

Influence of electron-beam superposition welding on intermetallic layer of Cu/Ti joint

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Abstract: QCr0.8 was electron-beam welded to TC4 and the effect of the intermetallic layer (IMC-layer) on the mechanical properties of the joint was investigated. The IMC-layers are joint weaknesses at the Cu fusion line in centered welding and at the Ti fusion line when the beam is deviated towards Cu. A new method referred to as electron-beam superposition welding was presented, and the optimal welding sequence was considered. The IMC-layer produced by centered welding was fragmented and remelted during Cu-side non-centered welding, giving a finely structured compound layer and improved mechanical properties of the joint. The tensile strength of joint is 276.0 MPa, 76.7% that of the base metal.

Key words: Cu alloy; Ti alloy; electron beam superposition welding; IMC-layer

1 Introduction

Cu and its alloys usually combine excellent properties of high thermal and electrical conductivity, high ductility and corrosion-resistance, and some Cu alloys also exhibit a high strength [1–3]. Titanium, as a traditional structural material, has excellent comprehensive properties [4,5]. Thus, the joining of Cu and Ti, which combines the properties of both materials, can meet multiple requirements of high thermal strength, good corrosion-resistance and high thermal and electrical conductivity. Additionally, there is an important academic and practical value in the investigation of welding Ti and Cu alloy. However, brittle intermetallic compounds such as TiCu , Ti_2Cu , Ti_2Cu_3 and Ti_3Cu_4 easily form between Ti and Cu owing to thermal effects because of the poor mutual solubility and the large physical and chemical differences between Ti and Cu [6,7]. At present, investigations of joining Cu and Ti alloy focus on solid-phase welding methods [8,9]. The results of the friction welding of Cu/Ti conducted by MESHRAM et al [10] show that a well-formed joint can be obtained and the maximum tensile strength reaches 228 MPa. KAHRAMAN and GÜLENC [11] investigated the microstructures and mechanical properties of an explosive welding Cu/Ti joint, and found that the length

and amplitude of the joint ripple increase with the addition of explosives.

Results of infrared brazing of Cu and Ti using Ag-based filler metal by SHIUE et al [12] indicate that an interface reaction layer of CuTi_2 , CuTi or Cu_4Ti_3 forms. SONG et al [13] investigated the diffusion welding of Ti–6Al–4V and tin bronze (ZQSn10–10) and found that IMC-layers form at the interface and the tensile strength of the joint is only 30% that of the base metal. However, solid phase joining, which has disadvantages such as great mass, a special joint form and low service temperature, is limited in the joining of plate butt joints. Having great advantages in the joining of dissimilar metals, electron beam welding was suited to the welding of Cu and Ti alloy [14,15].

The microstructures and mechanical properties of an electron-beam-welded joint of chrome bronze and titanium alloy were investigated in this work, and the distribution of the IMC-layer in the weld was mainly studied. A well-formed joint was obtained through remelting, which decreases the adverse effects of the IMC-layer.

2 Experimental

The materials used in this experiment were chrome bronze (QCr0.8) and TC4 titanium alloy (Ti–6Al–4V).

The chemical compositions of the base metals are listed in Table. 1. The samples had dimensions of 75 mm×35 mm×2 mm and were mechanically cleaned, and the surfaces of the samples were washed with acetone or ethanol. Clamped and fixed with a self-made fixture, the samples were welded using a MEDARD-45 pulse vacuum electron-beam welding machine whose vacuum reaches 5×10^{-4} mbar. The accelerating voltage, electron beam and welding speed used in the experiment were 55 kV, 18–25 mA and 8 mm/s, respectively.

Table 1 Chemical compositions of QCr0.8 and TC4 (mass fraction, %)

Metal	Cr	Al	V	Ti	Cu	Others
QCr0.8	0.4–0.7	–	–	–	Bal.	≤0.8
TC4	–	6.2	3.5	Bal.	–	≤0.2

The joint microstructure was observed using a PME OLYMPUS optical microscope and the tensile strength of the joint was measured with an INSTRON MODEL 1186 electronic universal testing machine. The weld phase composition was analyzed via X-ray diffraction (XRD, D/max-rb rotating anode) and the fracture morphology was analyzed using a scanning electron microscope (SEM, S-4700). The phase composition was determined with an energy dispersive spectrometer (SEM, S-4700) and the fine microstructure of the joint was analyzed using a transmission electron microscope (Philips CM-12).

3 Results and analysis

In the electron-beam centered welding of QCr0.8 and TC4, the electron beam source acts on the butt plane of the base metals as shown in Fig. 1. It is observed that there is a large melting amount of the TC4 base metal. The joint tensile strength is only 118 MPa, which is obviously lower than that of the base metal. QCr0.8 fractured at the fusion line, exhibiting the characteristics of brittle quasi-cleavage fracture, as shown in Fig. 1(a). Figure 1(b) shows that an IMC-layer with thickness of 10 μm formed at the fusion line of QCr0.8. The results of the pointwise energy spectrum analysis and the fracture scanning test indicate that the IMC-layer is a mixed layer of multiple Ti_aCu_b intermetallic compounds such as TiCu , Ti_2Cu and Ti_3Cu_4 phases. There are massive lattice distortions at the interface of intermetallic compounds, where the material has hard brittle characteristics and there are the formation and propagation of cracking, leading to tensile fracture at the fusion line of QCr0.8.

To obtain joints of high strength, methods of increasing the melting amount of QCr0.8 alloy, which can optimize the weld components and the microstructure of the joint, were considered. Results for

the non-centered electron-beam welding of QCr0.8 and TC4 with a deviation of 0.6 mm inclined toward the bronze are shown in Fig. 2. Figure 2(a) shows that there is a large melting amount of the Cu alloy, and the results of XRD analysis and transmission electron microscopy

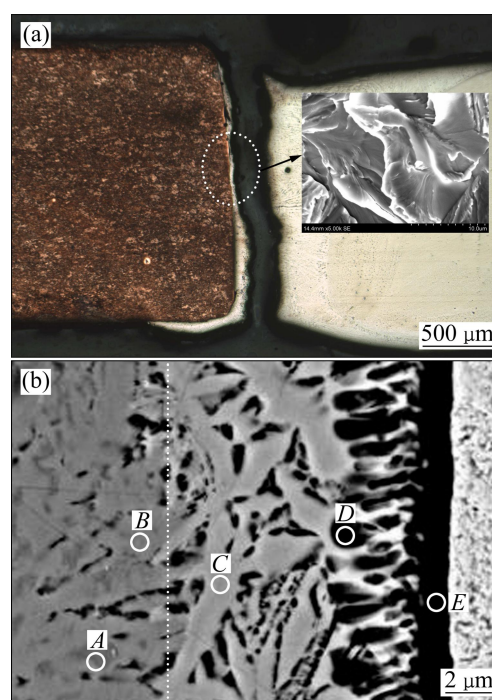


Fig. 1 Characteristics of centered welding: (a) Fracture position and characteristics; (b) Morphology of IMC-layer and EDS analysis

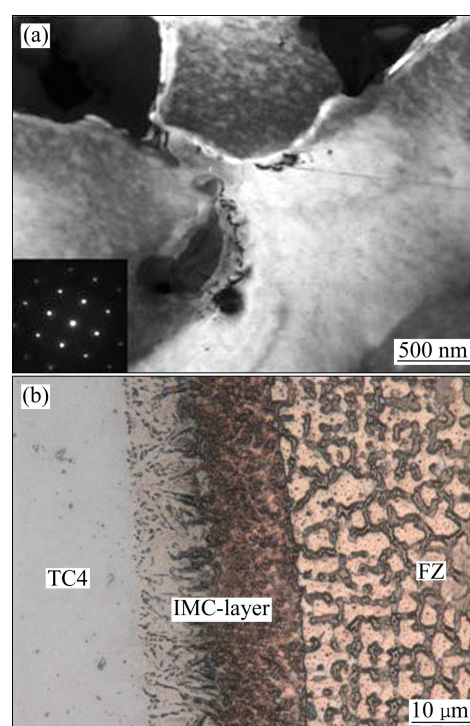


Fig. 2 Weld microstructures for Cu-side non-centered welding: (a) Weld; (b) Fusion line of TC4

show that the weld is mainly Cu-based solid solution. Thus, an IMC-layer does not form at the fusion line of QCr0.8 but exists at the fusion of TC4 with thickness of 20 μm , as shown in Fig. 2(b).

It is concluded from the above analysis that for both centered welding and non-centered welding, an IMC-layer forms at the fusion line of one base metal; here the tensile strength of the joint decreases and there exists tensile fracture. Therefore, methods should be adopted to decrease the adverse effect of the IMC-layer. Considering that the IMC-layer formed at fixed positions, secondary electron beam welding, in which the electron beam is shifted to the fusion line where IMC-layers form after primary welding, was used. Employing this method, the IMC-layer can be fragmented and remelted and the difference in the chemical compositions between the fusion lines on each side can be balanced; thus, the weld microstructure can be optimized. We refer to this method as an electron-beam superposition welding because the secondary weld is partially superposed on the primary weld, as shown in Fig. 3.

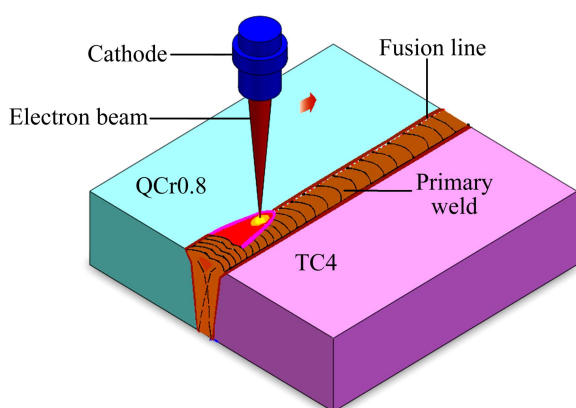


Fig. 3 Schematic diagram of electron-beam superposition welding

The non-centered welding of Cu and Ti with deviation of 0.6 mm inclined toward Cu was firstly conducted, and centered welding was then performed by moving the electron beam to the butt plane of the base metals. The aim was to eliminate the IMC-layer at the fusion line of titanium, and the results are shown in Fig. 4. After secondary welding, the weld exhibited good formation but had poor joint tensile strength of only 82 MPa. There was fracturing at the middle weld, which exhibited characteristics of brittle quasi-cleavage, as shown in Fig. 4(a).

Figure 4(b) shows the weld intersection morphology obtained by superposition welding. It is seen that the primary weld at left was still dendrite mainly composed of Cu-based solid solution. The IMC-layer formed in the primary welding was fragmented and remelted by secondary welding, and there were no IMC-layers at the

interface between the TC4 base metal and primary weld. However, there was a large amount of Ti element in the weld because of the large melting amount of TC4 alloy induced by the centered welding. The secondary weld was similar to the direct welding of QCr0.8 and TC4; thus, there was a reaction between the Cu element and Ti element and a new IMC-layer formed at the boundary line between the two welds. Therefore, there was fracturing at the IMC-layer in the middle weld and the tensile strength of the joint was lower than that of the joint obtained by centered welding.

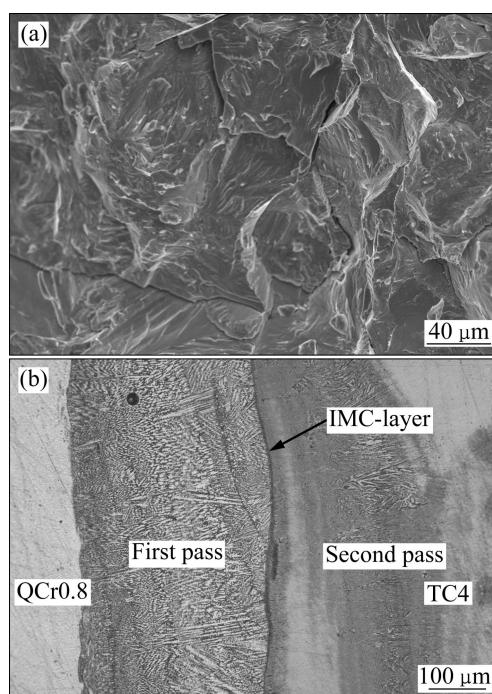


Fig. 4 Morphologies of non-centered and centered welding: (a) Fracture morphology; (b) Joint intersection morphology

To make the transition of the weld microstructure obtained by electron-beam superposition welding more reasonable, the welding sequence was adjusted. The centered welding at the butt plane was primarily conducted and secondary non-centered welding with deviation of 0.6 mm inclined toward Cu was then performed. Figure 5 shows the macroscopic morphology of the joint obtained by this welding sequence that a weld with good formation was obtained and the upper and back sides of the weld were comparatively smooth.

The intersection morphology of the joint obtained by centered welding and non-centered welding is shown in Fig. 6(a). There was a good transition between the two welds, and no obvious boundary lines or IMC-layers formed. Line scanning analysis along the line in Fig. 6(a) shows that the mass fraction curves of Cu and Ti were basically flat and there were no obvious transition characteristics, as shown in Fig. 6(b). There are connections between the line scanning analysis result and

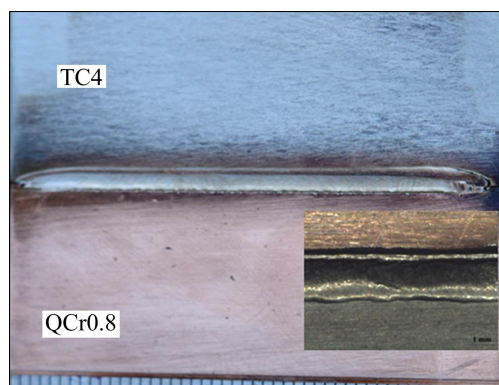


Fig. 5 Macroscopic morphology of sample obtained by centered welding and non-centered welding

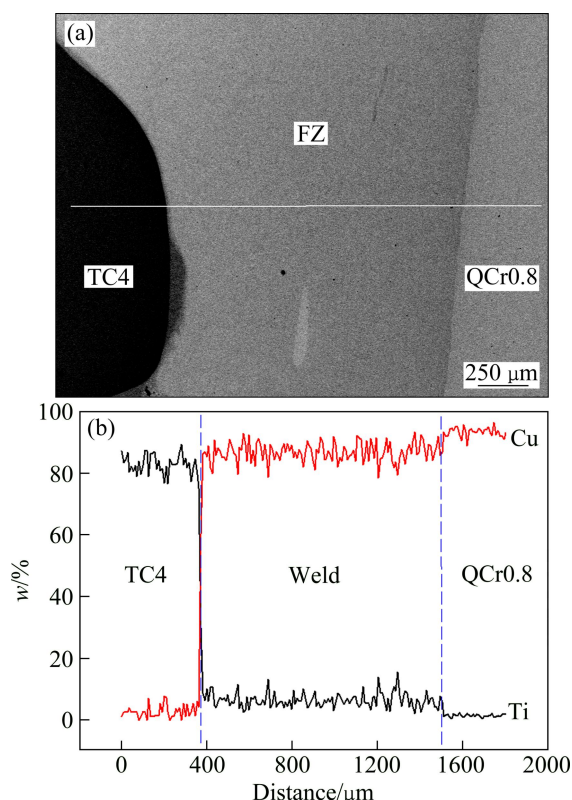


Fig. 6 Characteristics of centered and non-centered welded joint: (a) Intersection; (b) Element distribution

the weld compositions. Although there was much melting of the TC4 base metal in the primary centered welding, there was obviously less Ti element in the weld than in the TC4 base metal and the amount of Cu element in the weld is close to that in QCr0.8 alloy. When the primary weld was secondarily non-center welded by the electron beam, there were no IMC-layers because of the large compositional transition gradient and the joint morphology was similar to that obtained in one-pass welding.

Figure 7 shows the weld morphologies at the fusion line on both sides in the case of centered welding and

non-centered welding. It is seen from Fig. 7(a) that IMC-layers did not form at the fusion line near QCr0.8 alloy and there was no difference between the microstructure at the fusion and the weld microstructure. There were no obvious IMC-layers at the fusion line near TC4 alloy, where the phase composition was mainly the lamellar α -Ti phase crystallized from the initial β phase and the properties of the weld were improved.

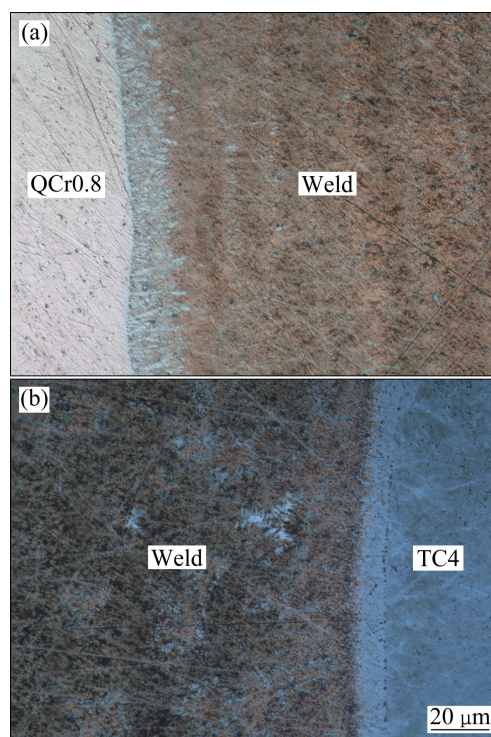


Fig. 7 Characteristics of transition layer in fusion line: (a) On QCr0.8 side; (b) On TC4 side

Tensile fracture usually occurred at the fusion line near QCr0.8 alloy in the joint obtained by centered welding and non-centered welding, but fracture at the fusion line near TC4 alloy was also possible. Fracturing did not wholly occur in the IMC-layer near TC4, demonstrating that the microstructures and properties were improved. Under the thermal effect of secondary welding, the Cu element distributed from the primary weld to the IMC-layer, leading to a high content of Cu element. In this case, the IMC-layer was mainly composed of α -Ti phase, which has good comprehensive properties and high ductility, and there was thus no fracturing at the IMC-layer.

Obvious necking appeared on the QCr0.8 alloy side of the joint after the tensile test, and the fracture exhibited hybrid characteristics, which were mainly local quasi-cleavage and dimple fracturing. The joint, whose tensile strength was 276.0 MPa or 76.7% that of the base metal, had good mechanical properties. Hence, electron-beam superposition welding, specifically centered welding and Cu-side non-centered welding, can

decrease the adverse effects of the IMC-layer by fragmenting and remelting the IMC-layer, leading to joints with good microstructures and mechanical properties.

4 Conclusions

1) IMC-layers, which are the sites of tensile fracturing, form at the fusion line in both centered welding and non-centered welding and lead to low tensile strength of the joint.

2) When non-centered welding and centered welding were applied, although the IMC-layer that forms in the primary weld can be eliminated, a new IMC-layer forms at the boundary between the two welds and the problem is not solved.

3) An IMC-layer that forms at the fusion line near Cu alloy in the primary centered weld can be fragmented and remelted by the secondary non-centered welding, and joints with good microstructures and mechanical properties are thus obtained.

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Cu/Ti 电子束叠加焊接对金属间化合物层的影响

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摘要: 对 QCr0.8/TC4 进行电子束焊接, 研究焊缝中金属间化合物层(即 IMC-layer)对接头力学性能的不利影响, 提出利用电子束二次叠加焊接方式来改善接头性能的思路。结果表明, 对中焊时在铜侧熔合线处形成的金属间化合物层, 偏铜侧焊接时在钛侧熔合线处形成的金属间化合物层, 是接头中的薄弱环节。利用电子束叠加焊接方式, 须合理设计焊接顺序。先进行对中焊, 再利用偏铜侧焊接, 可将第一道焊缝形成的金属间化合物层破碎重熔, 形成组织较好的化合物层, 改善接头的力学性能。接头的抗拉强度为 276.0 MPa, 达到了母材强度的 76.7%。

关键词: Cu 合金; Ti 合金; 电子束叠加焊接; 金属间化合物层

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