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Processing and characterization of laser sintered hybrid B_4C/cBN reinforced Ti-based metal matrix composite

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ABSTRACT

The purpose of this study is to make a boron carbide (B_4C) and cubic boron nitride (cBN) reinforced Ti6Al4V metal matrix composites (MMC's) by direct metal laser sintering (DMLS) technique using the continuous wave (CW) SPI fiber laser and to check the feasibility of the formation of three dimensional objects by this process. For this study, the process parameters like laser power density (3.528–5.172 W/cm^2 ($\times 10^4$), scanning speed (3500–4500 mm/min), composition of the reinforced materials B_4C (5–25% by volume) and cBN (3% by volume) were taken as input variables and hatching gap (0.2 mm), spot diameter (0.4 mm), layer thickness (0.4 mm) were taken as constant. It was analyzed that surface characteristic, density and the mechanical properties of sintered samples were greatly influenced by varying the input process parameters. Field emission scanning electron microscopy (FESEM), Energy dispersive X-ray spectroscopy (EDX) and X-Ray diffraction (XRD) were performed for microstructural analysis, elemental analysis, and recognition of intermetallic compounds respectively. Mechanical properties like micro-hardness & wear rate were examined by Vickers micro-hardness tester & pin on disc arrangement respectively. From hardness tests, it was observed that hardness property of the sintered specimens was increased as compared to the parent material. The XRD results show that there is a good affinity between Ti6Al4V-B_4C-cBN to produce various intermetallic compounds which themselves enhance the mechanical properties of the samples. From FESEM analysis, we can conclude that there is a uniform distribution of reinforcements in the titanium alloy matrix. Furthermore, the coefficient of friction (COF) was characterized by the irregular pattern and it tends to decrease with an increase in the volume % of reinforcement. The results obtained in this work may be useful in preparing the MMC's with improved mechanical properties and overall characteristics.

1. Introduction

Direct metal laser sintering (DMLS) is the rapid prototyping technique used in the fabrication of metals or composites. In DMLS, the components are built layer by layer so it is possible to produce much organic geometries, internal features and challenging passages that are difficult to cast. The DMLS machine uses the laser source to produce the 3-D components. In this process, a powder mixture is placed over the clean and flat platform inside the closed chamber with proper inert atmosphere. The laser scan over the powder mixture and heat generated fuses the metal powder into a solid part by creating the strong metallurgical bonding between the matrix and reinforcement. Then this formed layer is lowered and next fresh powder layer is submitted over the formed layer. This process is repeated again and again up to required thickness. The laser power, scanning speed is selected on the basis of size & shape of the powder. DMLS technique is gifted with various benefits such as (1) quickly produce the metal components, (2) design internal features and passages that cannot be cast, (3) does not require special tooling's like casting, (4) cost-effective, (5) Complex geometries etc.

Ti6Al4V is well known for its excellent properties like high strength, excellent corrosion resistance, low weight ratio, good oxidation resistance and bio-compatibility. Low wear resistance, low thermal conductivity, high coefficient of friction and high-cost results in limiting its use in other fields. Hence, these shortcomings of Ti6Al4V can be possibly reduced by the incorporation of reinforcements to make the metal matrix composite (MMC). These MMC combines the properties of both matrix and the reinforcement and generate a material with attractive properties. Boron carbide is considered to be a valuable reinforcement for Ti and Ti alloys in various applications that require excellent wear resistance, high hardness, lesser density, resistance to corrosion etc. It is also a promising source for the formation of intermetallics like titanium carbide, aluminium boron carbide, etc. which itself helps in enhancing the properties of MMC formed [1].

B_4C is considered being hardest material after cBN and diamond and its hardness ranges from 3885 HV to 4497 HV. It has excellent wear resistance, low density and high melting point and shows good resistance

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to chemical agents. These properties allow it to use in bulletproof vests, tank armors, nuclear power plants, cutting tools and dies, high pressure jet cutter nozzles etc. cBN is the well known hardest material with hardness ranges from 4589 to 5098 HV listed after diamond [2,3]. cBN powder size ranges from 0.1 μm to 80 μm and has exceptional thermal & chemical stability make it suitable to use in high temperature applications [4]. cBN powder can be used both for abrasive applications and for sintering applications. In the areas where wear resistance is one of the main requirements, cBN plays a crucial role to foster wear properties of the prepared product.

Till date, many research works have been accomplished in making the metal matrix composites (MMC's) and enhances their properties by adding suitable reinforcements. Namini et al. analyzed the surface characterization and mechanical properties of TiB_2 reinforced titanium MMC's using the process called spark plasma sintering (SPS) at 1050 °C under 50 MPa pressure. For this study, the 97.6 wt.% of Ti powder and 2.4 wt.% of TiB_2 were taken. This study demonstrates that there was increase in hardness, relative density and tensile strength due to the addition of TiB_2. There was a reduction in the bending strength due to the plastic restraint on the matrix by TiB whiskers [5]. Poovazhagan et al. investigated the performance characteristics of metal matrix nanocomposites of aluminium-nano boron composites fabricated with the help of ultrasonic cavitations-assisted casting process. Increase in the hardness and tensile strength takes place due to nano-B_4C addition in the matrix of aluminium alloy. Wear properties of the fabricated samples also get enhanced as compared to the monolithic aluminium alloys [6]. Sahoo et al. determined the effect of reinforcement on steel based composites. In this study titanium diboride with 2–4% (by volume) reinforced with steel matrix composite was fabricated with the help powder metallurgy through hot pressing method. This study reported that there was an enhancement of strength and the hardness with the increase in the titanium diboride [7]. Hu et al. investigated the influence on mechanical properties and surface characteristics of B_4C reinforced Al matrix composites with change in the process of manufacturing namely semi- solid and liquid stir casting process. This study determined that Aluminium-B_4C MMC's had lower hardness and tensile strength when prepared by semi-solid stir casting process compared to the liquid stir casting process [8]. Salimijazi et al. reported the change in the mechanical properties by deposition of the B_4C on Ti6Al4V alloy by vacuum plasma spraying (VPS). This study showed that the microhardness and the nanohardness increase as compared to the initial powder. He also observed that due to the decomposition of B_4C, soft phases were present at grains and grain boundaries resulting in the formation of microcracks &pores along the particles thus decreasing the hardness of sprayed structure as compared to bulk B_4C [9]. Moradi et al. fabricated the B_4C reinforced Ti6Al4V MMC's by vacuum plasma spray (VPS) process. This study reported that the composite formed has high microhardness and flexural modulus and low flexural strength. Due to presence of pores and microcracks, flexural strength decreases along the reinforcement-matrix interfaces. Moreover, the brittle fracture of B_4C phase and plastic deformation of alloy causes the erosive wear in the MMC's [10]. ota et al. analyzed the mechanical properties of TiC or B_4C reinforced Ti6Al4V with the use of spark plasma sintering. This study reported that the tensile strength of TiC/Ti6Al4V was 1058 MPa and B_4C/Ti6Al4V was 1095 MPa. Microhardness increases with increase in reinforcement volume fraction [11]. Singhal et al. carried out the sintering of cBN by injecting the fine cBN powder at high pressure (P = 50–60 kb) and high temperature (T = 1200–1500 °C) in presence of B_4C with a small amount of aluminium nitride with help of belt type apparatus. They reported that best composite was formed using 75 wt% of cBN at around 1450 °C, 50 kb in the mixture with maximum hardness of 3400 kg/mm^2 [12]

The dry sliding behavior of aluminium alloy hybrid MMC's (Al_2O_3/B_4C/Gr) was studied by Singh et al. using Taguchi design of experiments. MMC's were fabricated using the stir casting process. The results of this study revealed that the higher microhardness (HV) was obtained with higher values of Al_2O_3 (10%) in combination with graphite (3%) and B_4C (1%) which were having lower values [13]. Tan et al. fabricated the SiC microparticles and TiB_2 nano particles reinforced Al matrix hybrid MMC's by the process of powder metallurgy. This study reported the effect on mechanical properties & microstructure of the fabricated specimens by varying the TiB_2 content. They observed that by increasing the TiB_2 content, mechanical properties of the hybrid MMC's were improved [14]. Jia et al. worked on improving the thermal stability of the superhard materials and reported the characterization of bulk diamond-cBN-B4C-Si composites at a higher temperature and the pressure. The result of this study showed that the thermal stability of the prepared composite was high due to the formation of the covalent bonds B–C, C–N, Si–C. The onset oxidation temperature of the prepared samples was also higher than diamond, cBN, B4C [15]. Pagounis et al. Created the MMC's in which stainless steel was taken as the matrix and Al_2O_3/TiC/Cr_3C_2/TiN were taken as reinforcements with the help of hot isotatic pressing process. This study observed that wear properties of composites formed were enhanced without affecting corrosion resistance. The microhardness of the composites formed was also increased [16]. Sahani et al. did the comparative study on the SiC-B4C-Si cermets prepared with the help of pressure less sintering and the spark plasma sintering (SPS) process. This study reported that better densification with improved microhardness was achieved at lower temperatures than the conventional sintering by SPS technique [17]. Ashwath et al. fabricated the SiC and alumina reinforced aluminium alloy matrix material and determines the effect of ceramic reinforcements on microwave sintered MMC's. This study reported that there was increase in the Rockwell hardness and the compressive strength of the prepared samples by an increase in the weight % of reinforcements. Sample with 6 wt% Al_2O_3 have good ductility and formability [18].

Mehlmann et al. analyzed the results obtained by injecting B_4C powder into melt pool generated by CW CO_2 laser with the pneumatic powder delivery system. The study showed good adhesion between B_4C particles and the titanium matrix containing porous layers [19]. Shukla et al. examined the thermal effects and temperature distribution of Si_3N_4 ceramic by surface treatment using fiber laser and computed by finite element analysis (FEA). This study reported that temperature on the surface of Si_3N_4 increases which results in the change in the microstructure of Si_3N_4 and the densification of ceramic also took place [20].

Putaala et al. investigated the microstructure of laser sintered thick film paste of silver and further investigates its electrical and adhesion properties. The study showed that the samples fabricated have good adhesion and electrical conductivity was obtained upto 15% of bulk Ag [21]. Gisario et al. observed the effect of laser power and the interaction time on the surface morphology of the sintered bronze substrate. The bronze substrate was sintered using CW-diode laser (high power). This study showed that after the laser treatment, the surface roughness of the substrate decreases significantly. The results also showed the improvement in the resistance to wear & scratch and the average microhardness of the sample treated [22]. Fogagnolo et al. showed the influence of laser processing parameters on mechanical properties & surface characteristics of Ti6Al4V. This study reported that the product formed after the sintering operation was martensitic. The properties like yield strength, the ultimate compressive strength and young's modulus decreases as porosity increases. Use of high energy parameters results in more porosity which eventually decreases these above mentioned properties [23]. Lin et al. prepared a TiB_2+TiB reinforced composite coated on Ti6Al4V by laser cladding. This study reported that by increasing the laser power density, TiB_2 and TiB were distributed uniformly from top to bottom which results in increase in the average microhardness of the coating. Strengthening effect of TiB_2 and TiB also decreases the wear volume loss [24]. Sabelle et al. analyzed the effect of laser scanning pattern angle on the mechanical properties of layers formed with Cu–Sn–Ni powder. This study reported that there is significant change in the mechanical strength and the density of sintered samples. With increase in the laser scan angle, monolayer produced was correlated negatively and at an angle of 60° maximum UTS and minimum porosity was ob-