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Experience in HIP Diffusion Welding of Dissimilar Metals and Alloys

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Abstract. HIP solid-state diffusion welding is a controlled production operation at all the processing stages. Unlike other known solid-state welding techniques the HIP allows to provide strong and dense bonding with stability properties irrespective of the sizes and a configuration of the contact surfaces of materials welded. Here we present some special pilot examples of HIP diffusion welding of dissimilar metals and alloys: steel XM19-to-steel 316L, bronze Cu-Cr-Zr–to-steel 316L, copper M1–to-steel Fe-18Cr-10Ni-Ti-C, titanium alloy Ti-6Al-4V–to-steel Fe-18Cr-10Ni-Ti-C, single-crystal molybdenum-to-polycrystal molybdenum and titanium alloy-to-aluminum alloy.

Introduction

Solid-state diffusion welding (DW) is a main way to make a bimetallic structural material for space and nuclear application where a strong and dense bonding of materials with different chemical compositions is needed. This technology produces a monolithic joint resulting from a maximum closing of the contact surfaces due to their local plastic deformation at the increased temperature as well as the formation of metallic bond at the atomic level followed by a mutual diffusion of the components through the surface layers of the materials bonded [1]. Solid-state diffusion welding includes the following obligatory stages: the oxide film removal from contact surfaces, the actual contact formation, the surfaces activation, the chemical bond formation and diffusion. This sequence is true for all known methods of solid-state welding: cold bonding, explosion welding, percussion vacuum welding, friction welding, vacuum roll welding, induction and ultrasonic welding, etc. However, only the diffusion welding is the most universal and reliable method that allows controlling all four key technological parameters of process: temperature, pressure, dwell time and diffusion medium. The method of diffusion welding (DW) with use of hot isostatic pressing (HIP) can be considered as a kind of classical DW wherein technological parameters can be controlled within a wider range. Below we examined the influence of the HIP DW technological parameters on a welded joint quality.

Influence of HIP parameters

Temperature and pressure

Temperature and pressure are mutually dependent parameters in HIP technology. Specified pressure values in a HIP installation chamber are achieved by thermal expansion of working gas as the temperature increases. Thus, with computation of the necessary amount of gas at the room temperature performed, it is possible to reach the HIP operation conditions both in the temperature of 200 °C to 1200 °C and pressure of 20 MPa to 200 MPa ranges under any parameter combination. As the pressure is created by gas, the pressure value will be the same in

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any point of the HIP product contact surfaces despite the sizes and configurations of the parts bonded. As it is well known [2], if all-round compression pressure is applied to a crystal the concentration of vacancies in this case will then be equal to

$$Cp = Co \exp(-P\Omega/kT), \tag{1}$$

Where, *Co* is the equilibrium component concentration at $P=0$; Ω is the atomic volume; P is the all-round compression pressure; k is the Boltzmann's constant; T is the temperature. In this case the "minus" symbol denotes compression. That is, the amount of vacancies decreases with increase in pressure, such that the diffusive flow of atoms decreases too. In 1954, S. Storchheim *et al.* [3] established that the phase Ni_3Al_2 was not formed even at pressure of 170-300 MPa, only the phase Ni_3Al was formed at pressure higher than 300 MPa, and intermetallic phases were not observed at a pressure about 500 MPa. Thus it is possible to increase or reduce diffusion rate with pressure increasing or decreasing. In so doing it is possible to reach such process conditions wherein the nucleation and growth of undesirable phases can be depressed at the contact zone.

Dwell time

Theoretically the duration of a HIP DW technological parameters can be unlimited and depends only on the end result required. HIP DW excludes the void volume along a boundary of the dissimilar metal diffusion bonding that caused by distinction in partial component diffusion coefficients, for example, nickel and copper (Kirkendall's effect [3]), as owing to constantly applied pressure the formed vacancies are replaced with metal atoms having the largest diffusion velocity, here copper (Fig.1). Therefore, it is possible to create quite a wide transitional area in a contact zone of dissimilar metals (up to several hundred microns) by operating of HIP DW duration. Increasing the transitional area width will give the positive effect, for example, as damping layers between metals of greatly different coefficients of thermal expansion.

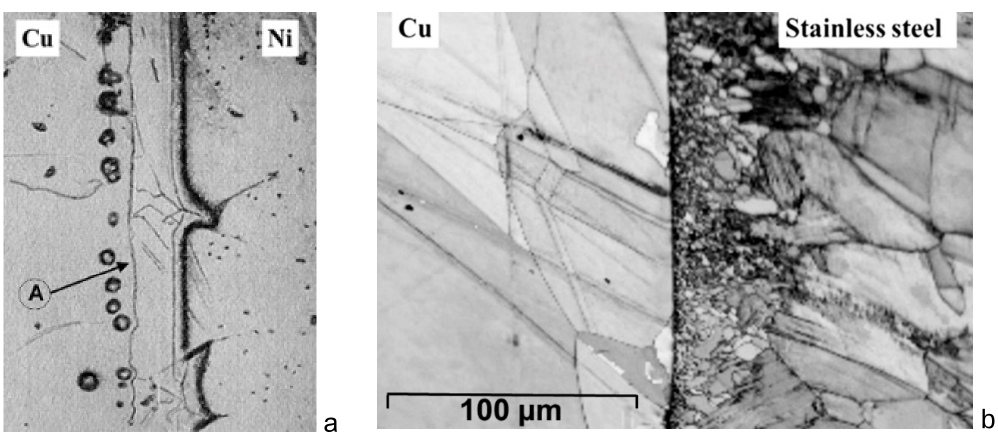


Fig.1 – Voids in copper of Ni-Cu diffusion bonding according to Le Claire A.D. and Barnes R.S. [3], A is the initial line of contact (a), absence of voids after HIP DW [4] (b)

Environment

Under the fine vacuum and at the high temperatures the dissolution of oxides promotes the formation of juvenile contact surfaces of the joints welded.

Materials Research Proceedings **10** (2019) 65-72 doi: http://dx.doi.org/10.21741/9781644900031-9

Experimental procedure

The following materials are used in this study: steel XM19 (chemical composition in wt%: 22 Cr, 12 Ni, 5 Mn, 2.5 Mo, 2.5 Nb, 0.2 V and the reminder Fe) in forging, steel 316L (in wt%: 17 Cr, 12 Ni, 2.5 Mo and the reminder Fe) in forging, stainless steel in wt%: 18 Cr, 11 Ni, 0.5 Ti and the reminder Fe in bar and sheet, bronze in wt%: 0.9 Cr, 0.1 Zr and the reminder Cu in sheet, titanium alloys in wt%: 6 Al, 4 V and the reminder Ti in bar; 4.5 Al, 5 V, 2 Mo, 1.2 Cr, 0.6 Fe and the reminder Ti in sheet, copper alloy M1 in bar, aluminum alloy in wt%: 6 Mg, 0.7 Mn and the reminder Al in sheet, single-crystal and especially pure polycrystal molybdenum in bars. To manufacturing of samples for test of mechanical properties and research of structure used one HIP diffusion bonding from party, and in a design of structural assembly of the diverter and mirrors were provided with special places for cutting of samples witnesses. Mechanical tensile strength testing was carried out according to requirements of the ISO 6892:1984, ISO 783:1989, ISO 783-89 standards. Microstructure was observed by of an optical microscope Zeiss Axio Observer with ImageExpert system and a raster electronic microscope JSM-6610LV equipped with Advanced AZtec EDS Detector. Metallographic samples were made with use of a combination of the machines which includes the Delta AbrasiMet Abrasive Cutter, SimpliMet 3000 Mounting Press and EcoMet 250 Grinder-Polisher.

Results

Steel XM19-to-steel 316L HIP Diffusion Bonding

Within an International Thermonuclear Experimental Reactor (ITER) program the diffusion welding has been performed of large-size parts of corrosion-resistant stainless steel AISI 316L and high-strength steel XM19 intended for pre-fabrication of the diverter attachment fitting (Fig. 2a). The structural assembly mass is equal to 760 kg and the summary diffusion bonded surface area is nearly 770 cm^2 (Fig. 2b) and 1260 cm^2 (Fig. 2c). Failure of the bimetallic tension specimens takes place on the base metal of steel 316L outside the diffusion bonding zone (Fig. 3a) as tensile strength of the HIP diffusion bonding zone is higher than tensile strength of steel 316L. In microstructure of the diffusion bonding zone steel XM19-to-steel 316L (Fig.3b) the presence of oxide phases is not detected. Besides, the common grains were observed in a contact area.

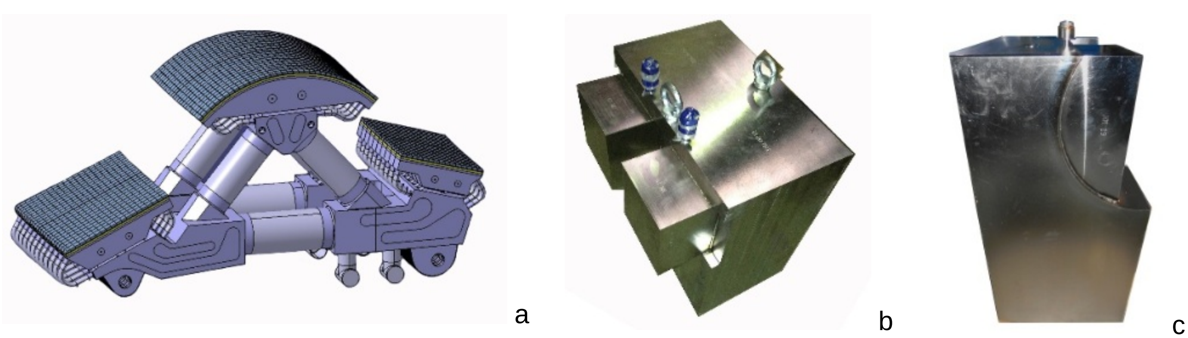
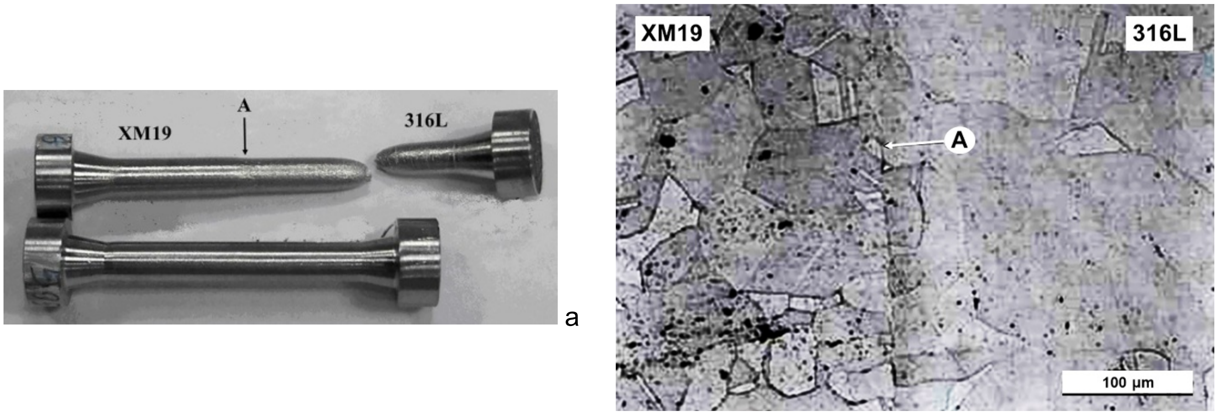


Fig.2 - Drawing of the diverter attachment fitting (a) and photographs of the bimetallic steel XM19-to- steel 316L HIP DW assemblies (b, c).

Materials Research Proceedings **10** (2019) 65-72 doi: http://dx.doi.org/10.21741/9781644900031-9



a b

Fig. 3 – The bimetallic tension specimens steel XM19-to-steel 316L before and after tensile testing (a), micrograph of a transitional layer (b), A – contact area [4].

Bronze Cu-Cr-Zr-to-steel 316L HIP Diffusion Bonding

A bimetallic bronze Cu-Cr-Zr-to-steel 316L heat exchanger of the first ITER wall is a complicated design with internal chambers and cooling channels (Fig**.** 4). Various welding processes for making pressure-tight contact surfaces of assembly parts prior to HIP are tested: manual argon-arc fusion welding; electron beam welding and automatic laser welding; the vacuum brazing and generally accepted one with the use of the capsule. Microstructure of the transitional layer of the HIP DW bronze-to-steel joint has much the same character despite the area and curvature of the contact surface. Thickness of a visible transitional layer is about 7 μm. A chemical composition of this layer contains elements characteristic of both for steel and bronze, and the chrome content here is higher than in the steel. The diffusion depth of copper into the steel reaches 30 μm beyond the transitional layer boundary. Diffusion depths of iron, nickel and chromium from steel into bronze are 50-100 μm, 40-60 μm and 5-7 μm, correspondingly. In bronze, at a distance of 1-3 μm from the transitional layer boundary a chain of inclusions takes place of up to 1μm and increased zirconium content, the nature of its formation being not determined (Fig.5).

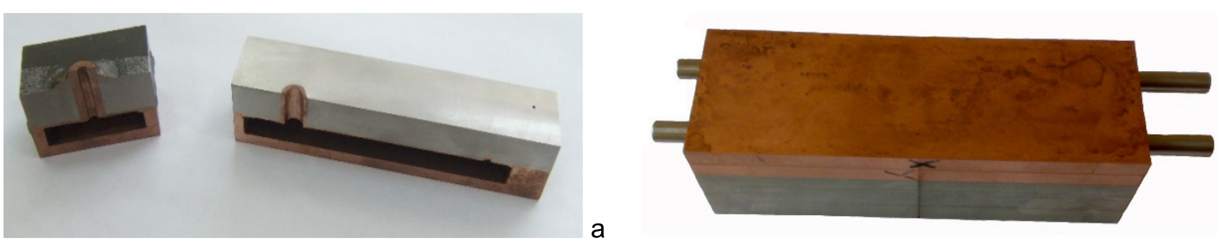

a b

Fig.4 – The models of bimetallic bronze Cu-Cr-Zr-to-steel 316L heat exchanger of the first ITER wall with internal chambers (a) and cooling channels (b) [4]

The post-HIP model of the first ITER wall was subjected to heat treatment in bronze standard mode: water hardening from temperature 980°C with the subsequent aging. After heat treatment tensile failure of bimetallic samples witnesses takes place on the main component of an alloy of bronze and average values of strength made 420 MPa at room temperature and 350 MPa at temperature of 250 ^{0}C.

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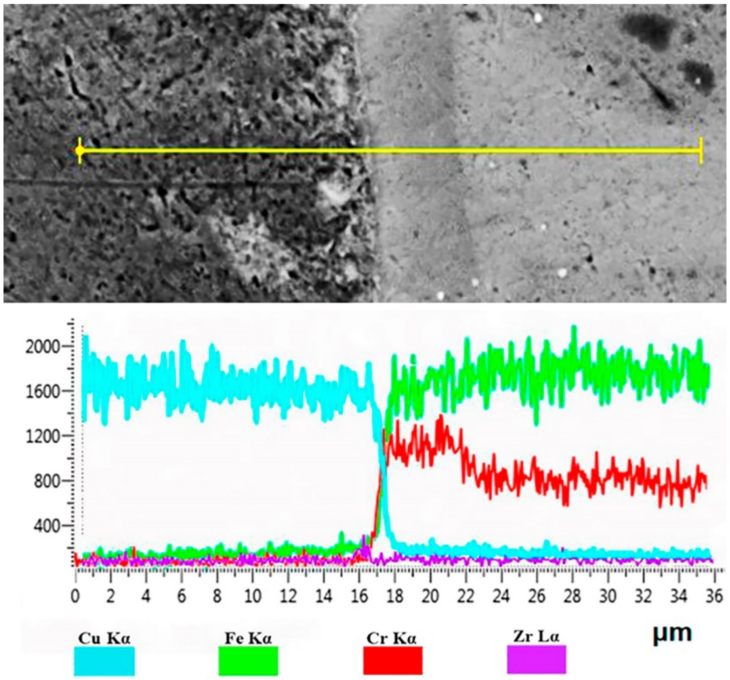
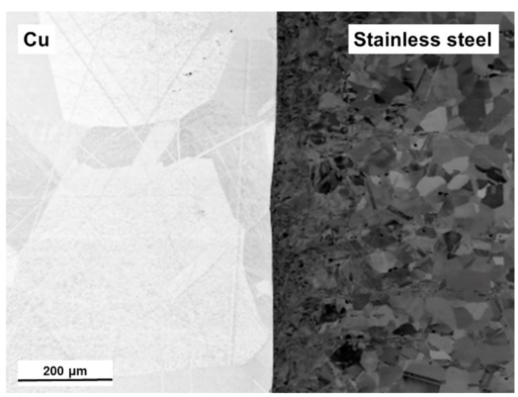


Fig.5 – Typical electron micrograph of bronze/SS HIP DW joint, pink line shows the region of alloying element spectrum

Copper / stainless steel HIP Diffusion Bonding

Copper/stainless steel adapters (Fig.6a) were made of 100 mm-diameter HIP DW-bimetallic bar-piece blanks followed by machining. The capsules each have 4 pairs of the piece blanks. The analysis of the microstructure testifies that the transitional layer of the HIP DW copper-to-stainless steel joint has 100% density (Fig.6b). Bending test of a 7x30x80-mm test piece cut from the bimetallic blank did not lead to its failure (Fig.6c)


a



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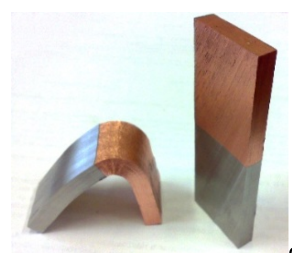

c

Fig. 6 – Copper-to-stainless steel adapter (a); micrograph of the transitional layer (b); a 7x30x80 mm test piece before and after bending tests (c) [4].

Ti6Al4V alloy / stainless steel HIP Diffusion Bonding

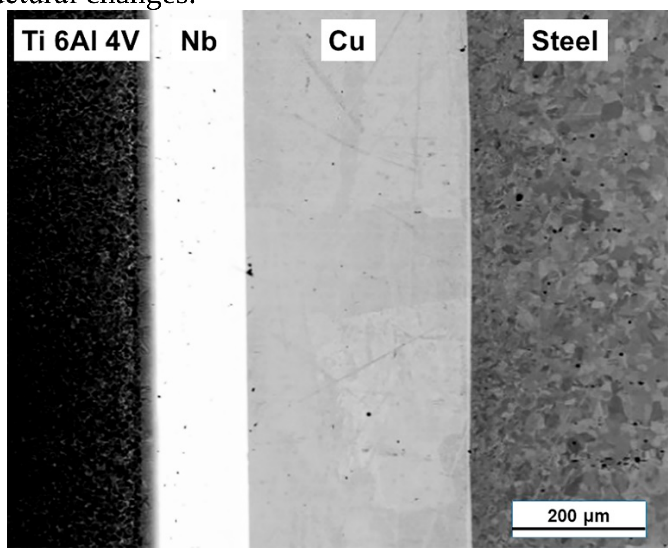
Direct Ti6Al4V alloy / stainless steel HIP DW does not give positive results. With increase in iron concentration more than 0.1 wt%, intermetallic TiFe and $TiFe_2$ are formed in titanium alloys, which embrittles the DW transitional layer. In practice [5], niobium and copper spacer-

Materials Research Proceedings **10** (2019) 65-72 doi: http://dx.doi.org/10.21741/9781644900031-9

foils are recommended for use in this case. Niobium and titanium form a continuous number of the solid solutions, and therefore, DW of them is not difficult. However, when reacted with carbon from steel niobium forms carbides along the total contact area, which embrittles the diffusion bonding transitional layer too. Carbon-tight, the copper spacer-foil located between niobium and steel does not allow forming niobium carbides. The relation between copper and niobium foil thicknesses is of 1.5 − 3.0 thereby initiating the failure on the base metal of the copper spacer-foil, which is responsible for stable strength properties and good ductility of the bimetallic joint obtained [6].

Ti6Al4V alloy / Fe18Cr10Ni1Ti stainless steel adapters (Figure 6a) were made of 50 mm-diameter HIP bimetallic bar-piece blanks followed by machining. The capsules each have 6 pairs of the piece blanks (Fig.7a). All the HIP diffusion bonding contact zones have 100%-densities and no ply separations and pores are observed. The diffusion width of the titanium-to-niobium contact zone is up to 35 μm (Fig.7b). The diffusion bonding width of the niobium to copper contact zone is up to 6μm without visible structural changes.


a



b

Fig.7 - Titanium-steel piece blanks (a), micrograph of the Ti6Al4V/Nb/Cu/SS joint [4] (b)

With diffusion from steel into copper, iron and nickel atoms diffuse into copper at the depth of up to 15 μm and 5 μm, respectively, of the visible contact line. The depth of copper diffusion into steel is observed up to 5 μm only. Thus the common diffusion width of copper-to-steel DW transitional layer reaches 20 μm. Room temperature tensile strength of the HIP diffusion bonding Ti6Al4V alloy-to-stainless steel is equal to 439 MPa. Ti6Al4V / stainless steel adapters have passed hydrostatic test at pressure of 7000 MPa / 700 bar. No leakage occurred.

Single-crystal molybdenum / polycrystalline molybdenum HIP Diffusion Bonding

Single-crystal molybdenum (Mo_{single}) is material of choice for producing the first mirrors of 200 mm x100 mm to be used in a diagnostics system for ITER Hydrogen Lines Spectroscopy [7]. Both the severe quality requirements and the complicated 250 mm-diameter blank technology determine very high price of the molybdenum single crystals. Therefore, a composite mirror design has been proposed. In this design, the reflecting part, produced from several parts of single-crystal molybdenum with the same orientation in the crystallographic planes, is joined by

HIP DW with the extra pure polycrystalline molybdenum (Mo_{poly}) of a relatively low price. The technology of joining the molybdenum single crystal with the base made of polycrystalline molybdenum should not cause recrystallization of the single-crystal molybdenum. The mechanical properties of the diffusion welded joint should be higher than the loads applied while mirror manufacturing (milling and turning, grinding, and polishing, etc.) and servicing. The HIP diffusion bonding between single-crystal molybdenum and polycrystalline molybdenum was achieved by the titanium foil interlayer of 0.1 mm thickness ($Ti_{0.1}$) [7]. The titanium and molybdenum form a continuous number of the solid solutions and therefore there is no danger of forming any embrittlement phases in the contact zone. Room temperature tensile strength of the HIP diffusion bonding $Mo_{single}/Ti_{0.1}/Mo_{poly}$ shows more than 380 MPa. Failure happens on a titanium foil interlayer and has viscous character. Loss of the mirror heat conductivity due to a titanium interlayer is less than 5 %. A sharply defined contact line and a visible homogeneous light transitional zone of ~ 5-10 μm thickness being a solid solution of molybdenum in titanium is observed on the both sides of the titanium foil interlayer within a diffusive zone of the $Mo_{single}/Ti_{0.1}/Mo_{poly}$ bonding (Fig. 8a). The composite single-crystal molybdenum mirrors with working surface area of 5000 mm^2 and 8000 mm^2 (Fig.8b) have successfully passed the tests carried out according to a special program, including tests in the conditions of heating to a temperature of 250 °C under hydraulic pressure up to 50 bar.

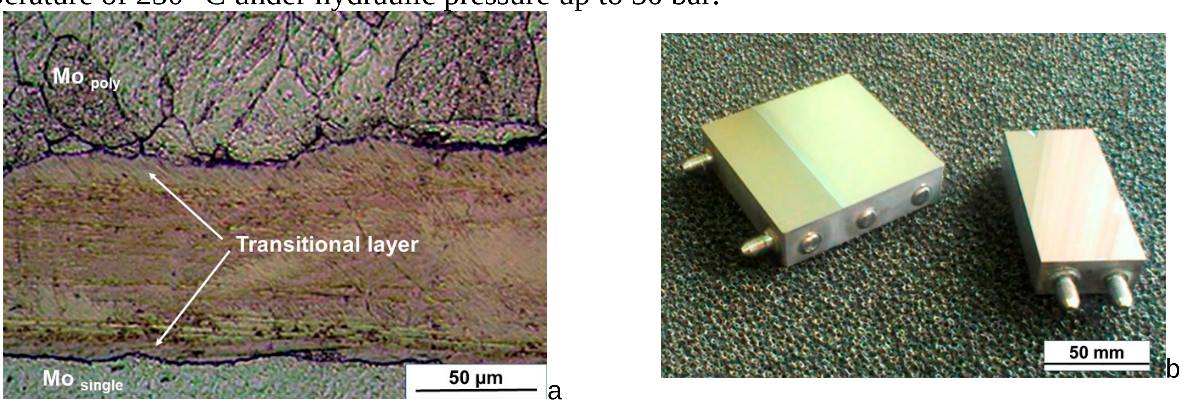


Fig.8 - Micrograph of $Mo_{single}/Ti_{0.1}/Mo_{poly}$ bonding (a) and experimental composite single-crystal molybdenum mirrors(b) [7]

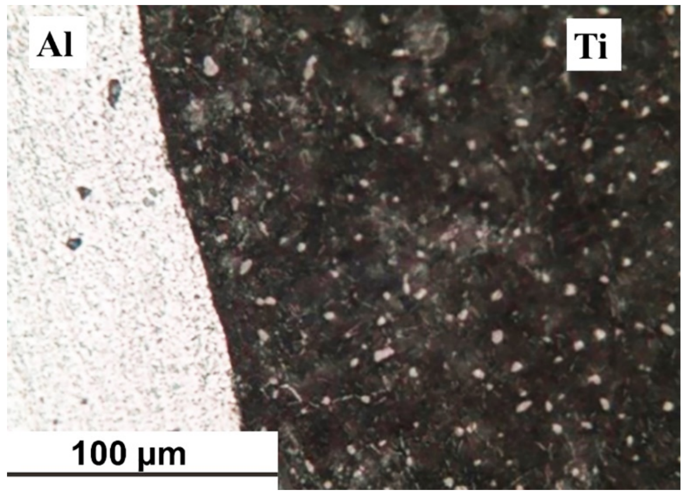
Titanium alloy / aluminum alloy HIP Diffusion Bonding

The fusion welding of bimetallic titanium alloy/aluminum alloy is impossible because intermetallic $TiAl_3$ and TiAl are formed in alloying zone at 1340 ^{0}C and 1460 ^{0}C, respectively. Ultimate solubility of titanium in aluminum is as low as 0.26-0.28 wt% and 0.07 wt% at 665 ^{0}C and at the room temperature, respectively. HIP DW allows for obtaining the titanium alloy-to-aluminum alloy bonding at a temperature of 500-560 ^{0}C without formation of the intermetallic in the contact zone. To increase the thin-walled bimetallic design serviceability it has been suggested that on the surface of titanium part a relief can be carried out as a thread profile having an identical radius of curvature equal to ½ height of the thread ledge with a base size equal to doubled height of the thread ledge [8]. The role of the relief is to obtaining a more developed surface in the contact zone and its activation due to intensity of the local shear deformation along the profile thread ledges and hollows and formation of the physical contact of the metals during HIP, which finally leads to an increase in mechanical properties and tightness. The existence of curvatures causes lack of stress concentration. The positive effect is reached when the relief

Materials Research Proceedings **10** (2019) 65-72 doi: http://dx.doi.org/10.21741/9781644900031-9

period quantity is not less than two of them on the bimetallic design wall thickness (Fig.9a). Shear strength of the samples with relief is 119MPa, which is twice higher than that of the joint without relief (τs =58 MPa). Intermetallic phases are not detected in the contact zone microstructure (Fig.9b).

a



b

Fig.9 – Bimetallic Ti-Al shear-test specimen (a), a micrograph of cross section of Ti-Al joint (b)

Conclusion

The HIP solid-state diffusion welding is a controlled production operation at all the processing stages. Unlike other known solid-state welding techniques the HIP allows for providing the strong and dense welded joint of stability properties despite the area and configurations of the contact surfaces of materials welded.

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