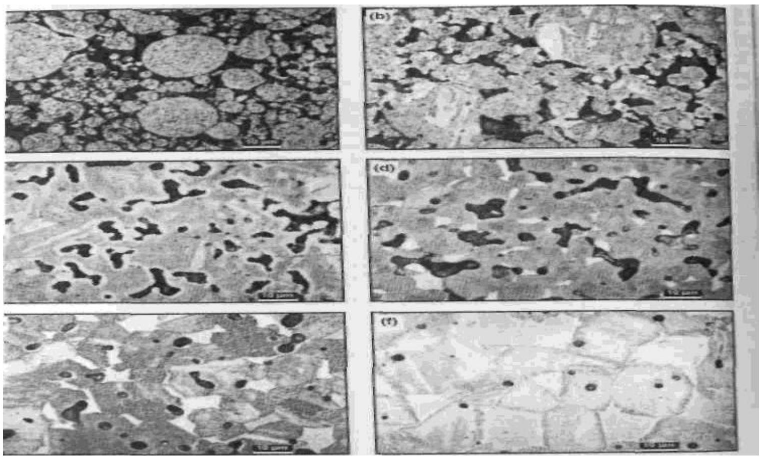


Figure 11. Pictures capturing the microstructure evolution in sintering. These pictures were tained by quenching a 17-4PH stainless steel (AISI630) from various temperatures durig heating to the peak temperature ofl365°C (24W°F); a) heated to 100O°C, b) 1100°C, c) '00°C, d) 1260°C, e) 1300°C, andf) 1365°C (Topcu , 2020)..

Consider two spherical particles in contact, In powder compacts there are many such contacts on each particle. As sintering progresses the bonds between contacting particles enlarge and merge. At each contact a grain boundary grows to replace the solid-vapor interface. Prolonged sintering would cause the two particles to coalesce into a single sphere with a final diameter equal to 1.26 times the original diameter. In a powder compact multiple neighbors exist on each particle, so bonds form at several locations on each particle. The initial stage of sintering is characterized by the growth of several necks on each particle, but the necks grow independent of each other. Without compaction the particles start with small contacts. Initially the pores are irregular and angular in shape. The neck represents a concavity that is filled in by atoms from convex areas over time. As the neck grows, the curvature is relaxed so the process slows. In the intermediate stage of sintering, the pores are rounded, yet the curvature around pores continues to drive mass flow and the filling in of concave regions. In the intermediate stage of sintering, the necks have grown large enough to interfere with each other and overlap (Topcu , 2020).

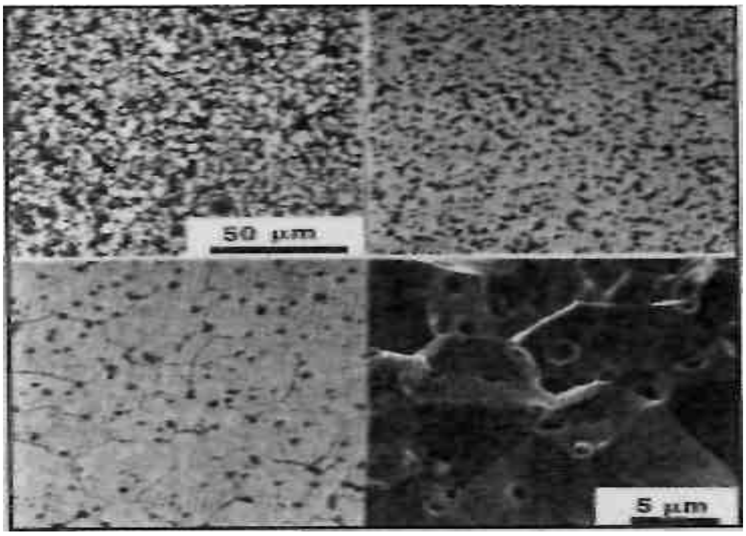


Figure 12. Four micrographs showing the progressive densification and grain growth during sintering (Topcu , 2020).

The black regions are pores and in the initial stage (upper left) the material is nearly half pores and small particles. In the intermediate stage (upper right) the pores are fewer and rounded. By the final stage (lower left) the grains have enlarged with fewer pores. The fracture surface (lower right) shows the spherical pores are sitting on the grain boundaries and are closed (Topcu , 2020).

In the intermediate stage, the pores are smoother and the density is up to 92% of theoretical. Grain growth occurs late in the intermediate stage, so the grain size is larger than the initial particle size. By the final stage of sintering, the pores are spherical and closed, and extensive grain growth is evident. The original particles are no longer visible in the microstruc-ture. The four micrographs shown in Figure 4.7 provide a perspective on this behavior. These photographs show the changes in density, grain size, and pore structure characteristic of sintering, in this case for a small tungsten powder. The scanning electron micrograph in Figure 8.13d is a fracture surface after sintering to the final stage. Spherical pores are present on the grain boundaries, which is a desirable feature for continued final-stage densification (Turan E. 2003).

Surface transport involves neck growth without shrinkage or densification. Surface diffusion and evaporation-condensation are the two most important contributors during surface-transport-controlled sintering. Surface diffusion dominates the low-temperature sintering of most materials. Evaporation-condensation is not as important, except in the sintering of low-stability materials such as those containing lead (Topcu, Ceylan, Yilmaz,2020).

In contrast, bulk transport controlled sintering causes shrinkage. The mass originates at the grain boundary, and sometimes at the particle interior, with deposition at the pore surface near the neck. Bulk-transport mechanisms include volume diffusion, grain-boundary diffusion, plastic flow, and viscous flow. Plastic flow is usually most important during heating, especially for compacted powders, but it declines in importance as the powder reaches the peak temperature. In contrast, amorphous materials, such as glasses and plastics, sinter by viscous flow, where the particles coalesce at a rate that depends on the particle size and material viscosity. Viscous flow is also possible for metals with liquid phases on the grain boundaries. Grain-boundary diffusion is fairly important to densification for most crystalline materials, and appears to dominate the densification of many common metals. While both surface- and bulk-transport processes give neck growth, the main difference is in density (or shrinkage) during sintering. Generally, bulk-transport processes dominate at higher temperatures(Turan E. 2003).

Application of the curvature equation to initial-stage sintering allows estimation of the difference in the vapor pressure, vacancy concentration, and stress in the sintering microstruc-ture. For example, the vapor pressure over the neck region is lower than equilibrium because the neck is concave. However, the bulk of the powder is emitting vapor at a pressure above equilibrium because of the convex curvature. As a consequence, over distances smaller than the particle size, there is a pressure difference. As water flows downhill, likewise this pressure difference causes a net mass flow into the neck region (Topcu, Ceylan, Yilmaz,2020).

For good sintering it is important to sustain pore attachment to grain boundaries, even during periods of rapid grain growth. A conceptual sketch of the changes in pore structure with sintering is given in Figure 13. The point contacts between particles grow into necks. After the initial stage, the grain boundary and pore configuration control the sintering rate. At the beginning of the intermediate stage, the pore geometry is highly convoluted and the pores are located at grain boundary intersections. With continued intermediate-stage sintering, the pore geometry becomes cylindirical and eventually collapses into closed spherical pores as densification reduces the pore diameter and grain growth extends the pore length [13].

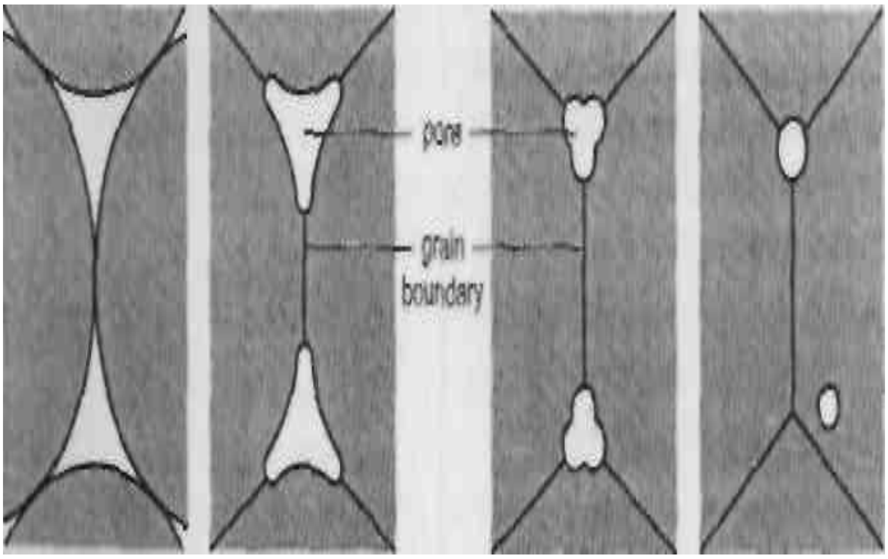


Figure 13. A schematic diagram of the pore-structure changes during sintering, starting with particles in point contact. The pore volume decreases and the pores become smoother. As pore spheroidization occurs, the pores are replaced by grain boundaries (Turan E. 2003).

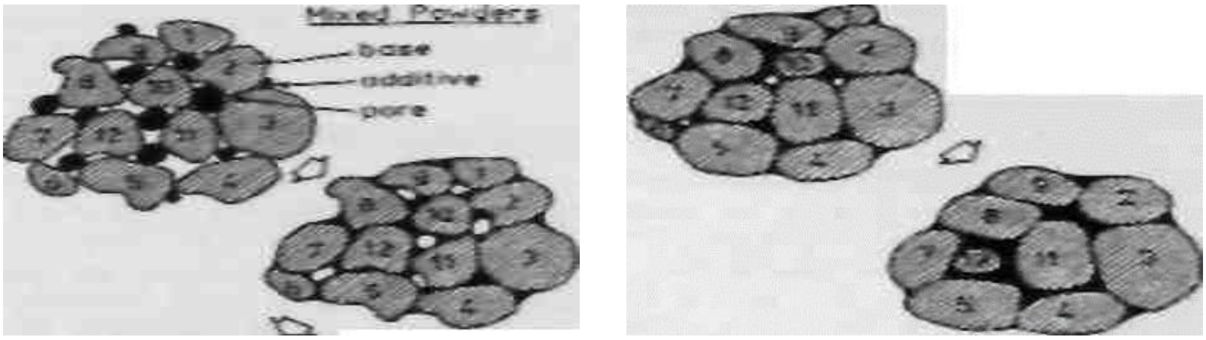


Figure 14. The classic stages of liquid phase sintering involving mixed powders which form a liquid on heating

-Mixed Powders

I Rearrangement liquid formation and spreading

II.Solution-Reprecipitotion diffusion, grain growth and sbope accommodation

III. Solid State pore elimination, grain growth and contact growth

The classic liquid phase sintering system densifies in three overlapping stages [26]. Figure 4.9 shows a schematic sequence of steps. Initially, the mixed powders are heated to a temperature where a liquid forms. With liquid formation there is rapid initial densification due to the capillary force exerted by the wetting liquid on the solid particles. The elimination of porosity occurs as the system minimizes its surface energy. During rearrangement, the compact responds as a viscous solid to the capillary action. The elimination of porosity increases the compact viscosity. As a consequence the densification rate continuously decreases. The amount of densificatiflp, attained jay rearrangement is dependent on the amount of liquid, particle size, and solubility of the solid in the ljguid particle size, and solubility of the solid in the liquid. Usually finer particles give better rearrangement. Full density (zero porosity) is possible by rearrangement if enough liquictis formed. It is estimated that 35 volume percent liquid is needed to obtain full density by rearrangement processes. However, rearrangement processes can be inhibited by a high green density or irregular particle shape. The particle contacts resulting from compaction form solid state bondsduring heating, thereby preventing rearrangement[26].

5.Experımental Studies

5.1 Materials

In this study, pure aluminum and composite reinforced with %5-%20 weight B4C particles of 15 μm were used. The materials were fabricated (Alfa Aesar ,Johnson Matthey GmbH& Co.KG) by a (PM) technique. Atomized aluminum powders (99.99 % purity ,density 2,699 gr/cm3) with a nominal size of 10 μm were used as raw   material. Commercially pure aluminum (Al) Powder and B4C were used as the matrix material. The reinforcement material was used as boron carbide (B4C) (Alfa Aesar ,Johnson Matthey GmbH& Co.KG- density 2,52 gr/cm3)particles. The average size of the boron carbide particles were about 27.19 μm. All these materials were used as purchased without any purification and modification.

5.2 Production of Composites

During the production of composites, %5-%20 weight B4C was reinforced to aluminum by means of a attrition milling.The maximum milling time was eight hours.The ball to powder weight ratio was 6:1 and the milling speed was about 400 rpm ,ball diameter : 20 mm stainless steel ball % 1 (wt) of acrowax was added as the process control agent after 60 C drying. Powder materials were formed easily by means of CIP 250 Mpa due to the ceramic behavior of the boron during process.The chosen sintering atmosphere was high pure argon and sintering of specimens were carried out at three different temperature (600 C ,625 C, 640 C), because other sintering atmospheres could cause deboronization of material at working temperature, due to the small atomic size of the boron and formation of gaseous hidrures. (BH2 and BH3)

Figure 15.1 Uniaxial Molding machine

Figure 15.2 Sinterig Furnace

Figure 16.1.Attrittion Milles Machine *Figure 16.2.Cold Isostatıc Peres*

5.3.1 Microscopic Examination

Metallographic samples were prepared from the longitudinal cross sections of the investigated composites by gentle grinding and polishing. All samples were grinded gently with 240, 500, 800 and 1000 mesh SiC emery papers. Afterwards samples were gently polished by Al2O3 solutions. Microstructures of the composites were investigated by Jeol JSM 7000F type field emission Scanning electron microscope (SEM) equipped.

5.3.2 XRD Analysis

Identification of the phases in pure AI powder and different , %5-%20 weight B4C powder composites were performed by using a Rigaku X Ray diffractometer. X-ray diffraction (XRD) analyses were performed by using Cu/Ka radiation with an incident beam angle of 2°.Diffraction angle was between 5-120°, with a step increment of 0.02° and a count time of Is.

5.3.4. Hardness, Density and Impact Experiments

Mechanical properties of the samples were determined by hardness measurements. Hardness tests were performed on metallographic samples by utilizing Instron Universal Hardness Tester Machine. Metallographic samples were used in order to find the hardness of the composites was measured by using a Vickers 1360 diamond indenter. Test load for each sample was 1000 g. Due to the trace of the indenter cover both matrix and reinforcement material, the hardness value stands for the bulk hardness of the composite. Results of hardness tests were evaluated by averaging the results of 10 successive measurements. Powder evolution was studied through powder apparent density.


Figure 17.1 Universal Hardness Tester


Figure 17.2 Impact Specimen of Molding

The impact tests were performed by using Zwick B5113 charpy-type impact test equipment having capacity of 50 J. The measurement sensitivity of the equipment was 0.2 J. The diameter and length of the impact test samples were 7 mm and 40 mm, respectively.

5.3.6.Creep Experiments

High temperature mechanical properties of the composites were determined by creep test. The lengths of the composites, which have 12 mm diameters, were about 24 and 40 mm. Creep behavior of the materials were investigated under different strain and temperature conditions.

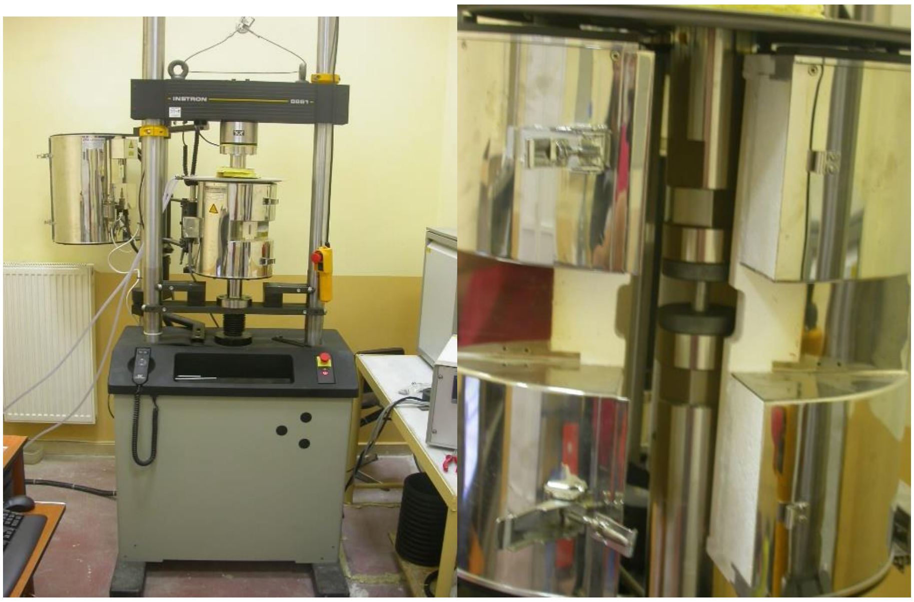

a) Creep testing machine *(b) Creep testing machine*

Figure 18. Creep Machine (a) and Creep Test (b)

6. Results and Discussion

Optimum processing conditions for composite fabrication were determined by examining the microstructures of multi-axially forged samples. The variation of microstructure upon application of multi-axial forging is presented in Figure 7.1. In as pressed discs, it was observed that all B4C particles were segregated around the Al powder chips and exhibited a network structure. Since network structure has detrimental effect on the mechanical properties, this type of microstructure is not desirable for an engineering material. Upon application of multi-axial forging the network structure tended to be eliminated by developing laminated structure. As the number of multi-axial pressing increases, alignment of B4C particles in one direction and breaking in the network structure is observed. In the present study, number of multi-axial forging is selected as two for further examinations.

6.1. Metallographic Investigation

The results of scanning electron microscope (SEM) examinations conducted on pure Al powder and composites reinforced with different % weight B4C particles are discussed below.

SEM micrographs of the pure Al matrix and Al+B4C composites are shown in Figures at various (x1000) magnifications. It can easily be seen that the B4C particles are distributed homogenously in the matrix and no segregation takes place at a particular region. However presences of the porosity at tips of the B4C particles are observed.

6.2 XRD Analyses

XRD patterns obtained from the pure Al powder and Al+B4C matrix composites are shown in Figures. The pattern belongs to pure Al matrix composites shows that composite composed of Al, B4C due to interfacial reactions between Al and B4C. The peaks of most expected.

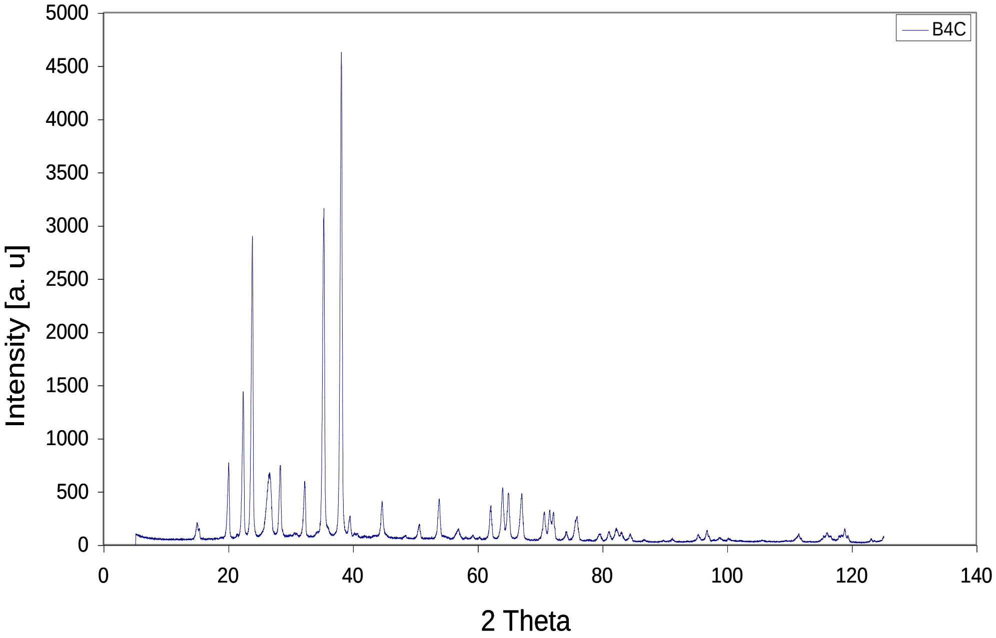


Figure 19. XRD pattern B4C particles

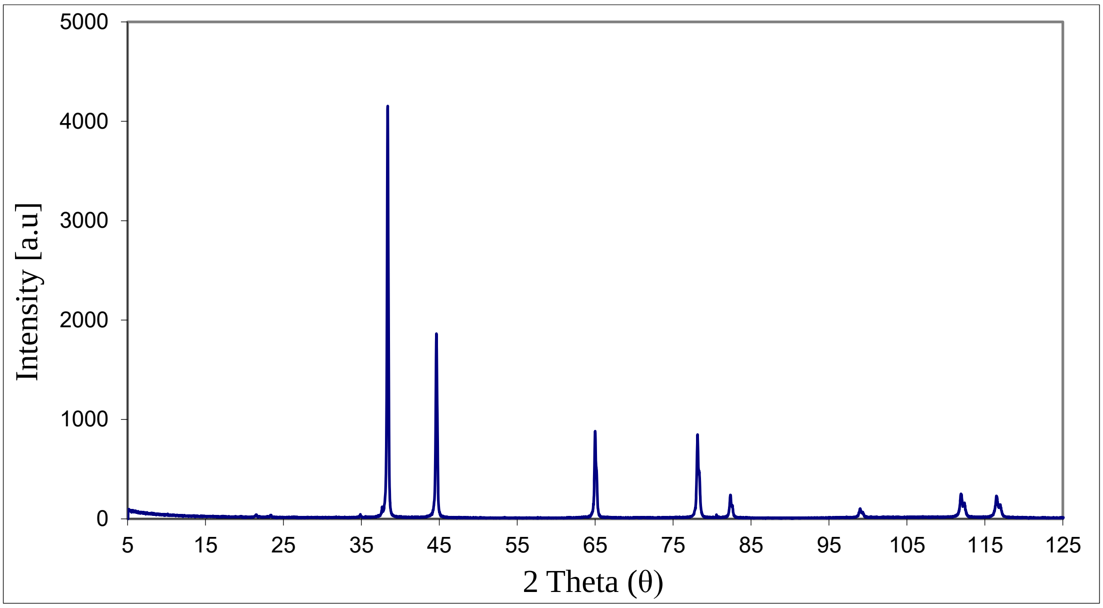


Figure 20. XRD pattern Al particules

The Bragg reflection peaks obtained from the specimens were matched with the potential phases in the structure by fixing of the 2θ values to the strongest reflected intensities. The main phases of Al and B4C (Norbide) appeared in the microstructures of both Pure al powder and different Containing % B4C metal matrix composites. As a result two different angles 37.8 and 23,5 % peak area increase.

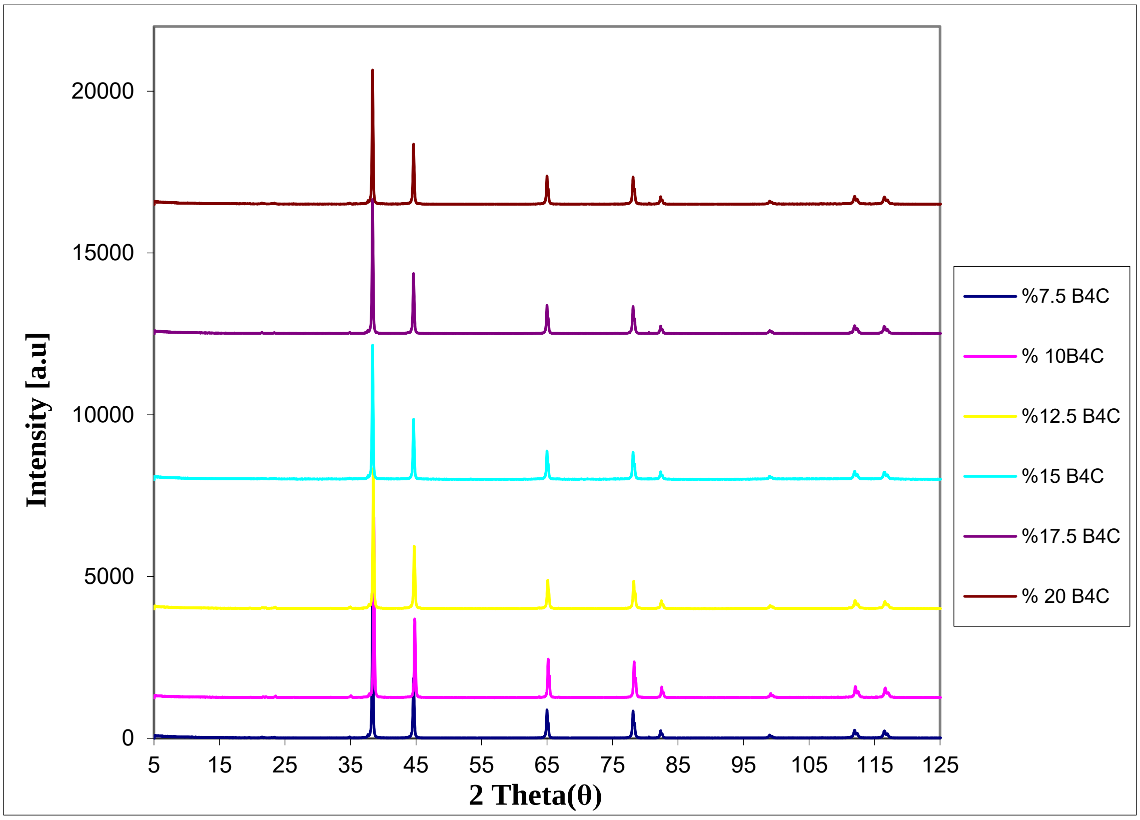


Figure 21. XRD patterns of Al powder containing different wt% B4C of the Al Matrix

Table 10.Increase peak % Area containing different wt % B4C of the Al Matrix

Materials	**Increase Peak %Area**	
	2 Theta (37,80-37,5 0)	**2 Theta (23,260-23,5 0)**
Composite cont. % 5 B4C	2,4	0,7
Composite cont. % 7.5 B4C	2,5	0,5
Composite cont. % 10 B4C	2,8	1,1
Composite cont. % 12.5 B4C	3,3	1,2
Composite cont. % 15 B4C	4,2	1,5
Composite cont. % 17.5 B4C	4,2	1,6
Composite cont. % 20 B4C	5	1,9

6.2. Hardness Test Results

The vickers hardness test has been carried out for four different compositions, three different sintering temperature. The average hardness values of the samples are listed in Table 11. Commercially extruded al powder is taken as reference sample. Hot pressed and multi axially forged samples produced from chips without reinforcing are coded as unreinforced Al powder and exhibited almost similar hardness that of reference al powder. Addition of B4C particles and application of sintering temper resulted in increase in hardness. In different sintering temperatures states increasing of B4C particle size tended to increase hardness slightly. The hardness of the composites are listed in Table 11. It is obvious that B4C addition increased the hardness of the composites considerably. The increase of hardness by addittion of B4C can be attributed to the solid solution hardening of the matrix as well as intermetallic precipitation discussed. Figure 6.3 shows that increase of hardness with increasing B4C content is almost linear.

Table 11. Micro hardness of pure Al and wt % B4C content of the Al Matrix composites

Materials	**Hardness (HV1)**		
	600 0C	**625 0C**	**650 0C**
Pure Al	38,1	36,6	25,8
Composite containing % 5 B4C	40,9	39,9	45,6
Composite containing % 7.5 B4C	43,8	42,9	53,5
Composite containing % 10 B4C	49,0	52,1	56,8
Composite containing % 12.5 B4C	56,1	61,1	66,6
Composite containing % 15 B4C	61,5	68,1	72,0
Composite containing % 17.5 B4C	64,8	77,2	74,8
Composite containing % 20 B4C	74,1	82,0	82,1

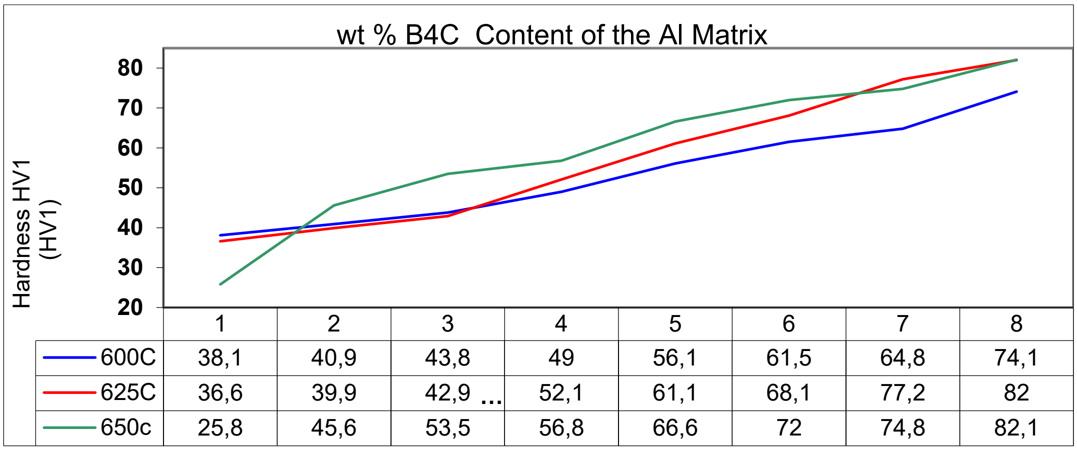


Figure 22. Hardness of the wt % B4C content of the Al Matrix

6.3. Density Test Results

The average density values of the samples are listed in Table 12. Commercially extruded al powder is taken as reference sample. Hot pressed and multi axially forged samples produced from chips without reinforcing are coded as unreinforced Al powder and exhibited almost similar density that of reference al powder. Addition of B4C particles and application of sintering temper resulted in decrease in density. In different sintering temperetures states increasing of B4C particle size tended to decrease density slightly. The density of the composites are listed in Table 12. It is obvious that B4C addition decrease the density of the composites considerably. Figure 8.2 shows that decrease of density with decrease B4C content is almost linear.

Table 12. Change of the density wt % Content B4C of the Al Matrix

Materials	**Density (gr/cm3)**		
	600 0C	**625 0C**	**650 0C**
Pure Al	2,5036	2,5445	2,5611
Composite containing % 5 B4C	2,4194	2,5346	2,5376
Composite containing % 7.5 B4C	2,3956	2,5140	2,5252
Composite containing % 10 B4C	2,3689	2,5073	2,5053
Composite containing % 12.5 B4C	2,3589	2,4934	2,4904
Composite containing % 15 B4C	2,3471	2,4902	2,4496
Composite containing % 17.5 B4C	2,3439	2,4975	2,3976
Composite containing % 20 B4C	2,3365	2,4901	2,3739

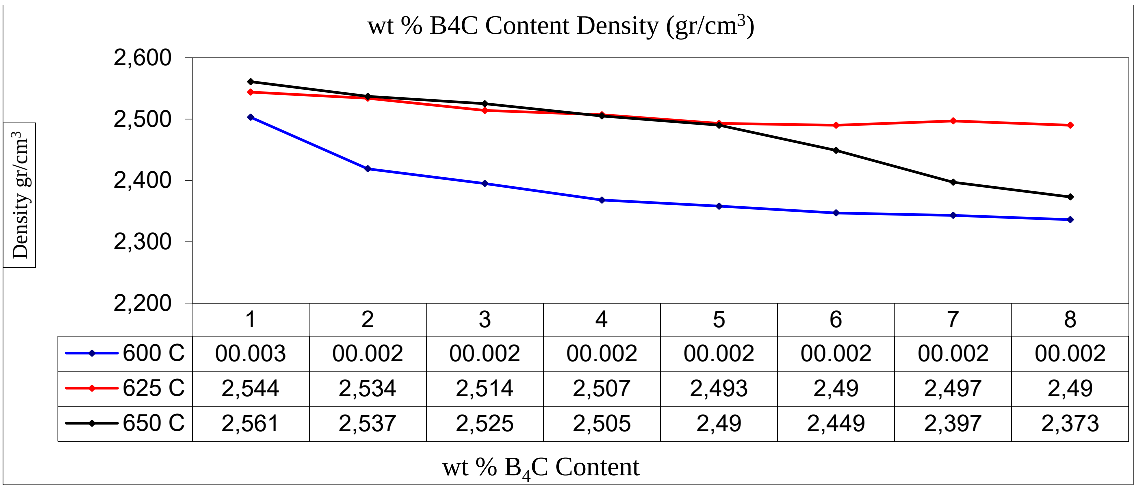


Figure 23. Change of the density as wt % content B4C of the Al Matrix

6.4 Impact Test Results

The results obtained from unaxial compression and impact tests are given in Table 13. The impact test results are plotted as a function of B4C content of the matrix in Figure 8.5. respectively. The decrease of B4C content of the matrix impact however, caused a reduction in impact resistance

Table 13 Impact Energy of the composites wt % B4C content of the Al matrix

Materials	**Impact Energy (KJ/m2)**		
	600 0C	**625 0C**	**650 0C**
Unreinforced Al	80	65	42
Composite containing % 5 B4C	59	48	38
Composite containing % 10 B4C	58	54	52
Composite containing % 15 B4C	26	28	24
Composite containing % 20 B4C	12	10	9

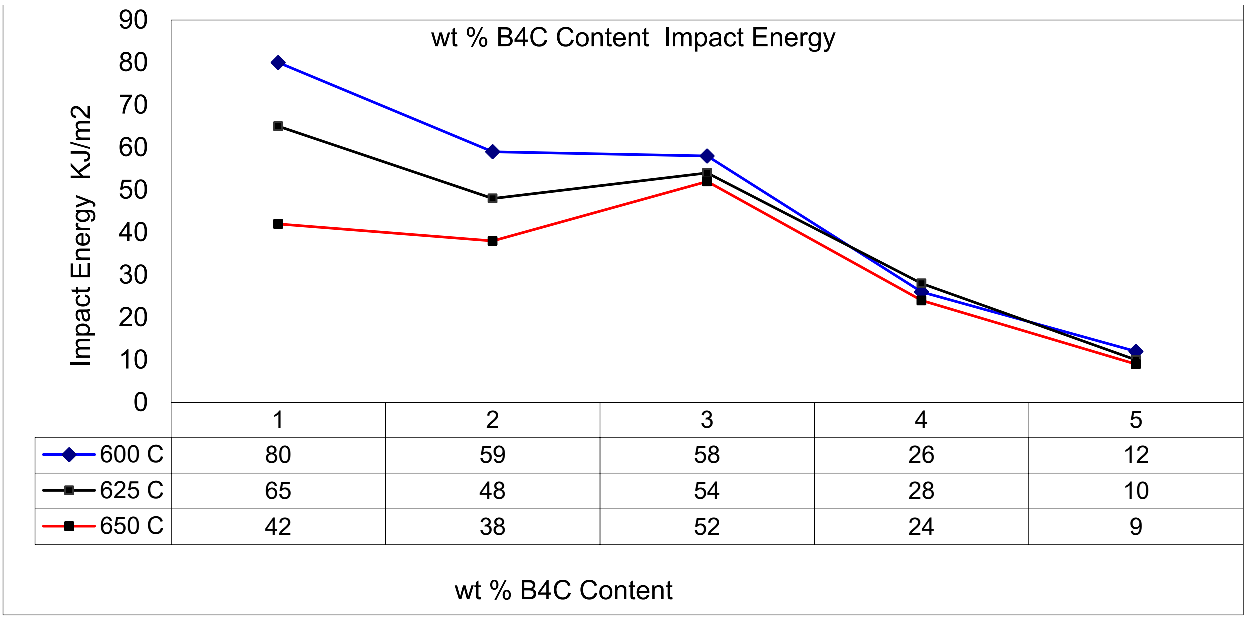


Figure 24. Impact energy wt of the wt % B4C content of the Al matrix.

Impact strength decrease very slightly up to B4C content of wt%. Further addition of B4C increased the strength from about 59 J to 9 J, probably due to significant reduction in porosity and precipitation of intermetallic compounds. On the other hand B4C addition resulted in a dramatic reduction in impact resistance up to about wt% B4C. At higher B4C contents impact resistance was kept almost constant.

6.5.Creep Experiments

In this work creep, pure Aluminum powder composites reinforced with different % weight (5,10,15 wt %) of particulate B4C were used. The composites were fabricated by the powder metallurgy method. Pure aluminum powder (Al), 5,10 and 15 wt % boron carbide (B4C) particulate reinforced Al (Al/B4C) composite were evaluated. These creep specimens were made viapowder mechanical milling followed by cold isostatic pressing (CIP) and sintering consolidation methods.

Compression creep specimens with a gauge diameter of 12-15 mm and gauge length of 25-30 mm were machined from the CIP rods. All the sintering specimens were treated at 913 K for 1 h, furnace quenched constant load creep tests without interruption were conducted in air at 723 K and 673 K The temperature of the specimens was monitored by three separated thermocouples. The specimens were maintained for 6 h at test temperature before loading. The creep strain of specimens was measured using unit cells test. High varying temperature and load mechanical properties of the composites were determined by creep test. As it (673 0K) is seen the Table 6.7 above, the compression strains decrease with increasing B4C in Al. Compression strains decrease in the same ratio from 5% to 15.

From an engineering mechanics point of view strain measured during the time dependent deformation of creep can be thought of as the macroscopic manifestation of the cumulative damage process under the action of temperature and stress. Therefore, predictive models of the creep deformation often include strain, strain rate, applied stress, the use temperature as well as various material-related constants such as activation energy for creep and stress exponent. For short- term creep test, the following equation can be constructed.

$$\Gamma = B\sigma^n$$

Where σ is stress, B is coefficient and n stress exponent, which can be determined for the relation. The activation energy for creep over a small temperature interval, where the controlling mechanism would not be expected to vary, researchers often make use of the temperature differential creep test method.

Steady- state creep is the basis for many extrapolation approaches. The strain rate for the steady-state creep regime can be modeled with a stress-dependent term and an activation energy term.

$$\Delta H_C = \frac{R\ln(\dot{\varepsilon}_1/\dot{\varepsilon}_2)}{(1/T_2 - 1/T_1)}$$

where ΔH_C = activation energy for creep

$\dot{\varepsilon}_1, \dot{\varepsilon}_2$ = creep rates at T_1 and T_2, respectively.

$$\dot{\varepsilon}_{ss} = A_{ss}\sigma^n \exp(\frac{-Q}{RT}) \qquad (*)$$

where Ass is constant, σ is the applied stress, n gives the stress dependence of the strain rate, Q is the activation energy for the critical step in the deformation process and T is the temperature.

The data, which is obtained from the tests, specimens were subjected to 673 K and 723 K, and 35 MPa and 45 MPa, and using the formulation given above, activation energy can be calculated as 50 KJ/mol K. n is computed as 3,15. Ass is obtained using equation *. It is 5,38 10-26(35 MPa),5,39 10-26.

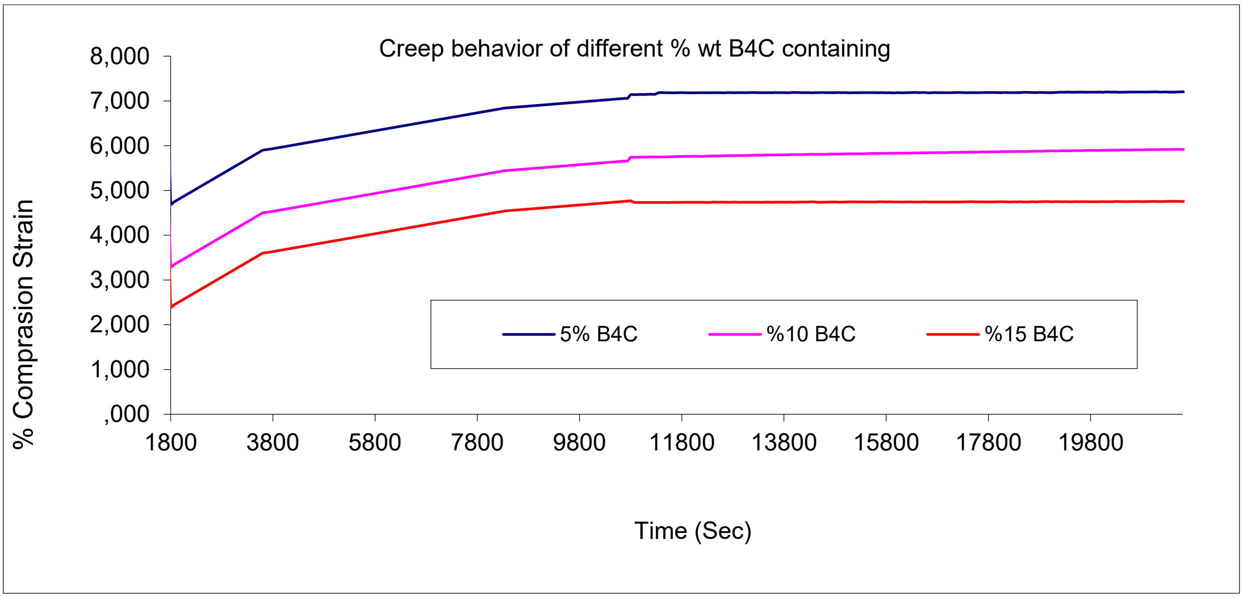


Figure 25. Creep behavior of different % wt B4C containing of f the MMC 673 0K.

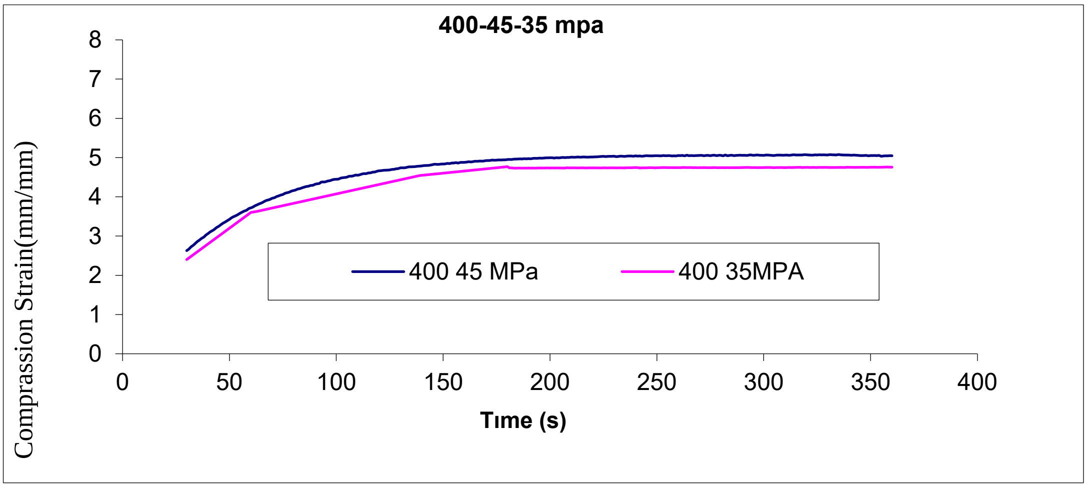


Figure 26. Creep behavior of different Stress of f the MMC.

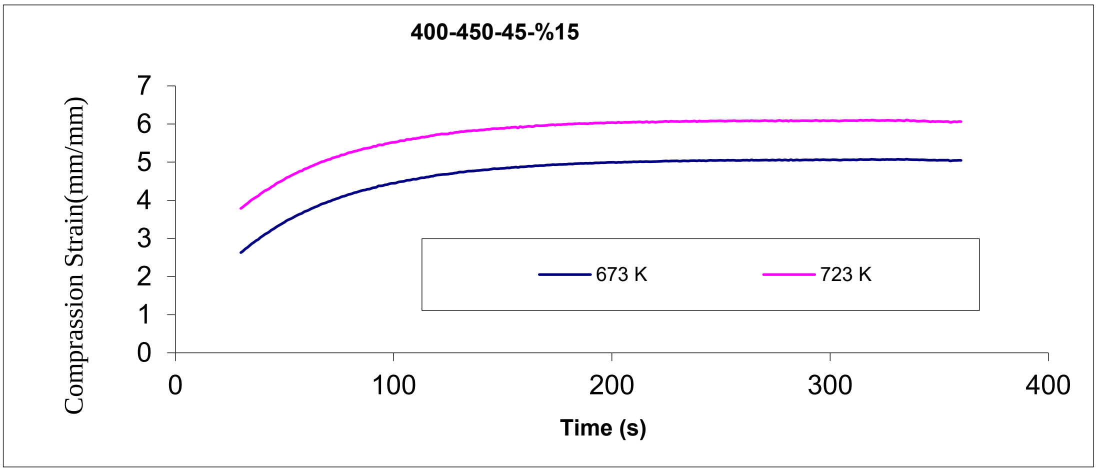


Figure 27. Creep behavior of different temperature of f the MMC 673 0K.

7. CONCLUSIONS

Results of this study can be stated as;

Aluminum specimens were reinforced with different B4C ratios. Density of Al varies with the ratio of B4C and as function of sintering temperature. It is observed that lower the weight percent of B4C, lower the density of the composite. In the case of hardness, it was observed that reinforced Al exhibited a better hardness than pure aluminum which was produced by powder metallurgy. In hardness tests, it is observed that addition of 15 % B4C is optimum because all specimens intersect at 625 0C. The impact energy decreased with B4C as expected.

In creep tests, compression strain was reduced with increasing B4C. Activation energy, n stress exponent constant and creep rate were calculated and they areas 50 kJ/mol, 3,15 and 4,117 10-6(for the specimen, subjected to 35 MPa and 673 K) and 9,09 10-6(for the specimen, subjected to 45 MPa and 673 K), respectively.

It is also SEM pictures were investigated. SEM pictures show that B4C particles increased with increasing B4C.

XRD analysis were used to find phase and crystal structure of the samples. The X-ray diffractions of the samples at various B4C ratio are shown in Figures 6,5. The reflections correspond to rhombohedra BC4 structure. The peaks at 2θ of 37.8°- 37.5, and 23.26- 23.5 belongs to the rhombohedra B4C phase. The high area observed at 2θ of and rhombohedra B4C (012). As also XRD patterns show that all of peaks to fit with B4C peaks.

When compared to untreated state, T6 temper improved wear resistance. The wear resistance increased slightly with increasing the size of boron carbide. Untreated and T6 tempered composites exhibited completely different corrosion behavior during corrosion tests. With increasing holding time in corrosion solution corrosion loss of untreated samples decrease while that of T6 tempered samples increased with respect to holding time.

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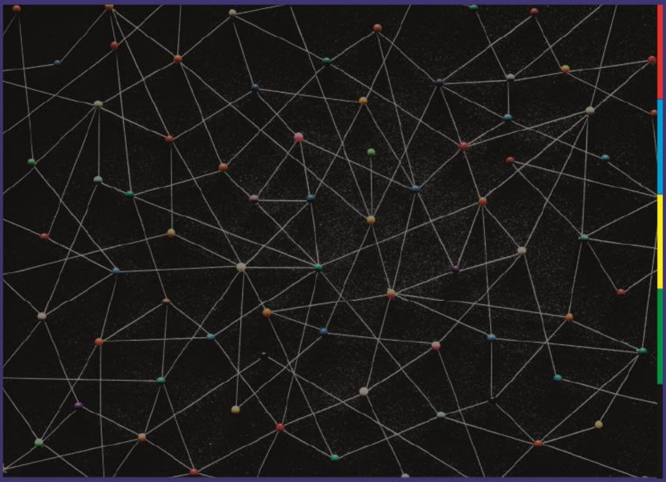
Examination of Mechanical Properties of B4C Particulate Reinforced Aluminum MMC Under Different ding Conditions



Powder Metallurgy is a highly evolved method of manufacturing reliable net shaped components by blending elemental or pre-alloyed powders together, compacting this blend in a die and sintering or heating the pressed part in a controlled atmosphere furnace to bond the particles metallurgically. The P/M process is a unique part fabrication method that is highly cost effective in producing simple or complex parts at final dimensions (Koczak, M. J. 1989).

MMC consist of at least one metal and a reinforcement material as continuous fiber, intermetallics particles, compounds, oxide, carbide or nitride in order to achieve requirements and expected properties which can not be met by single compound materials (Huda at all 1995). Nowadays production of metal matrix composites by liquid phase process is convenient in the production of MMC reinforced with particles. The driving force behind the development of MMC has been the attractive mechanical and physical properties and enhanced elevated temperature capabilities (Topcu at all 2020, Lee at all 2001). In addition, AMC reinforced with ceramic particles or whiskers have received considerable attention because they can be formed by standard metalworking practices. Apart from improved mechanical properties, other controlling attributes, such as coefficient of thermal expansion and wear resistance, are greatly improved by the addition of ceramic particles (Chapman at all 1999).

With good properties, such as high hardness, high melting point, good thermal conductivity and good electrical conductivity, boron carbide ceramics are excellent candidates for neutron absorption materials, wear resistant materials, electrode materials and cutting tools (Schwartz, M.M..(1984) , Topcu at all 2020). Among the outstanding physical and mechanical properties of boron carbide is its hardness, which is second after diamond and c-BN. This specific property comes along with other attractive properties such as high impact and wear resistance, low density, high melting point, and excellent resistance to chemical agents as well as high capability for neutron absorption.

Aluminum MMC are being considered as a group of new advanced materials for its light weight, high strength, high specific modulus, low co¬efficient of thermal expansion and good wear resistance properties. Combination of these properties is not available in a conventional material (Huda at all 1995). The use of Aluminum MMC has been limited in very specific applications such as aerospace and military weapon due to high processing cost. For applications at low temperatures, aluminum or aluminum alloys is a material of choice. Suggested applications for B4C-Al composites include its use as a structural neutron absorber, arm our plate materials, and as a substrate material for computer hard disks(Du, W .F,1997).

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