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Paper Title: Effect of sintering temperature on the properties of titanium matrix composites reinforced with $Al_{0.5}CoCrFeNi$ high-entropy alloy particles

Content :

Introduction

Titanium and titanium alloys are widely used in aerospace, industrial processes, biomedicine, chemical industry, marine, and automotive fields because of their low density, high specific strength, excellent thermal stability, excellent corrosion resistance, low biotoxicity, and good biocompatibility [[1], [2], [3], [4], [5]]. In order to further improve the mechanical properties of titanium alloys to meet the needs of the development of the aviation industry, researchers have carried out a large number of composites with titanium alloys as the matrix [6,7], but there is very little research on composites with pure titanium as the matrix.

Researchers added hard particles to the metal matrix so that the composites have a high specific strength, specific stiffness, and good wear resistance, but due to the difference between the coefficient of thermal expansion of the traditional ceramic-reinforced particles and the matrix [8,9], the elongation of composites is significantly reduced, and the traditional multi-component alloys are different. High-entropy alloys (HEAs) have five or more main elements and have an iso-atomic or near-iso-atomic composition. Alloys [10] exhibit many promising properties, including high strength and hardness [11], good wear resistance [12] and excellent thermal stability [13]. These properties are derived from four major effects of high-entropy alloys: the high-entropy effect, the slow diffusion effect, the severe lattice distortion effect, and the cocktail effect [14].

Lu et al. [15] prepared $CoNiFeCrAl_{0.6}Ti_{0.4}$/2024Al composites, and the results of the study showed that the addition of 7.5 vol% of nanocrystalline $CoNiFeCrAl_{0.6}Ti_{0.4}$ high-entropy alloy particles increased the strength of the composites to 419 ± 12 MPa, and elongation was about 8 %. This indicates that the high-entropy alloy as a reinforcing phase significantly improves the mechanical properties of the material. In the process of high-entropy alloy particles reinforcing metal matrix composites, high-entropy alloy particles and metal matrix diffused with each other to form an interfacial layer. Wang et al. [16] and others prepared $FeCoNi_{1.5}CrCu$/2024Al composites, and the results of the study showed that high-entropy alloy particles and Al matrix formed an interfacial layer with a thickness of about 80–120 nm, and the optimized interfacial layer's strength was up to 1331 MPa, the modulus of elasticity was 47.5 GPa, and the compressive strength, yield strength, and microhardness of the composites with a sintering time of 40 min reached 248 MPa, 227 MPa, and 93 HV, respectively. Yuan et al. [17] formed a diffusion layer between the particles and the matrix of the 5052 aluminum matrix composites after reinforcing them by heat treating $Al_{0.6}CoCrFeNi$. As the formation of the diffusion layer improved the hardness and Young's modulus of the composite, Yang et al. [18] prepared AlCoCrFeNi high-entropy alloy (HEA) particles-reinforced aluminum matrix composites (AMCs) by using the discharge plasma sintering (SPS) technique, investigated the formation of the interface between the HEA particles and the Al matrix, the tensile properties, and fracture behavior, and found that the interface has a two-layer structure. The interfacial layer is one of the important factors affecting the mechanical properties of composites, and the formation mechanism of the interfacial layer and its effect on the mechanical properties of composites are more complicated.

However, the diffusion mechanism of the interfacial layer has been little studied in the scientific community. Therefore, in this paper, $Al_{0.5}CoCrFeNi$/Ti composites were prepared by discharge plasma sintering at sintering temperatures of 750 °C, 850 °C, 950 °C, and 1050 °C. The sintering temperature of $Al_{0.5}CoCrFeNi$/Ti composites at different sintering temperatures was investigated. The microstructure morphology, elemental distribution, and mechanical properties of the composites at different sintering temperatures were comparatively analyzed to investigate the effects of the discharge plasma sintering mechanism and sintering temperature on the organization and mechanical properties of the composites.

Mechanical properties of composites

3.4.1. Microhardness test

Fig. 5 shows the hardness distribution of the composites at different sintering temperatures, and it can be seen that the composites have the highest hardness value of 438.8 $HV_{0.3}$ at a sintering temperature of 1050 °C and the lowest hardness of 409.2 $HV_{0.3}$ at a sintering temperature of 750 °C. The hardness of the composites increases as the sintering temperature rises due to the mutual diffusion of the high entropy alloy with the matrix, which produces an interfacial layer. The thickness of the interfacial layer increases as the sintering temperature rises, thus increasing the hardness of the composite. On the other hand, some elements of high-entropy alloys are precipitated at grain boundaries, and the precipitated phases on the grain boundaries increase with the increase in sintering temperature, which also improves the hardness of the composites. Sintering temperature of 1050 °C when the hardness value is the highest may be due to $Al_{0.5}CoCrFeNi$ high entropy alloy elements all diffusion and Ti matrix formed $AlCoCrFeNiTi_x$ solid solution. Under the influence of the effect of multi-alloy, Al, Co, Cr, Fe, Ni, and Ti elements of the different atomic sizes, electronegativity and inter-atomic interactions will result in the alloy's lattice structure changes, which increases the hardness of the composites. High mixing entropy in composites reduces the free energy of the system, and during cooling and solidification, multi-major element alloys are more likely to form random solid solutions. Researchers have formed $AlCoCrFeNiTi_x$ [21] solid solutions by adding Ti to high-entropy alloys and found that the addition of the Ti element has led to a dramatic increase in the hardness of the material due to the addition of atoms of Ti, which has led to the formation of a uniform lattice structure of multiple elements. This homogeneous solid solution structure hinders the movement of dislocations and the slip of grain boundaries, thus increasing the hardness of the coating.

Room temperature uniaxial compression experiment

Fig. 8 demonstrates the compressive true stress-strain curves of the composite at different sintering temperatures. Observing the curves, it can be found that with the increase of sintering temperature, the compressive capacity of the material is enhanced and then weakened, while the compression plasticity shows a tendency of weakening and then enhancing. The performance parameters at different sintering temperatures are listed in detail in Table 3. The $Al_{0.5}CoCrFeNi/Ti$ composites exhibited the highest compressive strength of 1638.8 MPa at a sintering temperature of 850 °C. Compared with the composites obtained under sintering conditions at 750 °C, the samples sintered at 850 °C showed an increase in yield strength and compressive strength of 59.6 % and 21.4 %, respectively. This phenomenon is mainly attributed to the increase in the thickness of the interfacial layer between the high-entropy alloy particles and the matrix, which strengthens the metallurgical bonding of the composites, hinders the dislocation motion, and thus improves the overall strength of the composites. As the sintering temperature was increased to 950 °C, the yield strength of the composites was 1217.2 MPa and the compressive strength was 1508.8 MPa, which decreased by 4.7 % and 7.9 % compared with that of the composites prepared at 850 °C. This is mainly attributed to the fact that the thickness of the interfacial layer is too thick, which may lead to the concentration of stresses and the formation of cracks and thus reduce the composites' strength and plasticity. The yield strength of the composites at a sintering temperature of 1050 °C was 1316.1 MPa, and the compressive strength was 1578.2 MPa, which increased by 8.1 % and 4.6 % compared with that of the composites sintered at 950 °C. This is probably due to the fact that the sintering temperature of 1050 °C allows the atoms inside the high-entropy alloy particles to obtain sufficient diffusion activation energy, which leads to the dissolution of the high-entropy alloy particles and the formation of the precipitated phases, thus reducing the strength and plasticity of the composites. Diffusion leads to the dissolution of the high-entropy alloy particles, and the high-entropy alloy elements exist in the form of precipitated phases in the titanium matrix, at which time the strengthening of the composite material is mainly in the form of diffusion strengthening.