Melt Infiltration Casting of Alumina Silicon Carbide and Boron Carbide Reinforced Aluminum Matrix Composites

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Abstract

This paper discusses the effect of processing details such as particle size, sintering temperature, preform preparation, aluminum alloy characteristics, and melt temperature on the final mechanical properties of ceramic phase reinforced metal matrix composites. Since alloy composition was determined as 7075 and 7085 optimum solutionizing and age-temperatures were studied to determine maximum hardness values. For only 7085 alloy best solutionizing temperature is 465°C and for 7075 alloy the maximum hardness achieved as 178 BHN after heat treatment at 475°C. Alloys were heat treated for recrystallization after hot rolling grain size were measured as 100-120 μm for 7085 alloy matrix.

Various sintering temperatures were used for preform preparation such as 1300-1450°C. In 85% Al2O3 reinforced 7085 Alloy based MMCs preforms sintered at 1450°C high hardness values were achieved as 545 BHN. Intermetallic phase was determined in 7075 and 7085 alloys selected as alloy matrix. AlCu intermetallic precipitate (θ phase) was determined as dominant second phase after T6 heat treatment but highly expected phase in 7000 series alloys MgZn2 (η phase) was not determined by XRD and SEM analysis techniques due to ultrafine precipitate size and homogeneous distribution.

Keywords: Composite materials; Armor materials; Ductility

Introduction

Development of metal-ceramic composite materials with possible lowest density and higher energy absorbing capacity is highly important for defense industry. So, many criteria’s should be considered when selecting of materials that are used in armor system. The impact resistance of shield materials against projectile is strongly required to be determined.

Scientific research on metal matrix composites and mechanical characterization by three point bending, hardness and impact toughness measurements are typical tests for performance characterization apart from ballistic tests.

Boron carbide is known with its extreme hardness of 30 GPa. It is the hardest third material after diamond and cubic-BN which are very expensive and hard to prepare. At temperatures above 1200°C its hardness value even exceeds that of diamond [1]. Combination of high hardness and low density makes boron carbide top candidate of armor materials. However low strength, high price, poor fracture toughness, sinterability and machinability of boron carbide limits its industrial applications [2]. Also, boron carbide doesn’t provide efficient protection to stop armor piercing bullet with high velocity due to amorphisation process that occurs in boron carbide in the presence of high pressure. At this pressure, ballistic performance of boron carbide drops because shear strength of boron carbide decreases. Another problem with boron carbide is its brittleness which makes them not suitable for multi-hit protection [3]. The popularity of silicon carbide for armor technologies has increased due to its improved cost/performance ratio relative to other candidate materials like alumina [4]. Silicon carbide is produced in larger scales because it has many fields of application areas compared with boron carbide. The price of silicon carbide is lower than that of boron carbide and ballistic performance of silicon carbide is very close to that of boron carbide. Thus many researchers have worked for production of armor system with as low boron carbide content as possible [5]. Silicon carbide is often mixed with boron carbide, but monolithic silicon carbide is also used in production of armor materials. Density of silicon carbide is 3.21 g/cm3 which are between that of boron carbide and alumina. Hardness of silicon carbide is very close to that of boron carbide. Thus for higher level ballistic threats silicon carbide is better alternative than boron carbide in spite of its higher density [3].

Although ceramic armors are used currently, low fracture toughness and high expense of them limits their widespread use. They do not provide efficient protection against multi-hit in a short space of time. After the first hit, armor system is expected to heavily damage and then any bullet would penetrate armor system which have already fractured [6]. Combining ceramic materials with a metal may provide better ballistic efficiency. So creating of porous ceramic preform, then infiltrating it with a ductile metal is considered as solution. Aluminum is most widely used infiltrated metal because of its low density, low melting point and outstanding ductility. It is also non-toxic, relatively inexpensive and easy to obtain. Molten aluminum reacts with boron...
carbide easily, thus infiltration process may be achieved. Resulted B₄C-
SiC-Al₂O₃-Al composites exhibit combination of high hardness and
toughness without defeating the aim of obtaining lightweight
structure [7]. It is very hard to obtain 100% dense B₄C-SiC-Al₂O₃
composites due to presence of strong covalent bonds, high resistance
to grain boundary sliding and absence of plasticity which limit their
diffusion coefficients in sintering process. Combination of high
temperatures and high pressures used in sintering process is the most
important economic problem besides the high cost of powders [7].
Compared with traditional sintering techniques, melt infiltration is a
promising process to produce composite with porous ceramic preforms
due to its several advantages. Near or near-net shape composites with
high volume fraction ceramics can be obtained. And these ceramic
phases can be uniformly distributed in composite structure. Resulted
composite exhibits high dimensional stability [8]. Residual stress
build up due to different thermal expansion of dissimilar materials
can be eliminated, thus residual porosities are prevented. Mechanical
properties of composite can be arranged via addition of appropriate
compounds or elements [9]. Using high strength aluminum alloy such
as 7075 as matrix alloy with addition of %10 SiC displays high flexure
strength values 600 MPa reported [9]. Reaction products and reaction
rate between ceramic and metal phases can be controlled. The most
important advantage of pressureless melt infiltration is that there is
no need to use high temperatures and high pressures (when wetting
condition is provided there is no need to apply pressure-pressureless
melts infiltration) that makes this process very economic. The most
important criteria of melt infiltration process are the wetting behavior
of the system. Wettability is the ability of a liquid to spread on a solid
surface and it demonstrates the extent of close contact between a liquid
and a solid [5]. The driving force for wetting is the reduction in free
energy of the system. Wetting of the ceramic phase by the metal must
be achieved for infiltration process because in the absence of wetting
there is no interfacial reaction between ceramic and metal phases [10].
With appropriate temperature and atmosphere conditions, wettability
between ceramic and metal phases is achieved and liquid metal is
drawn into the porous ceramic preform via capillarity thermodynamic
criteria [9] (Table 1).

Lee and Hong worked on production of high volume fraction SiC/
Al metal matrix composites by pressure infiltration method. High
volume fraction of metal matrix composites such as SiC/Al composites
containing nearly 70 vol% SiC particles could be fabricated without
forming residual porosity and Al vein layers by pressure infiltration
method controlling such process parameters for Al melt temperature
800°C, SiC preform preheat temperature 550°C, infiltration pressure
30-50 MPa and infiltration time 20-70 seconds after pouring Al
melt into ceramic preform [10]. The maximum pressure (130 MPa)
has been maintained until the melt has solidified. With this procedure, the
whole infiltration cycle does not take more than 120 s. [11] Pressure
infiltration is useful technique for fast and high volume production
of metal matrix composite systems having high liquid/solid surface
tension and difficult wetting conditions.

Melt infiltration with and without pressure techniques are not
always successful for all combinations. Since aluminum alloy surface
tension is a strong function of surface active elements and Mg content
of the alloy, wetting and liquid penetration is improved by high pressure
application on top of liquid aluminum during squeeze casting [12].

Results

Aluminum 7075 matrix with Al₂O₃, SiC and B₄C ceramic preforms
were infiltrated with and without pressure. In the beginning, melt
infiltration process was done by the first group of alumina preforms
that were sintered at 1000, 1100, 1200 and 1300°C whereas, only two of
them were characterized. Metal matrix composites that were produces
by the preforms (Figure 2).

After melt infiltration method, ceramic preform is confined by
molten metal. In order to be able to investigate the microstructure and
interfaces in between ceramic reinforcement and aluminum metal,
these specimens were examined after processing to reveal interface
microstructures.

Composites, produced by preform whose sintering temperatures
are 1300 and 1450°C. Obtaining high hardness values can be a
promising property for the ballistic performance. High hardness values
are needed in order to abrade the projectiles. As it was thought that
the hardness of the tool steels is about 530 HB, the average composite
hardness 545 HB can be considered as sufficient results for ballistic
armor plate material. Therefore, Alumina - 7085 aluminum composites
can be a good candidate for these applications (Figure 5).

Even if there is incomplete penetration along the interfaces,
melt infiltration was achieved successfully in most specimens since
aluminum phases were detected in the pores of alumina structure as
it can be seen in below figures. In other words, 7085 aluminum alloy
was completely sucked by alumina preform with the help of squeeze
casting. This shows that squeeze casting is a good method to produce
metal matrix composites if ceramic preform is wetted and completely
infiltrated (Figure 6).

In the beginning, ceramic plate was preheated at 500°C during 90
minutes. At the same time, mold was also heated up to 250°C. Composite
Table 1: Some important properties of boron carbide, silicon carbide, alumina and aluminium.

| Materials | Density (g/cm³) | Melting point (°C) | Hardness (Knoop) | Fracture Toughness (MPa.m⁻¹/₂) |
|-----------|-----------------|-------------------|-----------------|-------------------------------|
| B₄C       | 2.52            | 2445              | 2750            | 2.9-3.7                       |
| SiC       | 3.21            | 2730              | 2480            | 4.3                           |
| Al₂O₃     | 4.00            | 2070              | 2100            | 3.3-5.0                       |
| Al        | 2.70            | 660               | 120             | 29                            |

Figure 1: Actual and schematic view of metal infiltration process to produce metal composite.

Figure 2: Aluminum infiltrated composites after sintering and infiltration processing.

Figure 3: SEM images of the interface of alumina /7085 aluminum alloy composite sintered at 1300°C after infiltration.
Figure 4: SEM images of the interface of alumina /7085 aluminum alloy composite sintered at 1450°C after infiltration revealed incomplete penetration of liquid aluminum alloy.

Figure 5: Distribution of composite hardness values according to $\text{Al}_2\text{O}_3$ preform sintering temperature.

Figure 6: Microstructure of Boron Carbide – 7075 Aluminum composite.

Plate was just put inside the mold and molten 7085 aluminum is poured into the cavity and squeeze casting was performed. At the end of this process crack formation was seen at the center of composite. Therefore, it should be noted that confinement operation is not possible by squeeze casting process for boron carbide/aluminum composite structures because of different thermal expansion coefficient, too fine carbide size and wetting difficulties for these materials (Figure 7).

Since heat treatments to achieve T6 condition is not convenient for infiltrated composites infiltrated ceramic preform and backing 7075 plate should be prepared separately, then two layers should be integrated in the end. Therefore plain 7075 squeeze cast plates without ceramic preforms were studied to determine the optimum solutionizing time and temperature for peak hardness condition of T6 heat treatment. It can be seen that 475°C is the best temperature for solution heat treatment of 7075 aluminum alloy according to the hardness values. The average hardness of the specimens that were solutionized at 475°C was measured as 178 HB and it was noted as the best hardness result after T6 heat treatment of squeeze casted 7075 aluminum alloy (Figure 8).

After the production of the boron carbide-7075 aluminum composites, confinement experiment was done for these composites. In this experiment, square shaped boron carbide-aluminum composite that was produced by melt infiltration without pressure. By confinement of infiltrated composites it was aimed to improve corrosion behavior of these composite structures. The main aim is to cover boron carbide composite with aluminum alloy.

High pressure die casting machine was used as an alternative way to study and develop high strength aluminum alloy as matrix alloy for defence and automotive applications. During the production, the speed of injection piston of high pressure die caster was decreased to 0.7 m/sec and rheocasting was performed. Therefore, specimens were produced by rheocasting with high pressure die casting machine (Figure 9).

During this experiment, a special mold was used that give billets to machine tensile test specimens that were produced by rheocasting technique. Before machining, T6 heat treatments were operated for these specimens with the best conditions. These means that, 475°C was used as solutionizing temperature for 7075 aluminum alloy whereas, 465°C was used as solutionizing temperature for 7085 aluminum alloy. After that specimens were quenched in the water and they were aged at 120°C during 24 hours.

Conclusions

1. Both pressure and pressureless melt infiltration techniques yielded at least 85% ceramic phase containing composites.
2. Pressureless infiltration of B₄C preforms having 1-3 µm carbide powder size produced for with 7075 alloy yielded complete infiltration. On contrary pressure infiltration of the same combination was failed due to low liquid phase penetration.

3. Pressure infiltration of Al₂O₃ preforms with coarse ceramic powders 20-50 µm was completely infiltrated with 7075 alloy

4. To develop high strength backing alloy plate, rheocasting of 7075 alloy was performed and this process yielded 400-500 MPa tensile strength after solutionizing at 475°C temperature for 90 mins then quenched in the water and aged at 120°C during 24 h.

5. T6 Heat treatment of infiltrated 7075 based composites is found to be unsuccessful due to large difference in thermal expansion coefficients of metallic and ceramic phases.

6. For integration of plain alloy backing plate and infiltrated composites gluing with adhesive materials can be used

7. Highest composite hardness values (550 HB) were obtained at ceramic (Al₂O₃) preforms sintered at maximum sintering temperature of 1450°C.

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