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Production and characterization of titanium based metal matrix composites: a review

Titanium alloys are regarded as high strength and low-density alloys. It has wide range of applications such as in biomedical and automobile because of its high strength, low density, biocompatibility and good corrosion resistance. Titanium alloys can be produced by adding elements like aluminium, vanadium, molybdenum, zirconium etc. The powder metallurgy method is widely used method for production of titanium alloys because of its low cost of production. In this study, Ti6Al4V based composites synthesized by adding various reinforcements through powder metallurgy method are considered and the results from these studies are reported.

Keywords: Titanium, powder metallurgy, Ti6Al4V based composite, boron carbide, yttrium oxide, silicon carbide etc.

1.0 Introduction

Metal matrix-based composites (MMCs) can be prepared through a variety of techniques. Stir casting method is commonly used method for synthesizing MMCs (Boppana et al., 2020a,b; Bharath et al., 2014; Boppana et al., 2019; Boppana et al., 2021). Since powder metallurgy process generates little scrap, it is found to be advantageous over stir casting technique. With the advancement in technologies, there is a need to develop materials having superior strength and ability to withstand high temperatures. Titanium alloys and titanium-based metal matrix composites are very widely used engineering materials owing to its superior strength, low density, wear and corrosion resistance besides biocompatibility. Due to its excellent properties, it has wide variety of applications from aerospace to biomedical applications. The reinforcements generally added in titanium-based metal matrix composites are SiC, TiC, TiN, TiO_2, Si_3N_4, and TiB_2. Zr_2O_3 in oxide form, Ti_3Al, Ti_5Si_3 as intermetallic compounds are also included as reinforcements in the matrix. The specific young's modulus of the titanium alloys improved upon reinforcing with SiC, however they were found to be porous when synthesized through powder metallurgy method (Poletti et al., 2008).

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Titanium based metal matrix composites possess general demerits like low thermal conductivity and are usually difficult to be machined. Titanium alloys are produced with various reinforcements using powder metallurgy methods, hot extrusion, spark plasma sintering method, sever plastic deformation methods etc. Each method with different reinforcement exhibits different properties in titanium-based composites and using same reinforcement with different production methods also shows different attributes.

In this paper, a review is conducted on research work carried out on Ti6Al4V titanium alloy with different reinforcements like SiC (Poletti et al., 2008), B_4C (Prakash et al., 2018), Y_2O_3 (Ramaswamy et al., 2018), TiB_2-TiC (Anandajothi et al., 2017) using powder metallurgy method. An attempt is made to study the methodology adopted and comprehend the results of MMCs. Ti6Al4V alloy is most popular alloy of titanium alloys and contributes to about 50% use amongst all titanium alloys (Prakash et al., 2018). Titanium and its alloys exhibit poor tribological property and hence their usage in high friction and wear application is restricted. The resistance to wear can be improved by addition of reinforcements like SiC, TiB_2, TiC and TiN etc. Still a lot of research needs to be done to improve strength, high temperature performance, oxidation resistance and stiffness.

Powder metallurgy method is very widely used method for production of titanium-based MMCs. Isotropic properties of titanium and its alloys can be achieved at low cost using powder metallurgy method. But this leads to porosity however, it could be further improved using cold upsetting process. The conventional powder metallurgy technique utilized to synthesize titanium-based MMCs improves toughness and strength at a cost of loss in ductility (Ramaswamy et al., 2018). Metal matrix composites are prepared by blending the powders and cold compaction of powders to obtain green compacts using pressureless sintering under controlled atmosphere. TiC and TiB_2 ceramic reinforcement titanium-based metal matrix composites showed improvement in hardness and chemical stability at elevated temperatures (Anandajothi et al., 2017).

2.0 Reinforcement and methods

Ti6Al4V alloy reinforced with TiC and TiB_2 (2.5, 5 and 7.5 wt. %) was produced using powder metallurgy method (Anandajothi et al., 2017). The mean particle size of Ti6Al4V was 35μm while TiB2 (99.1% purity) and TiC (99.1% purity) were having mean particle size of 15 μm and 25 μm respectively. The particles were mixed using high-energy ball milling process and cold compacted and sintered at 1250˚C for 2 hrs in argon environment and cooled to room temperature. The densities were measured theoretically and experimentally by the rule of mixture and Archimedes' principle respectively. The hardness of samples was determined using Vickers tester with operating load of 3 N and dwell time of 10 seconds. The microstructure was observed using FESEM, while chemical composition was also reported.

Ramaswamy et al. (2018) used 98% pure powder of Ti6Al4V and reinforced it by yttrium oxide having 99.995% purity (size 40 nm) using ball milling and transferred into a metal die and gradual pressure was applied to obtain samples with 1, 2 and 3% of yttrium oxide. The green compacts were sintered in helium gas-controlled environment at temperatures of 1200 ˚C,1300˚C and 1400˚C for 2 hrs. The heating process was performed at 15˚C/min and cooling was done at 10˚C/min. SEM and XRD were performed to identify elemental compositions/phases and theoretical and experimental densities were later measured using rule of mixtures and Archimedes' principle respectively.

In the research study carried out by Prakash et al. (2018), the powders of Ti6Al4V and B_4C were mixed in a planetary tumbler mixer with B_4C percentage of 5% and 10% by weight. The blended powder was compacted in uniaxially press and sintered at a temperature of 1230˚C for 4 hrs. The standard samples were prepared by polishing with sand papers of various grades. To study the microstructure, analysis was done using SEM and XRD techniques. The theoretical and experimental densities were calculated with the help of rule of mixtures method and Archimedes' principle. With the help of Vicker's tester, the microstructure hardness was measured by subjecting to a load of 200g for 15 sec at five diverse positions on the specimen.

For evaluation of corrosion properties, the compacted specimen was cut into rectangular strips. Three electrodes set-up was used to study electrochemical behaviour of samples. Wear test was carried out and coefficient of friction was calculated from friction factor using wear pin sample by averaging the values obtained from three repeated tests.

Poletti et al. (2008) used the powder metallurgy techniques to prepare composites. The powders of Ti6Al4V reinforced with SiC particles were compacted and sintered using the conventional hot pressing, hot extrusion, ECAP, Spark Plasma Sintering (SPS) and compressive induction heating. In the conventional hot pressing, the dry or wet mixture of powders was placed in a graphite die and heated up to a temperature of 1000˚C with 10 K/min and cooled down with same rate in an argon environment. The powders of composites were filled in copper and steel cans and preheated to temperatures of 250 and 300˚C for 15 min. It was then passed through a rectangular channel with 12mm × 12mm size having intersection angle of 90˚. Samples were also prepared by placing the composite powders in a graphite die of 10 mm and then cold compacted and heated at a rate of 10 K/sec. The process was carried at high temperature but at a short time period. The powder mixture was heated using SPS method, stepwise between a temperature of 800˚C and 1100˚C. Sintering was carried out by using a holding time period of 0 to 5 min. The samples are prepared using hot extrusion to attain shear stresses with a ratio of extrusion of 1:16 in a heated die.

Anandajothi et al. (2017) synthesized Ti based composites by powder metallurgy method using Ti6Al4V, TiB_2 and TiC. The average size of Ti6Al4V, TiB_2 and TiC particle was 37.07, 15 and 21 μm respectively. It was found in the study that the theoretical and experimental densities increased with increase of TiB_2-TiC particles but it also exhibited additional pores that decrease the strength of the composites. Micro hardness tests were performed on the samples involving various percentages of TiB_2-TiC particles. It was observed that hardness was highest at 5% of TiB_2 and TiC particles added individually and it further decreased by increasing TiB_2 and TiC contents. EDS was carried out to confirm the elements present in the composites.

Ramaswamy et al., (2018) worked on Ti based composites reinforced with Y_2O_3. The presence of Y_2O_3 particles in the alloy was ascertained using SEM and XRD. The SEM images showed clear grain boundaries between the particles in the composites and reported an evenly distribution of Y_2O_3 in the titanium alloy. The addition of yttrium oxide increases the theoretical density of composites which was calculated using rule of mixture method. The experimental density or sintered densities for all samples was calculated using Archimedes' principle and with increase in sintering temperature, it was found that density too increased with sintering temperature. It was also noticed that the sintering density using 2% yttrium oxide was recorded highest as compared to 1 and 3% of yttrium oxide at all temperatures.

Prakash et al. (2018) had noted that addition of B_4C as a reinforcement in titanium alloy increased the hardness and experimental densities of composites but effected on porosity. It was also having the impact on strength of composites. The addition of B_4C forms the blend of TiB and TiC which in turn improves the hardness of composites. It was found that the 5% B_4C reinforced MMC showed improved corrosion resistance over 10% B_4C reinforced MMC. The wear resistance of the developed MMC had increased at higher load as compared to Ti alloy due to the fact that embedded reinforcement particles reduce the plastic deformation by hindering dislocation. It was observed that increase in B_4C reinforcement led to variation in coefficient of friction. Researchers also carried a worn surface analysis using SEM. The mechanism of wear was observed to be abrasion and delamination. The delamination wear mechanism was observed when the state of wear was severe. The rate of delamination was observed to be low in MMC as compared to Ti alloy. Hence, it was noted that wear rate for the developed MMC with B_4C reinforcement was observed to be low as compared to Ti alloy.

Poletti et al. (2008) performed various powder metallurgy techniques on titanium alloy reinforced with SiC particles. In the conventional hot-pressing methods, the reaction zone was observed with high porosity. Increase in sintering temperature, led to wider reaction zones. Better results were obtained at 900°C and 15 min consolidation time. Very less reaction zones were spotted using compressive induction heating but porosity was observed at the places where sintering was not done because of inhomogeneous distribution of SiC particles. The microporosity was reduced at high temperature with slower densification rate. At temperatures of 850-950°C, the hot extruded samples exhibited good results with lowest porosity and almost no reaction zone. The SiC particles are observed to be in the direction of extrusion. Sintered samples had 98% relative density at 910°C temperature and 60 min consolidation time. It was observed that hot extruded samples had reached the theoretical density at all temperatures. The research further showed that the density of composite obtained from SPS method increased with increase in temperature. A minimum temperature of 800°C was needed for densification of the samples. During SPS, it was observed that densification was more at the centre of cylindrical disc as related to periphery through 3-5% variation in porosity. Hence, it can be effectively applied for small size samples i.e., less than 15mm.

Hagiwara et al. (1992) reported about Ti related composites reinforced with ceramic particulates produced by means of powder metallurgy process using extra low chlorine Ti powder, Al_3Ti powder, FeB powder and Cr_3C_2 powders. It was noted that the elastic modulus improved with the addition of reinforcements.

Kundu et al. (2018) worked on direct metal laser sintering technique to synthesize titanium nitride reinforced Ti6Al4V alloy related MMCs. The composites revealed even distribution of reinforcement in the matrix. As the volume percentage of the reinforcement increased, the hardness values of the composites also improved. Intermetallic compounds in the composite like titanium dioxide were confirmed with XRD studies. Wear tests were performed on the unreinforced alloy and composite using pin-on-disc equipment. With the increasing content of reinforcement in the matrix, the coefficient of friction of the composite reduced. The method of preparing powders was considered to have a significant role in influencing the hardness of the composite.

Silicon nitride reinforced Ti-6Al-4V composite was synthesized by Kgoete et al. (2018) through SPS method. With the addition of reinforcement, the microhardness values of the composites were enhanced. XRD studies were used to confirm the presence of nitride phase in the matrix. SEM micrographs revealed that the reinforcement was evenly spread in the Ti alloy. The studies also reported that, the rate of corrosion reduced with the inclusion of reinforcement in the matrix.

Semetse et al. (2020) reported on the ZrO_2 reinforced Ti-6Al-4V composite prepared using powder metallurgy method. The compaction was done using SPS process. The hardness values of the composites improved with the inclusion of reinforcement.

Abe et al. (2020) worked on AlN/h-BN-reinforced Ti6Al4V composite through SPS process. The powders were mixed in a tubular mixer containing balls made of steel. A graphite die was used to prepare the composites of determined dimensions. In order to consolidate the powders, sintering was performed using spark plasma sintering equipment. The composites thus prepared exposed the absence of major porosities.

3.0 Conclusion

Powder metallurgy was effectively used as a method for synthesizing Ti based composites. The reinforcements like boron carbide, SiC and Y_2O_3 could be evenly dispersed in the matrix. Researchers remarked about optimum consolidation time during the fabrication of composites. The corrosion resistance improved with the addition of reinforcement like boron carbide in the Ti based matrix samples prepared through powder metallurgy.

Wear resistance also improved with the addition of reinforcements like boron carbide in the Ti based composite. The addition of yttrium oxide as a reinforcement in Ti6Al4V alloy increased the densification of composites.

It can thus be concluded that the powder metallurgy method can be effectively used for producing titanium matrix-based composites.

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