Review of Al Metal Matrix Composite and Basalt Fiber as a New Reinforcement for MMC

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Abstract: The development of high-performance engineering products made from natural resources is increasing worldwide, due to renewable and environmental issues. Among different types of natural resources, hard, and dense volcanic rocks can be found in most of the countries across the globe. These hard and dense volcanic rocks have been extensively exploited over the past few years. By using the volcanic rock basalt fiber is produced, this paper presents an overview of the developments made in the area of basalt fiber reinforced composites. This study, for the first time investigates the applicability of basalt fiber as a new reinforcing material for Metal Matrix Composites (MMCs) in terms of their availability in market, manufacturing methods, and overall properties through various experimental work for thermal stability and mechanical properties. It includes several critical issues and suggestions for future works, which underscore the roles of material scientists and manufacturing engineers and for the bright future of this new fiber material through value addition to enhance its uses.

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1. Introduction

Metal Matrix Composites (MMCs) is the widely used composite materials in aerospace, automobile, electronics and medical industries. They have outstanding properties like high strength, low weight, high modules, low ductility, high wear resistance, high thermal conductivity and low thermal coefficient of expansion. These desired properties are mainly manipulated by the matrix, the reinforcement element and the interface. Some of the typical applications of Metal Matrix Composites (MMCs) are bearings, automobile pistons, cylinder liners, piston rings, connecting rods, sliding electrical contacts, turbo charger impellers, space structures etc. Among the various reinforcement used, the most popular reinforcements are Silicon Carbide (SiC) and Alumina (Al_2O_3). Aluminum, Titanium and Magnesium alloys are commonly used as the matrix phase. The density of most of the MMCs is approximately one third comparing with steel density, resulting in high-specific strength and stiffness.

Metal Matrix Composites (MMCs) in general, consist of at least two components, one is the metal matrix and the other component is reinforcement. The matrix is defined as a metal in all cases, but a pure metal is rarely used as the matrix. In It is generally an alloy which is used as matrix by most of the Researcher. In productivity of the composite the matrix and the reinforcement are mixed together. In recent years, the development of Metal Matrix Composite (MMCs) has been receiving worldwide attention on account of their superior strength and stiffness in addition to their high wear resistance and creep resistance compared to their corresponding wrought alloys. The ductile matrix permits the blunting of cracks and stress concentrations by plastic deformation and provides a material with improved fracture toughness. Cast composites, where the volume and shape of phases is governed by phase diagrams, i.e. Cast iron and Aluminum-silicon alloys have been produced by foundries for a long time. The modern composites differ in the sense that any selected volume, shape and size of reinforcement can be introduced into the matrix. The modern composites are non-equilibrium mixtures of metals and ceramics, where there are no thermodynamic restrictions on the relative volume percentages, shapes and size of ceramic phases [1].

The high toughness and impact strength of metals and alloys such as Aluminium, Titanium, Magnesium and Nickel-Chromium alloys which undergo plastic deformation under impact is of interest in many dynamic structural applications of metallic composites. These materials have also been strengthened considerably by means of various strengthening principles (like grain boundary strengthening, cold working, solid solution strengthening, etc.) to improve their properties. But, these approaches are often found to affect the toughness and durability at elevated temperatures or under dynamic service conditions. One of the important objectives of metal matrix composites, therefore, is to develop a material with a judicious combination of toughness and stiffness so as to decrease the sensitivity to cracks and flaws, at the same time to increase the static and dynamic properties.

This necessity eventually leads to the efficient reinforcement of metals and metal alloys by unidirectional or multidirectional implantation of whiskers or continuous fibers. The reinforcement effect occurs due to the extraordinary high strength of whiskers and fibers with diameters below a few micrometers. Thus, the field of Metal Matrix Composite (MMCs) began in the mid of 1960's with the realization that whisker reinforced MMCs can be competitive with continuous fiber reinforced composites [2], from the standpoint of mechanical properties [3].

The complex fabrication routes, limited fabricability [3, 4] and the small difference in property enhancement between whisker and particulate reinforcement [5] and moreover, the health hazards associated with handling SiC whiskers [6, 7] have shifted the emphasis recently more towards particulate or chopped fibers rather than whisker reinforcement of metals, especially Aluminum, because of its light weight and good wettability with silicon carbide [8]. The important shift in metal matrix composite technology began in the mid of 1980's with frequent discontinuous reinforcement taking the place of continuous reinforcement such as carbides, nitrides, oxides and elemental materials like carbon and silicon.

While discontinuous whisker reinforced MMCs are still under development for aerospace applications, automotive components fabricated from particulate and discontinuous fiber reinforced MMCs, which exhibit essentially isotropic properties, are already in mass production, led by the introduction of diesel piston by Toyota in 1983 followed recently by engine and cylinder blocks from Honda [9, 10].The present trend, therefore, seems to be towards the development of discontinuously reinforced Metal Matrix Composites which are gaining widespread acceptance primarily because they have recently become available at a relatively low cost compared to unidirectional-and multi-directional continuous fiber reinforced MMCs and the availability of standard or near standard metal working methods which can be utilized to form these MMCs [11]. Discontinuously Reinforced Aluminium (DRA) composites composed of high strength aluminum and its alloys reinforced with silicon carbide particulates or whiskers are subclass of MMCs. The combination of properties and fabricability of aluminium Metal Matrix Composites makes them attractive candidates for many structural components requiring high-stiffness, high strength and low weight [12].

Nowadays, researchers across the globe are focusing mainly on Aluminium [13] because of its unique combination with good corrosion resistance, low density and excellent mechanical properties. The unique thermal properties of Aluminium composites such as metallic conductivity with coefficient of expansion that can be tailored down to zero, added to their prospects in aerospace and avionics.

Thus, entire families of light weight composites, though considered impossible just a few years ago, are either available now or hovering on the brink of commercialization. For example, a series of Aluminium matrix composites reinforced with silicon carbide particulates have been developed by Duralcan USA, Div. Alcan Aluminium corp., San Diego, California [14]. A high temperature creep resistant titanium alloy has been developed as matrix material for the National Aerospace plant by Timet for McDonnell Douglas. Titanium alloy, reinforced with continuous silicon carbide filaments, is hot isostatically, pressed by Textron for turbine engine shafts [15]. CERAMTEC AG (Germany) is currently utilizing matrix material for MMC products are Aluminium and specially the Al Si9Cu3 standard alloy. Apart from being fairly inexpensive in comparison with other light metals (e.g., magnesium and titanium), it has delivered outstanding results in many automotive and aerospace applications and is noted for its uncomplicated processing properties. In practice, the matrix may be constructed of almost any other light alloy or non-ferrous metal, particularly magnesium. They are also developing new ceramic cutting tools, and also superior material for cylinder linings. Titanium [16] has been used in aero engines mainly for compressor blades and discs due to its higher elevated temperature resistance property. Magnesium is the potential material to fabricate composite for making reciprocating components in motors and for pistons, gudgeon pins, and spring caps [17]. It is also used in aerospace due to its low coefficient of thermal expansion and high stiffness properties combined with low density. The choice of Silicon Carbide as the reinforcement in Aluminum composite is primarily meant to use the composite in missile guidance system replacing certain beryllium components because structural performance is better without special handling in fabrication demanded by latter's toxicity [18, 19]. Recently Aluminumlithium alloy has attracted the attention of researches due to its good wettability characteristics [20].

Successful development and deployment of Metal Matrix Composites are critical in reaching the goals of many advanced aerospace propulsion and power development programs. The specific space propulsion and power applications require high temperature, high thermal conductivity and high strength materials. Metal Matrix Composites either fulfill or have the potential of fulfilling these requirements [21]. Metal Matrix Composites also offer considerable promise to help automotive engineers to meet the challenges of current and future demands. It is, thus evident from literature that we can successfully reinforce the SiC, Al_2O_3, TiB_3, boron and graphite in the Aluminum matrix alloy. The reinforced Aluminum matrix alloys have made significant strides from laboratory towards commercialization. But, the understanding of factors that influence the physical and mechanical properties of these materials is really a challenge [22], because they are sensitive to the type and nature of reinforcement, the mode of manufacture and the details of fabrication processing of the composite after initial manufacture.

2. Material and Methods

2.1 Basalt fiber

A hard, dense volcanic rock can be found in most of the countries across the globe. Basalt is an igneous rock, which means it began in a molten state. For many years, basalt has been used in casting processes to make tiles and slabs for architectural applications. Additionally, cast basalt liners for steel tubing exhibit very high abrasion resistance in industrial applications. In crushed form, basalt also finds use as an aggregate in concrete. More recently, continuous fibers extruded from naturally fire-resistant basalt have been investigated as a replacement for asbestos fibers, in almost all its applications. In the last decade, basalt has emerged as a contender in the fiber reinforcement of composites. Proponents of this late-comer, claim their products offer performance similar to S-2 glass fibers at a price point between S-2 glass and E-glass, and may offer manufacturers a less-expensive alternative to carbon fiber for products in which the latter represents over-engineering.

2.2 Volcanic rock with a future

Basalt as a natural volcanic igneous rock has its origin at a depth of hundreds of kilometers beneath the earth and it reaches the surface as molten magma. When magma reaches the surface, it cools down and can be mined as a raw material. In addition to its main components, this volcanic rock contains silicon and oxygen plus other valuable elements such as calcium, magnesium, iron, sodium, potassium, aluminum and titanium. Basalt fiber or fiber is a material made from extremely fine fibers of basalt, which is composed of the minerals plagioclase, pyroxene, and olivine. It is similar to carbon fiber and fiberglass, having better physic mechanical properties than fiberglass, but being significantly cheaper than carbon fiber. It is used as a fireproof textile in aerospace and automotive industries and can also be used as a composite to produce products such as tripods.

The first attempts to produce basalt fiber were made in the United States in 1923. These were further developed after World War II by researchers in the USA, Europe and the Soviet Union especially for military and aerospace applications. Since declassification in 1995, basalt fibers have been used in a wider range of civilian applications.

The first samples of BCF were received at the scientific research institute in Ukraine of the Soviet Union in 1959- 61. The thirst samples were rough and inelastic, but as a matter of fact it was already a continuous basalt fiber. The following efforts led to production of continuous basalt fibers of satisfactory quality at labs installation in 1963. It was in 1963, when the first publication about BCF appeared in “The Glass and Ceramics" magazine

- This publication was followed by a lot of works, which were focused on three main directions:

1. Development of technologies & equipment for BCF production;
2. Research on fiber characteristics;
3. Development of samples of BCF materials and study of possible fields for their application.

- By 1971 a certain amount of experience was gathered. It included the research of basalts and their chemical characteristics, characteristics of basalt melts, analyses of BCF durability, its chemical & thermal stability; research of possible fields of application
- By 1985 the first industrial installation for BCF production was designed and launched. BCF industrial production was started at the "Teplozvukoizoliacia" (means “Heat and sound proofing”) factory near Kiev. Within several years, some other plants with annual output between 350 and 500 tons were launched.

This kind of equipment used had obvious advantages, so it was able to produce high-quality fibers with diameters of 6, 9 and 13 microns (standard basalt fibers diameter). Along with the advantages, this equipment had some shortcomings, such as high energy consumption on unit of production, great weight of bushings and rather low productivity. In Soviet time the main consumer of basalt materials was the defense industry (the armaments industry). So there was no attention paid to the high cost of BCF production.

- By the end of 1980's and the beginning of 1990's the specialists from the Ukrainian factory built feeding installations in Georgia and Kazakhstan. With collapse of the USSR in 1991, the centralized financing of BCF activities came to an end. According to the rough estimation by experts, the USSR spent ten million of USD to develop basalt technology. This was quite significant sum to the Soviet standards.
- In 1990- 1992 laboratory specialists led by Victor Kibol built a feeding installation at a factory of fiber glass in a Sudogda Town, Russia. Those two plants were the main manufacturers of BCF in the world at that time. They started to export BCF and BCF materials to Europe, America, Canada and Japan. Scientific research institutes in Kiev and Moscow, as well as fiber glass factories in Berdyansk and Sudogda were working on development of materials on the basis of BCF, such as fabrics of the various types, reinforcing nets, road construction nets, composites, profile plastics, armature, pipes, cylinders, tanks, electro insulation materials.

2.3 Manufacturing of Fiber

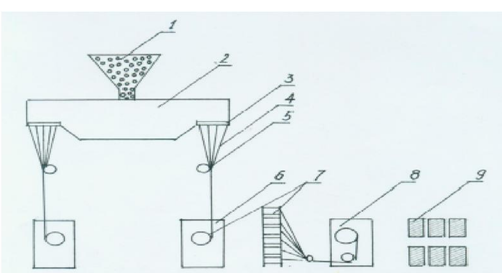

Figure 1: Manufacture of Fiber

- Basalt rocks are crushed in 5~20 mm fraction
- Crushed rocks are transported into the furnace melting (2) by loader (1)
- Basalt is melted at 1400 -1600 º C
- Passes through a platinum alloy set holes of bushing (3)
- Continuous filament formation with a diameter 9~15 microns (4) is lubricated through the lubricator (5) and reeling up by the winding machine (6) on bobbins (7) Rewinding of primary string by machine (8)from bobbins (7) on roving spool (9)

Basalt fibers are used in a wide range of application areas such as:

- Chemical
- Construction and marine sectors
- Wind power
- Transport and
- Aerospace industries.

This is due to their superior properties: they not only boast good mechanical and chemical resistance, but also have excellent thermal, electric and acoustic insulation properties.

3. Characteristic of Basalt Fiber

3.1 The raw material for basalt fibers:

- A naturally occurring mineral- volcanic rock
- Basalt ranges from dark gray to black
- Mineral fibers -100% inorganic
- Fiber compatibility to matrix resins is ensured by using organic sizing agents
- Basalt in rock form is found in every country
- Used as crushed rock in construction and road building
- Composed of 100 % mineral continuous filaments
- Gives the best compromise between tenacity, suppleness and cost
- The product presents no hazard to health and environment
- It is very suitable for asbestos replacement
- Its Golden-brown appearance is used for decorative purposes

Main features of basalt fiber reinforcements:

- High strength
- High modulus
- Corrosion resistance
- High temperature resistance
- Extended operating temperature range
- Easy to handle

3.2 Need for the Reinforcement of Basalt Fiber into Aluminium Matrix

To obtain optimum performance from composite materials, there is an advantage to selecting the shape and size of the reinforcement material to fit the application. It is apparent that different material types and shapes will have advantages in different matrices. For instance, silicon carbide whiskers have been particularly effective in toughening Al_2O_3 and Si_3N_4. Both silicon carbide whiskers and silicon carbide grit have been effective in increasing the modulus of aluminium alloys [24]. It is, however, apparent from the literature that particulates offer greater flexibility in tailor making the properties of interest. Thus researchers have worked out separately to reinforce SiC, Al_22O_3 (i.e. carbides, Nitrides and oxides) TiB_2, Boron and Graphite into the aluminium matrix to achieve different properties and are expensive.

The hardness of Al7075/basalt fiber composite increases as the addition of basalt fiber content and the increment in hardness attributes to fiber particles dispersion in soft aluminium alloy matrix. The addition of short basalt fiber significantly improves the yield strength and the ultimate tensile strength of Al7075, when compared with that of unreinforced matrix. The ultimate tensile strength of Al 7075/Basalt fiber composite when reinforced with 6 vol. % is increased by 65.51%. The improvement in strength values under tensile loading occurs without affecting the tensile ductility [25].

Several studies have shown that fiber reinforced composites are more efficient than other types of composites. Currently, the typical continuous fibers chosen and used for metal matrices are boron, graphite (carbon), alumina, and silicon carbide. These ceramic fibers are designed to be used in a variety of industrial and commercial applications. Although, these fibers offer superior properties (high temperature stability, low thermal conductivity, low heat storage etc.), their production cost is high. A new type of reinforcing fiber produced from basalt rocks through melting process, the so called basalt fiber, was first manufactured in 1972 and used in a Soviet aerospace research program in the 1980 s. These fibers were initially used in military and aerospace, but after 1995 they began to be widely used in non-military applications. From this point of view the chemical composition, the silicon oxide (optimal range 43.3–47 wt. %) dominates, Al_22O_3 (optimal range 11–13%) is next in abundance and CaO (optimal range 10–12%), MgO (optimal range 8–11%) and Fe_2O_3 (optimal range 9–11%) are closely similar. Other Oxides, such as Na_2O, TiO_2, K_2O and Mn_2O_3 are almost always below the level of 5%. The existence of this wide range of chemical composition is mainly due to the different environmental conditions during formation of basalt rocks [2] the basalt fibers exhibit excellent resistance to corrosive media as well as high values of elastic modulus, hardness and wear resistance. In comparison with glass fibers, basalt fibers exhibit superior mechanical properties, better chemical stability and improved thermal and electrical insulation. It is also known that the basalt fibers have greater failure strain as well as better impact and fire resistance with less poisonous fumes as compared with carbon fibers. At the same time, basalt will be selling at a price well below that of other ceramic fibers. Due to these advantages, the applicability of the basalt fiber for a structural strengthening material is highly expected [26].

3. Conclusion

Based on the above study, the ever-increasing demand for low cost reinforcement has stimulated the interest towards production and utilization of Basalt fiber (a material made from the basalt rock) that contains major elements like SiO_2, Al_2O_3, Fe_3O_3, TiO_3, and Na_2O for the preparation of a metal matrix composite for producing a composite material with better properties. Basalt fiber has been used as a reinforcing composite material for the construction industry [3–5] and for making polymer matrix composites [6–10]. However, the applicability of basalt fiber as a reinforcing material for Metal Matrix Composites (MMCs) has not yet been investigated. The prospects of using basalt fibers as reinforcing components in metallic matrices significantly depend on the stability of fibers to the effect of processing conditions. The level of mechanical properties of these composites depends on numerous factors. Among all two of the factors are the most important, namely the interfacial characteristics of a metal-fiber system and the residual strength of a reinforcing fiber in the composite after processing. It is obvious that these factors depend on the technological features of introducing the fibers into the metallic matrix. The aim of the present paper is to investigate the applicability of basalt fiber as a new type of reinforcement to aluminum alloys. For this reason, first the thermal stability of basalt fiber were tested when it is placed in a furnace and exposed to different temperatures and/or in direct contact with molten aluminum have been evaluated. Then a special processing route for making Al/basalt composites is developed and finally the effect of basalt fiber volume fraction on the mechanical properties of these composites is evaluated.

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