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Research Article

Morphological Investigation of Al-Cu-Fe Quasi-Crystalline Thin Film on Ti-6Al-4V Alloy

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ABSTRACT

Magnetron sputtering was used in the current study to deposit the quasicrystal (QC) coating on the Ti-6Al-4V alloy. After the sputtering process, a continuous argon flow at 700°C was used for two hours to anneal the Al-Cu-Fe coated samples. The microstructure and morphology of mixed powders and Al-Cu-Fe QC coatings were examined using scanning electron microscope (SEM) analysis and X-ray diffraction (XRD). The $Al_{62.5}Cu_{25}Fe_{12.5}$ powder mixing was used as the target of the magnetic sputtering process. Al-Cu-Fe thin layer's deposition on the Ti-6Al-4V alloy surface took place with no cracks and a thickness of approximately 4000 nm. As shown by calculations, five facet shapes had a size of nearly 643 nm. The XRD patterns confirmed the presence of Al_3Fe, $AlTi_2$, and $Al_{65}Cu_{20}Fe_{15}$ phases after the post-heat treatment coating.

1. Introduction

The unprecedented characteristics of titanium and its alloys, comprising biocompatibility, high strength-to-weight ratio, and low elasticity modulus, have enabled their extensive employment in various industries, including automotive, biomedical, and aerospace. Despite its distinctive characteristics, Ti-6Al-4V alloy has limited practical applications, particularly concerning tribological functional properties [1]. Since quasicrystalline materials are significantly hard and remarkably corrosion-resistant, they can be promising candidates for various practical applications. Research [2] has highlighted the potential titanium alloy's wear resistance enhancement (grade five) by developing mixed quasi-crystalline (QC) coatings. Al-Cu-5Fe coating had a 2.8 times higher wear resistance than the substrate. Even though QCs face practical limitations as structural materials because of their brittleness, researchers are increasingly interested in their applications as functional materials in various areas, including catalytic agents for hydrogen production, due to their unique properties [3, 4].

Plasma spray and High-Velocity Oxygen Fuel (HVOF) have extensive applications in producing quasicrystalline coatings, however there may be several challenges in their utilization, including porosity, unmelted particles, cracks, and oxides [5, 6]. One of the extensively used methods for deposition wear and corrosion-resistant coatings is magnetron sputtering. The substrate temperature is among the influential factors in the quasicrystalline phase formation [7, 8]. The semicrystalline phase is developed following QCs deposition on the substrates under room temperature and subsequent heat treatment.

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Yet, the main challenge of adjusting stoichiometry in QCs still requires consideration [9-12].

Al-Cu-Fe-based quasicrystalline thin films on Si and Al_2O_3 substrates represent exceptional surface and mechanical characteristics. Reports show that quasicrystals directly grew in multilayer Al-Cu-Fe thin films following the heat treatment process [13]. The assembled targets' three-electrode ion-plasma sputtering enabled successfully employing quasicrystalline and film coating [14]. The Al-Cu system ensured the quasicrystalline phase formation under temperatures nearly >500 (T>500°C) [15]. The i-phase experienced increased amount and grain size during the annealing process [16]. More nucleation rates were reported for phases with a polyhedral atomic substructure in QCs throughout the system [17]. If AlCuFeB coating is applied under such conditions, cracks may be generated within the targets over the film deposition, leading to statistical deviations in the coating composition [7]. The Al–Cu–Fe QCs are highly resistant to corrosion and have appropriate hydrogen storage to be used throughout catalytic reactions. Under low temperatures, similar thermal characteristics can be found between these alloys and zirconia oxides, known to be excellent insulators [18].

In the current research, the QC coating was deposited on the Ti-6Al-4V substrate using magnetron sputtering, then investigating and comparing the microstructural of the substrate and the coated sample.

2. Experiments

Experiments were conducted using aluminum, iron, and copper powders which were considered to have a 99.9% purity. A planetary ball mill with a 150-rpm rotation speed was used for 1.5 h to mill the powder mixture, then its drying and compressing into discs using a uniaxial hydraulic press. The next steps were to prepare and wash the surface of the samples. Magnetic sputtering was then employed to deposit Al-Cu-Fe coating on Ti6Al4V alloy under a 2.5×10^{-3} mbar pressure argon gas, and room temperature. After the sputtering process continuous argon flow at 700°C was used for two hourss to anneal the Al-Cu-Fe coated samples [9,10]. The samples underwent X-ray diffraction measurements after annealing using the Grazing-XRD method. SEM (VEGA II SCAN) and FESEM were utilized to examine the samples' microstructure. Moreover, a relative metal composition was determined by energy-dispersive X-ray spectroscopy. The schematic image of the sample preparation and sputtering process is shown in Fig. 1.

3. Results and Discussion

Fig. 2. indicates the cross-section and the elemental distribution map prepared from the AlCuFe coating's cross-section, revealing a nearly 4000 nm thickness for the AlCuFe thin film. The target showed no cracks or breaks throughout the 135 minutes of sputtering, appropriately preparing it by the mixing methodology, ultimately resulting in the development of an AlCuFe thin film. Fig. 2. shows the micrograph of the samples prepared using the backscattered electron detector, indicating a brighter area associated with the thin film than the substrate. AlCuFe coating formation on the Ti-6Al-4V

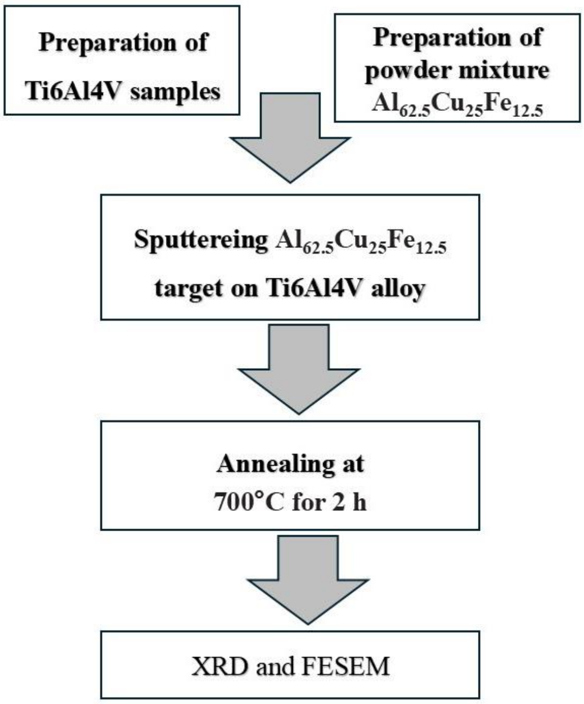

Fig. 1. Schematic image of the sample preparation and sputtering process 4V substrate.

alloy as the substrate was highlighted by the distribution of titanium and vanadium elements and Al, Cu, and Fe. As shown by the evidence, neither Cu nor Fe could be found in the substrate areas, revealing increasing gradients for Cu and Fe and a decreasing trend toward Ti thin film areas. Other researchers have found an 85-260 nm thickness for Al-Cu-Fe and thin film [19]. In addition, sputtering has led to 200-260 nm thicknesses for Al-Cu-Fe and Al-Cu-Fe-Sc quasi-crystalline films [20]. Besides, the distribution map of aluminum, copper, iron, and oxygen elements of AlCuFe quasi-crystalline coating proved the significantly high catalytic effects for methanol steam reforming [21, 22].

Fig. 3. indicates the thin film as sputtered and post-heat treatment morphology under 700°C for two hours. As shown in Fig. 3-a. sputtering, the surface of the coating is completely uniform and no cracks or separation have been observed. After heat treatment under 700°C for two hours, Five-facet morphology was obtained after heat treatment under 700°C for two hours. A thoroughly continuous coating surface is observed with no evident cracks during post-annealing.

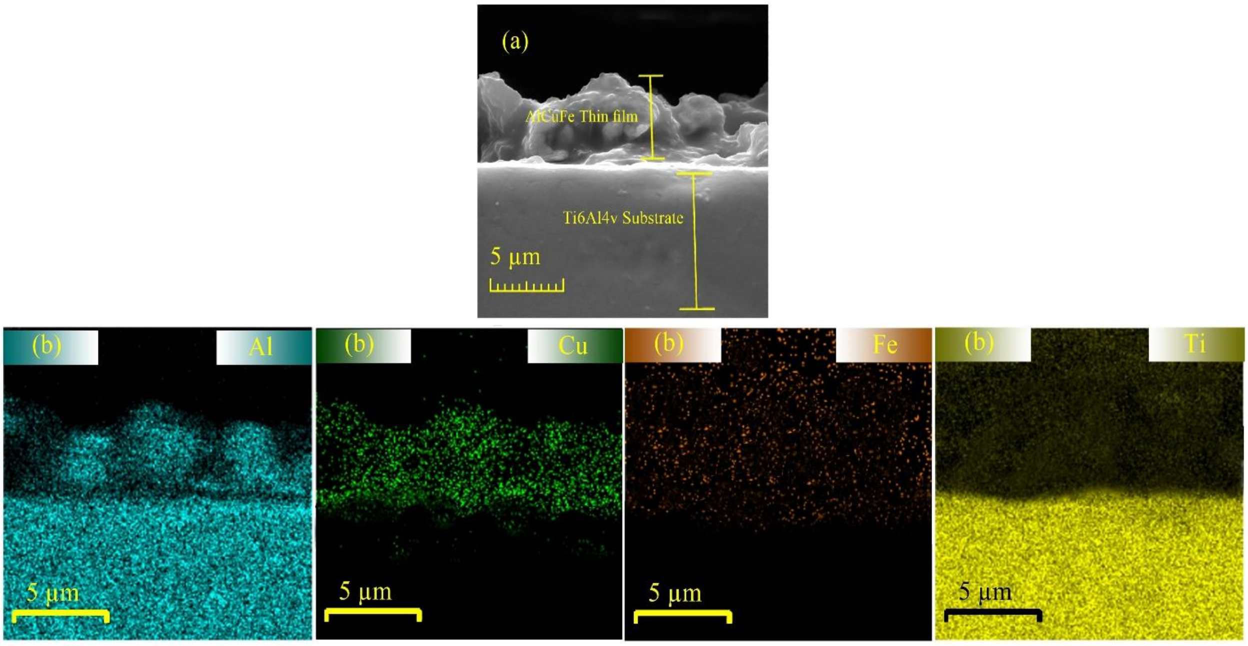

Fig. 2. (a) Cross-section AlCuFe coating on Ti-6Al-4V substrate, (b) distribution of elements of as sputtered AlCuFe coating on Ti-6Al-4V substrate.

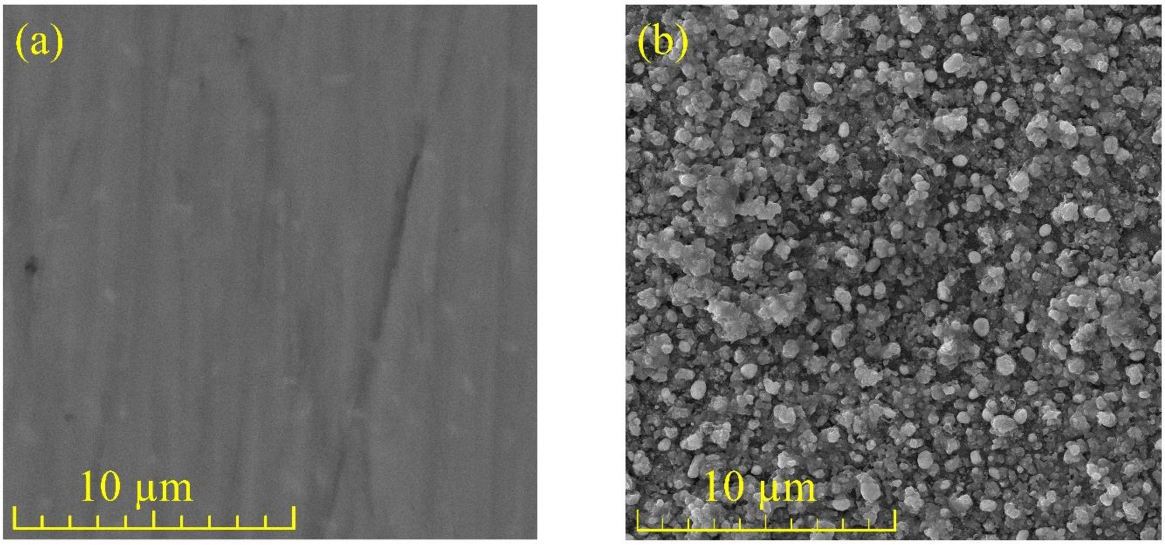

Fig. 3. AlCuFe coating surface morphology on Ti-6Al-4V substrate (a) as sputtered, (b) post-heat treatment under 700°C and two hours.

Fig. 4. shows the post-heat treatment morphology of thin film under 700°C and two hours at high magnification (magnification 5000, 35000, and 70000). During sputtering and post-annealing, a thoroughly continuous coating surface with no evident cracks. The five-facet morphologic representation, highlighting the existence of quasicrystal, was found in the morphology of the annealed thin film. The five-facet shapes had a size of about 643 nm as can see in Fig.4. c. Fig. 5 shows the distribution map of the thin film element following a 2 h heat treatment at 700°C, leading to a completely continuous coating surface with no visible cracks. The identical Al, Cu, and Fe elements' distribution on the AlCuFe thin film surface justifies the AlCuFe coating development. It presents some areas with no titanium, indicating the formation of a coating on the Ti-6Al-4V substrate.

Fig. 6. reveals the XRD findings for post-annealing and as-sputtered AlCuFe coating on Ti-6Al-4V. The XRD pattern associated with the AlCuFe coating confirms that Al_3Fe, $AlTi_2$, and $Al_{65}Cu_{20}Fe_{15}$ quasi-crystalline ternary phases. The quasi-crystalline phase of $Al_{65}Cu_{20}Fe_{15}$ after annealing has been reported in other studies [1, 23]. The Al_3Fe, $AlTi_2$, and $Al_{65}Cu_{20}Fe_{15}$ phases mentioned in the XRD result have been reported in previous research [24, 25]. Based on the five-facet morphology (as shown in Fig. 4.) of the shapes and the identification of the $Al_{65}Cu_{20}Fe_{15}$ phase, the AlCuFe quasi-crystal thin film has been successfully obtained.

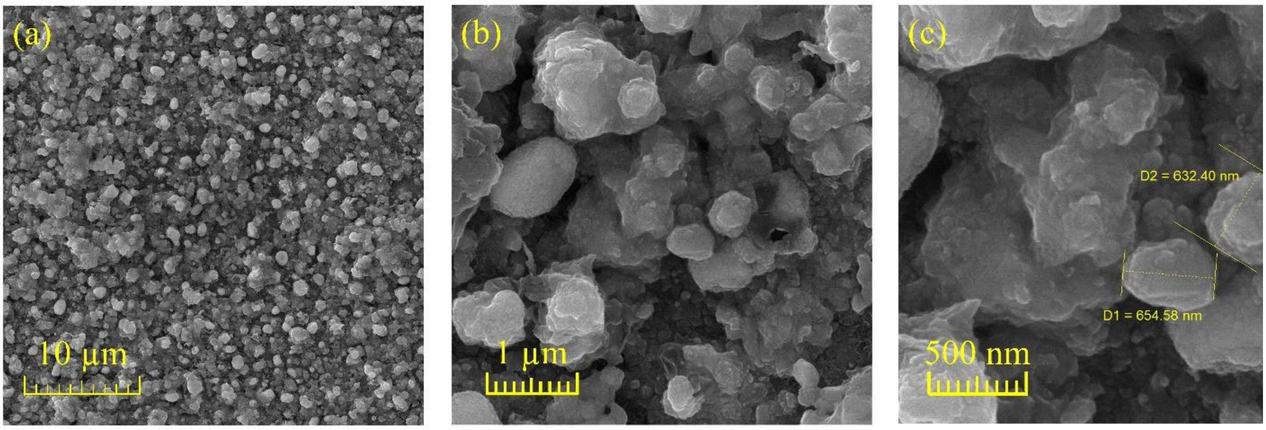

Fig. 4. Surface morphology of post-heat treatment thin film under 700°C and two hours (a) Magnification 5000, (b) Magnification 35000, (c)Magnification 70000.

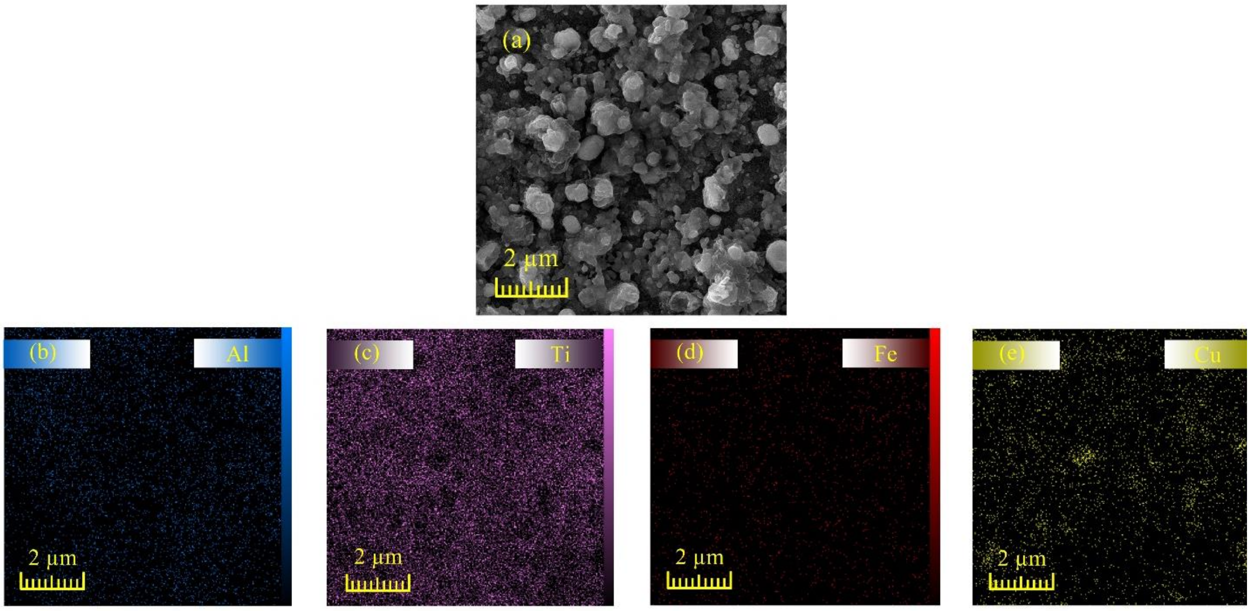

Fig. 5. (a) Surface morphology of post-heat treatment thin film under 700°C and 2 h, distribution map for the thin film's elements: (b) Aluminum, (c) Titanium, (d) Iron, (e) Cooper.

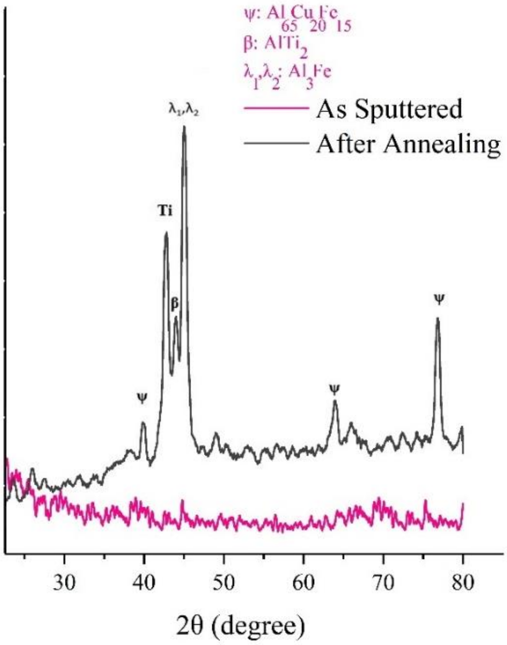

Fig. 6. XRD results for AlCuFe coating on Ti-6Al-4V as sputtered and post-annealing.

4. Conclusions

- Deposition of the Al-Cu-Fe thin layer on the surface of the Ti-6Al-4V alloy was successfully conducted with no cracks and an approximately 4000 nm thickness.
- The size of five facet shapes was calculated to be about 643 nm.
- The XRD patterns associated with the post-heat treatment annealed coating confirmed that Al_3Fe, $AlTi_2$, and $Al_{65}Cu_{20}Fe_{15}$ phases were present.

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