

Influence of diffusion bonding parameters on the structure and properties of titanium and stainless steel joints with copper interlayer

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ABSTRACT

Purpose of this paper is investigating if the effect of diffusion bonding parameters on the microstructure and mechanical properties of the joints.

Design/methodology/approach: Titanium and X5CrNi18-10 stainless steel samples were joined by diffusion bonding using copper foil as a filler metal at temperatures of 850, 875, 900, 925, 950 and 1000°C. From the stainless steel site of joint in all samples, regardless of the temperature of the process, there were formed layers of FeTi phase, and additionally layers of Fe₂Ti at 925, 950 and 1000°C.

Findings: The structure of the joint from the titanium site was composed of the eutectoid mixture α Ti+CuTi₂ and layers of phases CuTi₂, CuTi, and Cu₄Ti₃. Hardness of joints reached higher value than for titanium and stainless steel, and it achieved value from 185 to 580 HV. The hardest phase was FeTi. The maximum shear strength was achieved for joints performed at 900°C.

Researches limitations/implications: The structural examinations have shown significant changes in joints and relatively expansive diffusion zones on the borders of the joined materials. Structures of joints depended on the temperature of the process.

Originality/value: The useful properties have led to a considerable interest in joining titanium and titanium alloys to steel (especially stainless steel) for application in aerospace, transportation, petrochemical and power generation industries.

Keywords: Titanium; Stainless steel; Copper; Diffusion bonding

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PROPERTIES

1. Introduction

Titanium is a lightweight metal with the highest strength-to-weight ratio of any metal and an excellent corrosion resistance. The two useful properties have led to a considerable interest in joining titanium and titanium alloys to steel (especially stainless steel) for application in aerospace, transportation, petrochemical and power generation industries [1-3]. Welding of titanium and stainless steel is difficult due to the very low solubility of iron in alpha titanium at room temperature. When the two materials are joined by conventional fusion welding it results in segregation of chemical elements and formation of hard and brittle intermetallic phases near the interface [4]. It has been shown that pure silver, silver base alloys, titanium base alloys and copper base alloys can be used to braze titanium to steel [5]. Brazing involves melting of the filler material. Unfortunately titanium reacts easily with most liquid filler materials and forms intermetallic phases located as continuous brittle and hard layers on braze boundaries [6]. It has been reported that also joints produced by direct diffusion bonding between titanium and stainless steel show the formation of iron, chromium and titanium base reaction products, especially the formation of FeTi, Fe₂Ti, σ , Fe₂Ti₄O and TiC in the diffusion interface [7]. Therefore the most suitable way to achieve strong joints of titanium to stainless steel seems to be diffusion bonding using an appropriate filler metal. Nickel, copper, aluminum and their alloys were used as an intermediate materials [3,8-10]. Among these materials copper is the most useful metal because it does not form any intermetallic phases with iron (as does aluminum) and its melting point is much lower with respect to nickel. Eroglu et al. [11] reported that Cu-Ti base intermetallic phases have higher plasticity than the Fe-Ti base intermetallics. Furthermore, our previous work [12] demonstrated that the Cu-Ti-Fe-based intermetallics show a good capacity for plastic deformation and are capable of effectively stopping microcrack propagation. The present investigation reports diffusion bonding of titanium and X5CrNi18-10 stainless steel using copper as an interlayer. The effect of diffusion bonding parameters on the microstructure and mechanical properties of the joints has been investigated.

2. Experimental procedure

The chemical compositions and room-temperature mechanical properties of titanium, X5CrNi18-10 stainless

steel and copper used as a intermediate metal are given in Table 1.

Table 1. Chemical compositions and mechanical properties of the base materials

Material	Chemical composition, wt. %		
Stainless steel X5CrNi18-10	Fe: 77.99, C: 0.04, Cr: 18.09, Ni: 9.92, Mn: 1.28, Si: 0.65		
Titanium	Ti: 99.02, O: 0.41, Al: 0.26, Fe: 0.12, V: 0.09, Cr: 0.05, C: 0.02, Mo: 0.02		
Copper	Cu: 99.99, approximately 0.001 of: Fe, Ni, Zn, Sn, Pb, Sb, As, S		
Mechanical properties			
	Offset yield strength, MPa	Ultimate tensile strength, MPa	Fracture elongation, %
X5CrNi18-10	218	557	44
Titanium	348	548	16
Copper	68	219	45

Titanium and stainless steel were received in the form of cylindrical rods having 12 mm diameter. From the base materials there were machined cylindrical specimens of 10 mm diameter and 15 mm length. The joining surfaces of the cylinders were prepared by conventional techniques using several stages of grinding papers and polished on 1 μ m diamond suspension. The copper foil of 0.1 mm thickness was used as an intermediate metal. Both surfaces of the foil were polished on diamond suspension. There were cut circular profiles from the copper foil having 10 mm diameter. As it was necessary to remove oxide layers, the stainless steel cylinders and copper foils were etched in an aqueous 5% solution of HNO₃, while the titanium cylinders in an aqueous 2% solution of HF. All specimens were then cleaned ultrasonically in acetone and dried rapidly in air. The joined titanium and stainless steel cylinders with inserted copper interlayer were kept in contact in a steel clamp. After that the samples together with the fixture were placed into a vacuum furnace. The compressive stress of 5 MPa along the longitudinal direction was applied at room temperature. The diffusion bonding was carried out at 850, 875, 900, 925, 950 and 1000°C for 60 minutes in 10⁻³ Pa vacuum. After diffusion bonding, the specimens were cut longitudinally, mounted in a cold setting resin, mechanically prepared initially with a grade 1000 abrasive paper and finally using Struers polishing machine and 1 μ m diamond suspension. Microstructural observations were performed using a JEOL JMS-5400 scanning electron microscope (SEM) and a Carl Zeiss NEOPHOT 2 optical

microscope (OM). Before the samples were examined with the optical microscope they had been etched. The titanium side was etched in an aqueous solution of 88 ml H₂O, 8 ml HNO₃ and 4 ml HF. The stainless steel side was etched by a solution containing 3 g FeCl₃, 10 ml HCl, and 90 ml C₂H₅OH. A mixture containing 20 g CrO₃, 75 ml H₂O, and 5 ml HNO₃ was used for etching pure copper and intermetallics comprising copper. The chemical compositions of the phases were determined in atomic percent using an electron probe microanalyser Oxford Instruments ISIS-300. The microhardness along the cross-section of the diffusion bonded joints was performed by a Hanemann microhardness tester mounted on the NEOPHOT 2 microscope under load of 0.981 N for a dwelling time of 15 seconds. The shear strength of the bonded joints was evaluated at room temperature using an INSTRON screw machine at a crosshead speed of 10⁻² mm·s⁻¹. Three samples were tested at each processing parameter.

3. Results and discussion

3.1. Microstructural characterization

In order to study the effect of bonding temperature on the joint microstructure samples were bonded at 850, 875, 900, 925, 950 and 1000°C for 60 minutes. The microstructures of joints prepared at 875, 900 and 925°C are presented in Fig. 1.

The results of the metallographical and structural investigations of the joints demonstrated significant diffusion changes and relatively wide diffusion zones on the boundaries with joined metals. The structures of the joints varied importantly depending on joining temperature (Fig. 1). As was demonstrated previously [13], the phases

present in the structures were intermetallics: CuTi₂, CuTi, Cu₄Ti₃, FeTi, Fe₂Ti and solid solutions based on intermetallic phases or substrate metals (Fig. 2). The Fe₂Ti phase formed only when processing temperature was higher than 900°C. Due to high migration of copper in the temperature range of 850 to 1000°C the diffusion of chemical species is easy through interlayer. Therefore titanium can migrate to the stainless steel side and iron can also migrate to the titanium side. Hence, the copper interlayer of 0.1 mm thickness cannot prevent the formation of brittle Fe-Ti base intermetallic phases (Fig. 2b). The thickness of the reaction products increases with increase in the bonding temperature. It is worth noting that the migration of Cu (strong β -stabilizer element) and Fe in the titanium substrate lower the eutectoid transformation temperature of Ti and α - β phase aggregate can form by the decomposition of β Ti during cooling [3].

3.2. Hardness and shear testing

Microhardness measurements of titanium substrate, interface zone and steel substrate were performed for all processed samples. The maximum hardness values in the range of 420 to 580 HV were achieved at the stainless steel-copper interface due to the presence of the FeTi and Fe₂Ti intermetallic phases. At the titanium-copper interface and in the middle of the joints hardness values are 302 ± 22 HV and 238 ± 52 HV, respectively. A significantly higher hardness of joints was observed at higher processing temperature, which is due to the formation of hard Fe-Ti base intermetallic phases and diffusion of iron, chromium and nickel to Ti-Cu base intermetallic phases. The shear strength of the diffusion bonded joints with the change in bonding temperature is given in Table 2 and Fig. 3.

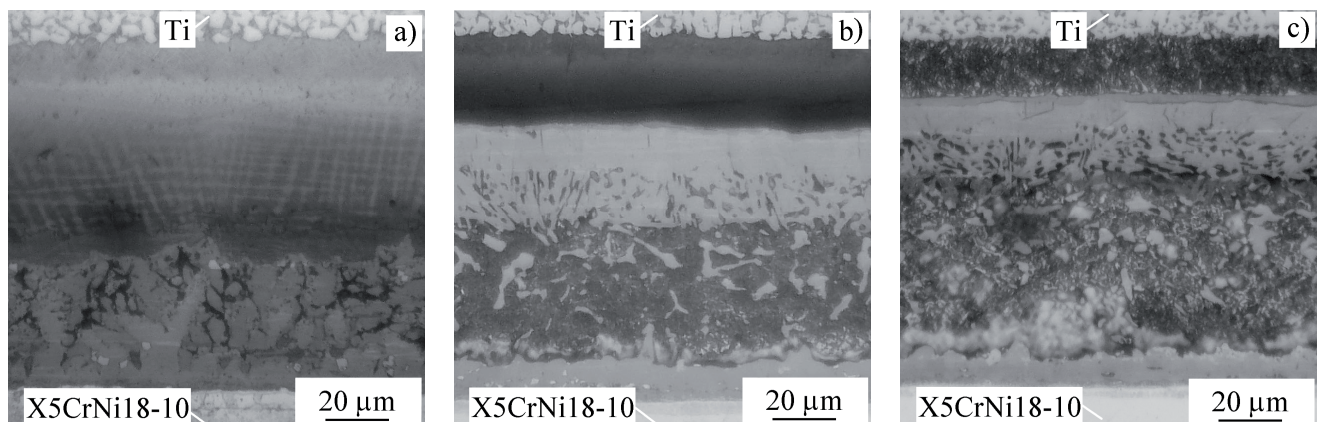


Fig. 1. Optical micrograph of the joints prepared at 875 (a), 900 (b) and 925 °C, (c) for 60 min

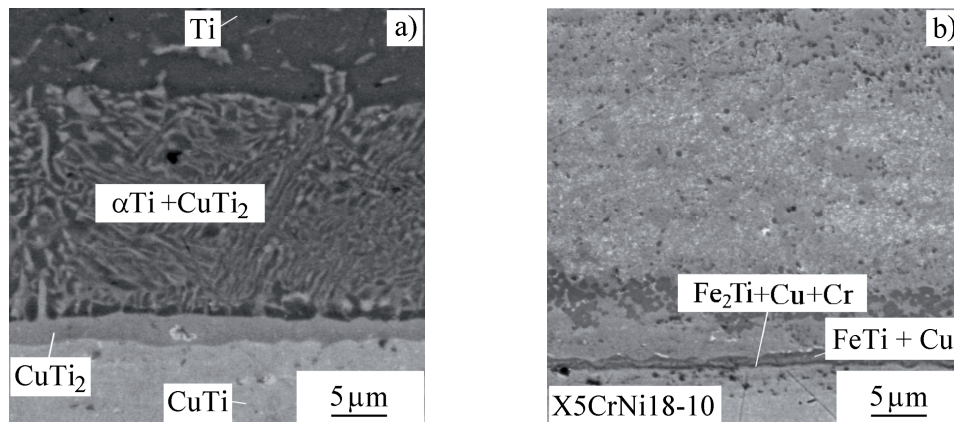


Fig. 2. SEM microstructure of the titanium-copper (a) and stainless steel-copper (b) interfaces processed at 925°C for 60 min

Table 2.
Shear strength of the processed joints

	Joining temperature, °C					
	850	875	900	925	950	1000
Shear strength (MPa)	196 ± 7	238 ± 3	258 ± 4	252 ± 3	217 ± 4	134 ± 4

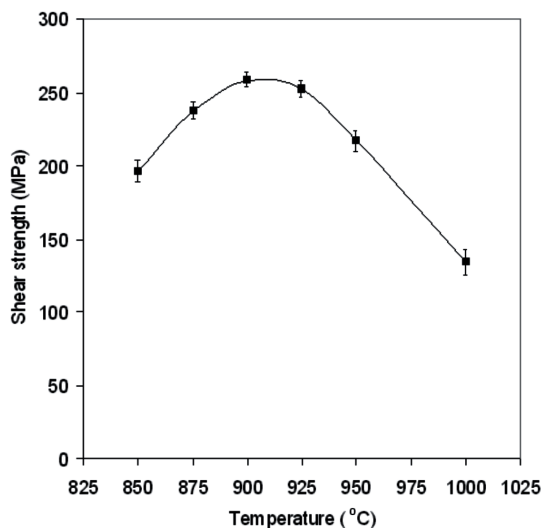


Fig. 3. Shear strength of the bonded joints processed at 850-1000°C

When the bonding temperature is 850°C, the shear strength of the diffusion couple is low. It is probably caused by the incomplete coalescence of the mating surfaces. With an increase in the joining temperature, the shear strength increases and reaches its maximum value at

900°C. This temperature encourage the mass transfer of the alloying elements across the interface and the coalescence of the mating surfaces can be achieved. For joints processed at 850, 875 and 900°C the fracture during the shear test occurred along the reaction layers which contained CuTi_2 and CuTi intermetallics. Beyond 900°C diffusion bonding temperature, the width of Fe-Ti base intermetallics noticeably increased and the shear strength of joints decreased with an increase in the joining temperature. The fracture during the shear test occurred along the layers contained hard and brittle FeTi and Fe_2Ti intermetallic phases. Ghosh et al. [14-16], Qin et al. [17] and Kundu et al. [3,18] also indicated that the shear strength at higher joining temperature is governed by the increased volume fraction of discontinuities resulting in embrittlement of the transition joints

4. Conclusion

The diffusion bonding of the titanium and X5CrNi18-10 stainless steel using copper foil as a filler metal was carried out at 850, 875, 900, 925, 950 and 1000°C for 60 minutes under the compressive stress in vacuum. The investigations of the diffusion-bonded joints revealed the following:

1. The structural examinations show significant changes in joints and relatively expansive diffusion zones on the borders of the joined materials. Structures of joints strongly depends on the temperature of the process. The structure of the joints from the titanium site is composed of the eutectoid mixture $\alpha\text{Ti}+\text{CuTi}_2$ and layers of phases CuTi_2 , CuTi , and Cu_4Ti_3 . From the stainless steel site of joint in all samples, regardless of the temperature of the process, there were formed layers of FeTi phase, and additionally layers of Fe_2Ti at 925, 950 and 1000°C.
2. The microhardness test across the joints indicates that the hardness in the joints interfaces reaches higher value than for titanium and stainless steel, and it achieves value from 185 to 580 HV. The hardest is the FeTi intermetallic phase.
3. The maximum shear strength is achieved for the diffusion-bonded joints performed at 900°C due to the better coalescence of mating surfaces than for joints obtained at 850 and 875°C, and owing to the finer width of the Fe-Ti base intermetallics than for joints performed at temperatures beyond 900°C.

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