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Laser additive manufacturing of bimetallic structure from TC4 to IN718 via Ta/Cu multi-interlayer

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Abstract

Titanium alloys and nickel-based alloys have their own unique properties, and the bimetallic structure composed of the two alloys can be widely used in the aerospace field. However, the bimetallic structure which is fabricated by directly joining titanium alloys and nickel-based alloys via traditional methods is more sensitive to cracks due to the formation of intermetallic compounds. In this work based on laser additive manufacturing (LAM) technology, the TC4/IN718 bimetallic structure without metallurgical defects (such as cracks) was successfully fabricated via a Ta/Cu multi-interlayer. The test results indicated that the Ta/Cu multi-interlayer could effectively avoid the generation of Ti–Ni and Ti–Cu intermetallic compounds between TC4 and IN718. A good metallurgical combination was formed in each interface from TC4 to IN718 without metallurgical defects. The phase evolution from the TC4 region to the IN718 region was as follows: $\alpha$-Ti $\rightarrow$ $\alpha$-Ti + $\beta$-Ta $\rightarrow$ $\beta$-Ta $\rightarrow$ $\beta$-Ta + $\gamma$-Cu $\rightarrow$ $\gamma$-Cu $\rightarrow$ $\gamma$-Cu + $\gamma$-Ni + laves $\rightarrow$ $\gamma$-Ni + laves. The ultimate tensile strength of the bimetallic structure at room temperature was 369.32 MPa.

1. Introduction

Titanium alloys have high specific strength, good corrosion resistance, and wide biocompatibility, so they are widely used in aerospace, petrochemical, biomedical and other fields [1, 2]. Nickel-based superalloys are used as raw materials for high-temperature service environment components in the aerospace field due to their excellent oxidation resistance and mechanical properties at high-temperature [3]. Therefore, the bimetallic structure formed by a high-quality combination of titanium alloys with high specific strength, and nickel-based alloys with outstanding high-temperature performance, could combine their respective advantages and improve the functionality of manufactured parts.

However, due to the great difference in the physical and chemical properties between titanium alloys and nickel-based alloys, the direct combination would produce a series of problems (such as cracks, etc.). Brazing [4] and diffusion bonding [5, 6] are traditional methods for manufacturing bimetallic structures of dissimilar metals, but they are limited by production conditions and production efficiency. However, laser additive manufacturing (LAM) provides a wide range of possibilities concerning the geometry and the materials used [7, 8]. Bobbio et al [9] reported that the main reason for cracking in the functionally graded structure fabricated by the linear gradient transition of TC4 and Invar alloy is the formation of brittle Ni$_3$Ti and NiTi2 intermetallic compounds (IMCs). Chatterjee et al [10] proved that the brittle TixNiy IMCs are the important factors leading to cracking in the laser-welding of titanium alloys to nickel-based alloys.

In addition, based on LAM technology, many scientists have made significant attempts to eliminate the TixNiy IMCs that formed in the metallurgical bonding process of titanium alloys and nickel-based alloys. Shang et al [11] selected Cu as the interlayer for the combination of TA15 and IN718 via LAM and found that the Cu interlayer could inhibit the generation of Ti–Ni IMCs, but the direct combination of TA15 and copper led to the formation of Ti–Cu IMCs at the TA15/copper interface that increased the crack sensitivity. Onuik et al [12]
discovered that copper was fully diffused into the nickel-based alloy in the IN718/copper bimetallic structure fabricated by laser engineered net shaping technology, and no IMCs formed at the interface. Therefore, it can be speculated that the formation of Ti–Cu IMCs could be impeded by choosing an ideal material, which would not form IMCs with Ti and Cu, to be used as an interlayer between titanium alloys and copper. Gao et al.[13] successfully laser welded TC4 to copper via niobium (Nb) interlayer without the formation of any IMCs. This shows that Nb is an ideal interlayer for the bonding of titanium alloys and copper. Tantalum (Ta) and Nb have similar properties, and both of them are body-centered-cubic (bcc) metals that are easy to dissolve in β-Ti, and they both have excellent physical and chemical properties such as high melting point, good corrosion resistance, and excellent ductility at low temperature [14, 15]. Therefore, it can be inferred that Ta could replace Nb as the interlayer between TC4 and copper to impede the formation of IMCs. In addition, according to the binary alloy phase diagrams of Ta-Cu and Cu-Ni, it is known that no IMCs would form between Ta and Cu, and Cu and Ni [16, 17]. Therefore, it can be inferred that the Ta/Cu multi-interlayer is an ideal interlayer for bonding titanium alloys to nickel-based alloys.

In this study, titanium alloy TC4 and nickel-based alloy IN718, which are widely used in manufacturing important aerospace structural parts, were chosen as the raw materials for fabricating the bimetallic structure. The microstructure at each interface and the tensile properties at room temperature of the TC4/IN718 bimetallic structure with a Ta/Cu interlayer, fabricated by LAM, were systemically studied.

2. Materials and methods

The additive manufacturing experiment was carried out in an LDM 8060 LAM system, having a maximum component manufacturing dimension of 800 mm × 600 mm × 900 mm, developed and produced by Raycham CO. LTD. (Nanjing, Jiangsu, China). The system consists of a 6000 W fiber laser, a 3-axis mechanical working table, an argon-purged chamber, a computer numerical control system, and a coaxial powder delivery system. The Ar chamber during experiments was kept such that the content of oxygen was lower than 20 ppm.

The raw materials for the bimetallic structure manufacturing were powders of TC4, IN718, Ta, and Cu, with a particle size ranging from approximately 75 μm to 150 μm, produced by the plasma rotating electrode process (PREP). The main chemical compositions of IN718 are (wt.%): 52 Ni, 19 Fe, 18 Cr, 5 Nb, 3 Mo, and other trace elements. TC4 contains 6.75 wt% Al, 4.5 wt% V, 0.25 wt% Fe, 0.2 wt% O, 0.08 wt% C, and the balance is Ti. Commercial hot rolled TC4 plate with 20 mm thickness was used as the substrate.

As shown in figure 1, the bimetallic structure sample was fabricated by LAM. During the LAM process, the main process parameters for depositing TC4, Ta, Cu, and IN718 are presented in Table I. There were two each of the Ta and Cu interlayers, with the thickness of each interlayer being about 0.5 mm. In this paper, the TC4/IN718 bimetallic structure with the Ta/Cu interlayer was divided into three interfaces (TC4/Ta interface, Ta/Cu interface, and Cu/IN718 interface) and four regions (TC4 region, Ta region, Cu region, and IN718 region). In order to investigate the microstructure at each interface and region, the vertical (parallel to the build-up direction) specimen was chemically etched by the reagent (5g CuCl2, 50 ml C2H5OH, and 50 ml HCl) for 150 s after polishing, and finally etched with the etching agent (a mixed solution of HF: HNO3: H2O = 1: 6: 7) for 15 s. The microstructure of the three interfaces and the four regions were characterized by a Gemini SEM300 scanning electron microscope. Energy dispersive spectroscopy (EDS) was used to confirm the chemical composition of the three interfaces of the bimetallic structures. The phase evolution from the TC4 region to the
IN718 region was analysed by an XRD-7000 diffractometer at a scanning speed of 4°/min. The Vickers hardness of the bimetallic structure was measured by a Vickers indenter (HVS-1000A). The room temperature tensile properties of the TC4/IN718 bimetallic structure were tested by a universal testing machine (MTS-1000) with a loading rate of 0.5 mm min⁻¹; the geometry and dimensions of the tensile specimen are shown in figure 1(c).

### 3. Results and discussion

#### 3.1. Evolution of phases and microstructures of the bimetallic structure

The XRD profiles of the three interfaces and the four regions in the TC4/IN718 bimetallic structure with the Ta/Cu bilayer are presented in figure 2. The XRD tests indicated that the bimetallic structure phase was composed of \(\alpha\)-Ti (hcp-Ti), \(\beta\)-Ta (bcc-Ta), \(\gamma\)-Cu (fcc-Cu), \(\gamma\)-Ni (fcc-Ni), and laves. The phase evolution of the interlayer with the Ta/Cu bilayer in the bimetallic structure was as follows: \(\alpha\)-Ti \(\rightarrow\) \(\alpha\)-Ti + \(\beta\)-Ta \(\rightarrow\) \(\beta\)-Ta \(\rightarrow\) \(\beta\)-Ta + \(\gamma\)-Cu \(\rightarrow\) \(\gamma\)-Cu \(\rightarrow\) \(\gamma\)-Cu + \(\gamma\)-Ni + laves \(\rightarrow\) \(\gamma\)-Ni + laves. The XRD results show that no Ti–Ni or Ti–Cu IMCs were generated in the three interfaces and four regions of the TC4/IN718 bimetallic structure with the Ta/Cu bilayer.

![Figure 2. The XRD profiles of the three interfaces and the four regions in the TC4/IN718 bimetallic structure with the Ta/Cu bilayer.](image)
interlayer. The reduction of IMCs effectively reduces crack sensitivity. Although the laves phase (Fe$_2$Nb, Cr$_2$Nb) is found near the Cu/IN718 interface, the laves phase is an inherent IMC in IN718. Due to Ta being the stable element of β-Ti in dual-phase titanium alloys (α + β), Ta solid solution (Ta-bcc) and Ti solid solution (Ti-bcc) are infinitely mutually soluble. In addition, according to the equilibrium phase diagram of Ta-Ti, it can be seen that Ta and Ti are in finite solid solutions to each other [16]. On the basis of the equilibrium phase diagrams of Ta–Cu and Cu–Ni, it can be seen that Ta and Cu, and Cu and Ni are in finite solid solutions to each other, respectively [18, 19]. Therefore, no IMC would form between the main elements contained in adjacent regions. For this reason, the Ta/Cu multi-interlayer could be considered as the ideal interlayer for fabricating TC4/IN718 bimetallic structures by LAM.

Figure 3 shows the microstructure and EDS maps of the bimetallic structure with Ta/Cu interlayer. (a) Microstructure and associated EDS maps of the TC4/Ta interface, (b) microstructure and associated EDS maps of the Ta/Cu interface, (c) microstructure and associated EDS maps of the Cu/IN718 interface.

Figure 3. Microstructure and EDS maps of the TC4/IN718 bimetallic structure with Ta/Cu interlayer. (a) Microstructure and associated EDS maps of the TC4/Ta interface, (b) microstructure and associated EDS maps of the Ta/Cu interface, (c) microstructure and associated EDS maps of the Cu/IN718 interface.
Ta. Moreover, due to Ta having a higher melting point, the higher laser power was used to deposit the Ta interlayer, which promoted the diffusion of Ti and Ta. It is obvious that the TC4 region below the TC4/Ta is mainly composed of a basketweave structure which consists of $\alpha$-Ti and $\alpha + \beta$. It is also worth noting, as shown in figure 3(a), that the acicular $\alpha$-Ti far from the TC4/Ta interface is relatively thick, with an approximate size of 16.90 $\mu$m $\times$ 1.10 $\mu$m, while the acicular $\alpha$-Ti near the TC4/Ta interface is finer with an approximate size of 7.83 $\mu$m $\times$ 0.40 $\mu$m \cite{20}. The Ta region above the TC4/Ta interface is mainly composed of a Ta solid solution in which the diameter of the equiaxed grains is about 50 $\mu$m. $\alpha$-Ti is distributed at the equiaxed grain boundaries of the Ta solid solution.

Figure 3(b) shows the microstructure and associated EDS maps at the Ta/Cu interface. It can be clearly seen that both the Ta and Cu elements are diffused into each other’s region at the Ta/Cu interface, indicating that metallurgical bonding was formed at the Ta/Cu interface without any metallurgical defects. Because of the high melting point of Ta, it is difficult for Cu to diffuse into the grains of Ta, and so it is mainly concentrated in the equiaxed grain boundaries of Ta. The results of the XRD in figure 2 show that there are only Ta phase and Cu phase near the Ta/Cu interface, indicating that choosing Ta as the interlayer between TC4 and copper could effectively prevent the formation of Ti–Cu IMCs \cite{17}. This is consistent with the results of the XRD near the Ta/Cu interface. Due to the difference of lattice types between $\beta$-Ta and $\gamma$-Cu, and the great difference between the melting point of Ta and that of Cu, $\beta$-Ta would solidify before $\gamma$-Cu during the cooling process. Therefore, the structure of the Ta region below the Ta/Cu interface is composed of a large number of equiaxed $\beta$-Ta with an approximate size of 30 $\mu$m, and a small amount of grain boundary $\gamma$-Cu, due to the fact that the low melting point Cu was squeezed to the grain boundaries by the high melting point Ta during solidification. Moreover, the structure of the Cu region above the Ta/Cu interface is composed of a large amount of $\gamma$-Cu and a small amount of $\beta$-Ta, contributing to achieving good metallurgical bonding at the Ta/Cu interface \cite{21}.

Figure 3(c) exhibits the microstructure and associated EDS maps at the Cu/IN718 interface. It can be obviously seen from the EDS maps that the Cu elements and the main elements contained in IN718 have diffused into each other’s region at the Cu/IN718 interface. The XRD results show that there are only $\gamma$-Ni, $\gamma$-Cu, and a small amount of laves phase near the interface of the Cu/IN718, and no IMCs are formed in the Cu-Ni system \cite{19}. It is to be noted that the laves phase (Fe$_2$Nb, Cr$_2$Nb) is an inherent IMC of IN718, which is usually distributed at the grain boundary of $\gamma$-Ni \cite{22}. From the distribution of the Nb elements at the Cu/IN718 interface, it can be inferred that the bright white structure at the grain boundary of $\gamma$-Ni mainly contains the laves phase. Since $\gamma$-Cu and $\gamma$-Ni have the same lattice structures (bcc), leading to good compatibility and wettability between them, which is helpful for the good combination between Cu and IN718 \cite{23}. The microstructure at the interface of Cu/IN718 is mainly composed of solid solutions of $\gamma$-Cu and $\gamma$-Ni. The Cu region below the Cu/IN718 interface consists of a large number of equiaxed $\gamma$-Cu (about 17.89 $\mu$m in diameter), a small amount of petal-shaped $\gamma$-Ni (7.21 $\mu$m $\times$ 6.53 $\mu$m), and tiny amounts of ($\gamma$-Ni + Fe$_2$Nb + Cr$_2$Nb) eutectic structure. The IN718 region above the Cu/IN718 interface consists of a large number of equiaxed $\gamma$-Ni (about 11.33 $\mu$m), a small amount of ($\gamma$-Ni + Fe$_2$Nb + Cr$_2$Nb) eutectic structure that is distributed at the grain boundaries, and a small amount of equiaxed $\gamma$-Cu (about 6.40 $\mu$m). A solid solution with $\gamma$-Cu and $\gamma$-Ni as the matrix was formed at the Cu/IN718 interface, indicating that metallurgical bonding was formed at the interface.

The distribution of elements near the three interfaces was measured by EDS line scanning, as shown in figure 4. Since the heating and cooling process of LAM is in a non-equilibrium state, the temperature gradient is relatively large, and each interface forms a heat affected zone (HAZ), but the HAZ is relatively narrow \cite{24, 25}. These factors lead to great changes in the composition of the elements near the interfaces of TC4/Ta, Ta/Cu, and Cu/IN718. The main elements contained in the four regions have obvious diffusion phenomena at their corresponding interfaces, which indirectly shows that each interface has formed metallurgical bonding. From

Figure 4. (a) EDS line scan across the TC4 and Ta interface; (b) EDS line scan across the Ta and Cu interface; EDS line scan across the Cu and IN718 interface.
the EDS composition analysis results in figure 4(a), due to the high diffusion coefficient of Ti in Ta, the content of Ti near the TC4/Ta interface is about 50%, while it is reduced to 30% in the Ta region. It can be seen from figure 4(b) that the content of Ti in the Ta region near the Ta/Cu interface decreases sharply, and there is almost no Ti element in the Cu region. As shown in figure 4(c), the content of Ti in the Cu region and the IN718 region near the Cu/IN718 interface is almost zero. The above results indicate that the Ta/Cu interlayer effectively avoids direct contact of Ti with Cu and Ni, which prevents the formation of Ti–Cu and Ti–Ni IMCs to some extent. The reduction of IMCs reduces the crack sensitivity of the TC4/IN718 bimetallic structure. It is worth noting that the large variation of Ta and Cu content in the Ta region near the Ta/Cu interface is due to the distribution of \( \gamma \)-Cu in the \( \beta \)-Ta grain boundaries. Moreover, the large variation of Ni and Cu content in the IN718 region is due to the good compatibility of \( \gamma \)-Cu and \( \gamma \)-Ni, which make the Cu and Ni interwoven.

Ta region and Cu region avoided the direct combination of TC4 region and IN718 region, thus preventing the generation of Ti–Ni IMCs. The Ta region between the TC4 region and the Cu region avoided the direct combination of TC4 and Cu, thus preventing the generation of Ti–Cu IMCs. In addition, the good metallurgical bonding was formed at Ta/TC4 interface and Ta/Cu interface without any IMCs. The Cu region avoided the direct combination of the Ta region and the IN718 region to generate IMCs. Moreover, no IMCs would form between Cu region and IN718 region; a high-quality combination was formed at the Cu/IN718 interface.

3.2. Vickers hardness and tensile properties
Vickers hardness profiles of the TC4/IN718 bimetallic structure with a Ta/Cu interlayer are shown in Fig. 5. The zero point represents the Ta/Cu interface. The hardness values of the TC4 region were close to 347 Hv, which is similar to the TC4 hardness value that was reported in the reference [26]. The hardness values of the Ta region and Cu region were stable at about 289 Hv [27] and 280 Hv [28], respectively, which are similar to that of pure Ta and pure Cu. This phenomenon is because the Ta region and the Cu region mainly contain Ta phase and Cu phase, resulting in no IMC formation in these regions. The hardness values in the IN718 region were stabilised at
about 278 Hv, which is close to that of IN718 fabricated by LAM [29]. Based on the above results, the hardness values of the four regions are maintained at the normal level, and no IMC with high hardness was formed in the bimetallic structure, indicating that the Ta/Cu interlayer could prevent the generation of IMC from TC4 to IN718.

The room temperature tensile properties of the TC4/IN718 bimetallic structure with a Ta/Cu interlayer were investigated. Figure 6(a) shows the stress–strain curve of the TC4/IN718 bimetallic structure, which shows that there is no obvious yield stage before fracture. The ultimate tensile strength of the bimetallic structure is 369.32 MPa, with an elongation to fracture near 0.64%. Compared with the reference [30] values that used laser welding of TC4 and IN718 with Nb foil and Cu foil as the interlayer, the tensile strength of the TC4/IN718 bimetallic structure was increased by 1.4 times, which indicates that Ta/Cu as an interlayer could effectively improve the bonding strength of the TC4/IN718 bimetallic structure.

As shown in figure 6(b), the fracture morphology of the bimetallic structure mainly presented a quasi-cleavage fracture. The phase composition of the fracture surface was analysed by XRD technology. Figure 6(c) shows that the peak intensity of the Ta phase is much stronger than that of the Cu phase, indicating that the fracture position of the bimetallic structure is at the Ta region near the Ta/Cu interface. This is due to the fact that in the Ta region below the Ta/Cu interface, the γ-Cu is mainly distributed in the equiaxed grain boundaries of β-Ta, which weakens the mechanical properties of β-Ta.

4. Conclusions

In the present work, the TC4/IN718 bimetallic structure without macro cracks and microscopic metallurgical defects was successfully fabricated by LAM technology, with using Ta/Cu as the interlayer. The results show that the Ta/Cu interlayer could effectively prevent the generation of the Ti–Cu and Ti–Ni IMCs. Metallurgical bonds were formed at the interfaces of TC4/Ta, Ta/Cu, and Cu/IN718. The ultimate tensile strength of the bimetallic structure was 369.32 MPa, indicating that it is a promising method to use Ta/Cu as the interlayer to fabricate TC4/IN718 bimetallic structures by LAM.

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