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Industrial Paper

Study on feasibility of the dissimilar 316L/Nb/Ti6Al4V WLAM clads

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Abstract

Wire and laser additive manufacturing technique was used for attempting the creation of dissimilar 316L/Nb/Ti6Al4V cladded assemblies. The binary clads of niobium wire on titanium (Nb/Ti6Al4V) and 316L (Nb/316L) substrates were produced and underwent three-point bending test. The Nb/316L clads suffered from a lack of adherence because of a high mismatch in fusion temperatures between the wire and the substrate. On the contrary, monopass and multipass Nb/Ti6Al4V clads were defect-free and resistant to the bending test up to 10 mm deflection for 100 mm long clad. The three-material assembly produced by depositing the 316L wire on the top of Nb/Ti6Al4V clad presented a complex microstructure and suffered from local crack formation. The EDS analysis of element distribution in Nb/Ti6Al4V and 316L/Nb/Ti6Al4V clads allowed establishing the mapping of the mixing processes and explaining the local embrittlement of the final product.

Keywords: titanium ; niobium ; stainless steel ; WLAM

1. Introduction

Titanium and stainless steels have good corrosion resistance, high mechanical properties and are biocompatible. Therefore they find a wide application in aeronautical, medical and chemical industries. To improve structural properties and reduce cost, it may be interesting to join them. However, they have important mismatch in thermal expansion coefficients (Table 1) and easily form brittle Fe_2Ti, FeTi and $Cr_7Fe_{17}Ti_5$ intermetallics (Pryadko & Ivanchenko (2008)) that makes their direct welding very delicate. To avoid these brittle phases, a popular solution consists in using an interlayer metal. Among commercially available Ti-compatible metals, only vanadium has adequate metallurgical compatibility with steel (Tomashchuk & Sallamand (2018)). It allows obtaining defect-free welds with joint coefficient close to 100%, however, it is expensive and not biocompatible, which prohibits its use in biomedical applications. Niobium is fully compatible with titanium, biocompatible and less expensive than vanadium. However, it has very low solubility in iron and forms brittle intermetallics Fe_7Nb_6 and Fe_2Nb (Lyakishev (1997)). Recently a 1 mm thick niobium interlayer was used in pulsed laser welding of 316L (Zhang et al. (2018) and Inconnel 718 (Gao et al. (2018)) to Ti6Al4V. In both cases, the formation of brittle intermetallics was limited to a thin reactive layer between 316L and niobium edges, induced by the heat conduction from the neighboring niobium/Ti6Al4V melted zone. The temperature at 316L/niobium interface exceeded the eutectic temperature of 1175°C, however, the creation of extended melting zone did not take place. The resulting joints presents an UTS of 370 MPa for steel and 145 MPa for Inconnel 718, with brittle fracture occurring in the reactive layer. Milder thermal conditions during the hot rolling of titanium and steel sheets with 0.5 mm thick niobium interlayer at 900°C prevented the accumulation of intermetallic phases and resulted in ductile fracture of the bimetallic assembly (Zhao et al. (2014)).

The industrial pieces welded by laser often have complex geometries, therefore the cutting of the inserts from a plate is costly. Laser assisted cladding of the intermediate materials in form of a wire on the one of joint edges

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allows avoiding material loss. In the present study, the possibility of production of 316L/Nb/Ti6Al4V assembly by the successive cladding of dissimilar fillers is investigated, in view of possible production of tubular joints.

Table 1. Thermal properties of materials.

Properties	Units	Ti6Al4V	Pure Nb	316L
Melting point /solidus - liquidus	K	1877-1933	2741	1663-1713
Boiling point	K	3560	5015	3013
Thermal expansion coefficient	10^{-6} K^{-1}	8.6	7.2	16.5
Thermal diffusivity	mm²/s	2.9	23.4	3.8

2. Materials and methods

The WLAM experiments were made at the Institut Maupertuis (Rennes, France) on the demand of SME Laser Rhône-Alpes. A Trumpf Trudisk 12002 laser source with 1030 nm wavelength, 12 kW maximum power, 600 µm fiber diameter and Precitec Coax Printer head with coaxial wire supply fixed on a FANUC M710iC/70 R30i-A robot were used (Fig.1). A box filled with argon was used for gas shielding. Niobium wire was cladded on a 3 mm thick plates of 316L stainless steel and Ti6Al4V titanium alloy. After successful niobium cladding on Ti6Al4V plate, a 316L filler wire was added on the top of niobium clad. The performed tests are summarized in Table 2.

Table 2. Experimental plan: summary of experiments and retained operational parameters.

Experiment	Summary of experimental plan	P (W)	V (m/min)	V_{wire} (m/min)
Nb clads on 316L plate	28 conditions, 3 attempts each. Poor quality clads.	1650	1 - 0.1	2
Nb clads on Ti6Al4V plate	24 conditions 3 attempts each, 12 multipass clads.	1750	1	2
316L clads on Nb/Ti6Al4V	4 attempts on the two-pass Nb/Ti6Al4V clad.	1750	0.8	2

Bending test in three-point configuration (Institut Maupertuis, Rennes, France) was performed on 10 mm wide and 100 mm long strips machined parallel to the cladding direction and turned upside down, with aim to evaluate the deflection of the center of the strip associated with detachment of the clad. Microstructure analysis (Laboratory ICB, Le Creusot, France) was made for four Nb/Ti6Al4V and 316L/Nb/Ti6Al4V assemblies using a scanning electronic microscope (SEM) JSM-6610LA (Jeol) equipped with an energy dispersive spectroscopy analyzer (EDS) operating at 20 kV acceleration voltage, whereas backscattered electrons micrographs were made at 10 kV.

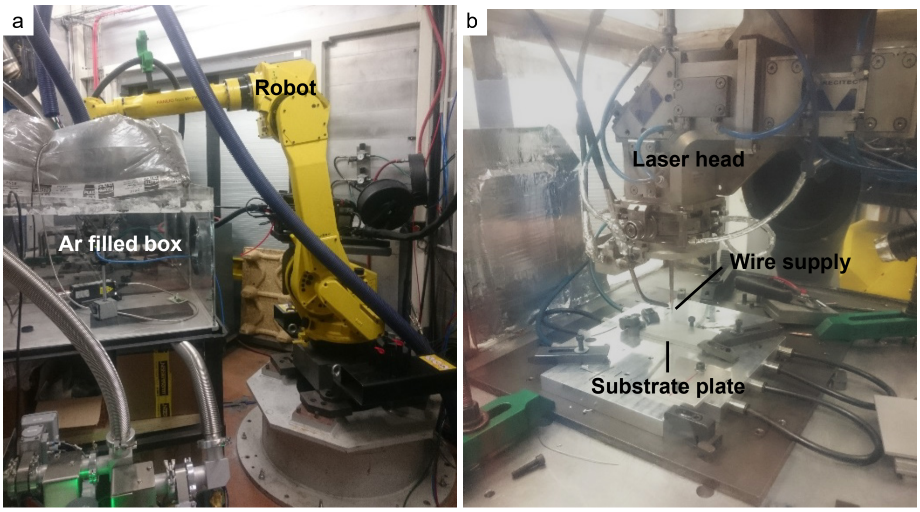

Fig. 1. Experimental setup: (a) external and (b) internal view.

3. Results and discussion

The cladding of niobium wire on 316L plate was delicate because of relatively high melting point and high thermal diffusivity of niobium compared to those of steel (Table 1). The use of high welding speed produced a non-uniform clads suffering from the loss of cohesion with the substrate. This defect is commonly called “cold drop”. After a high temperature metal drop falls on a cold plate, it is rapidly solidified without dilution in the substrate, resulting in a low quality assembly. The presence of an insulating oxide layer on the substrate surface is another problem to overcome in such a condition. On the other hand, the progressive decrease of welding speed led to a sudden excessive fusion of the substrate and the creation of highly heterogeneous and badly cracked melted zone (Fig. 2a). The accumulation of brittle Fe-Nb phases produced cold cracks over all region of tested conditions. Therefore, the idea of cladding of niobium on 316L plate was discarded.

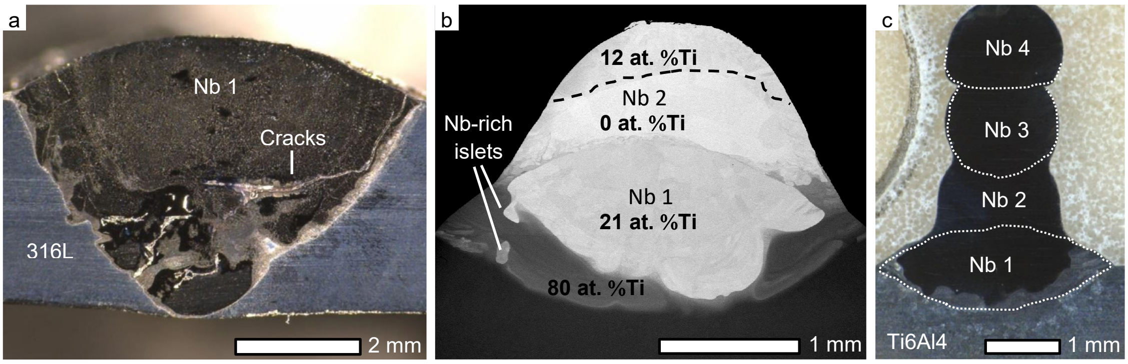

Fig. 2. (a) Typical niobium cladding on 316L plate (V = 0.1 m/min), (b) SEM image of two niobium layers cladded on Ti6Al4V plate, (c) four niobium layers cladded on Ti6Al4V plate.

Niobium has lower mismatch in fusion points with Ti6Al4V alloy compared to steel, which allowed correct deposition of niobium wire without excessive melting of Ti6Al4V substrate (Fig. 2b). The first pass (Nb 1) resulted in a strongly dissimilar melted zone, where the melted niobium containing 21 at. % Ti was surrounded by a thick layer of Ti-rich melt (~80 at. % Ti) at the bottom and thin Ti-rich layer on the top. The global dilution of the Ti6Al4V substrate was about 37 %, basing on the measurements of crosscut areas. Ti-rich zones contained fragmented Nb-rich islets with up to 85 at. % Nb. The second niobium layer (Nb 2) was correctly deposited on the first one, however, some mixing with the underlying Ti-rich regions took place. Whereas the bottom part of the Nb 2 clad was composed exclusively by pure melted niobium, the top of the clad contained a zone with 12 at. % Ti. This curious effect was observed repeatedly and can be explained by the difference in densities of liquid Ti and Nb. However, this mixing did not induce any metallurgical problems since the clads contained only (α+β Ti, Nb) dendrites of different composition. The two pass clads underwent bending test and resisted up to the displacement of 10 mm. The defect-free clads containing up to four niobium layers were successfully obtained (Fig. 2c).

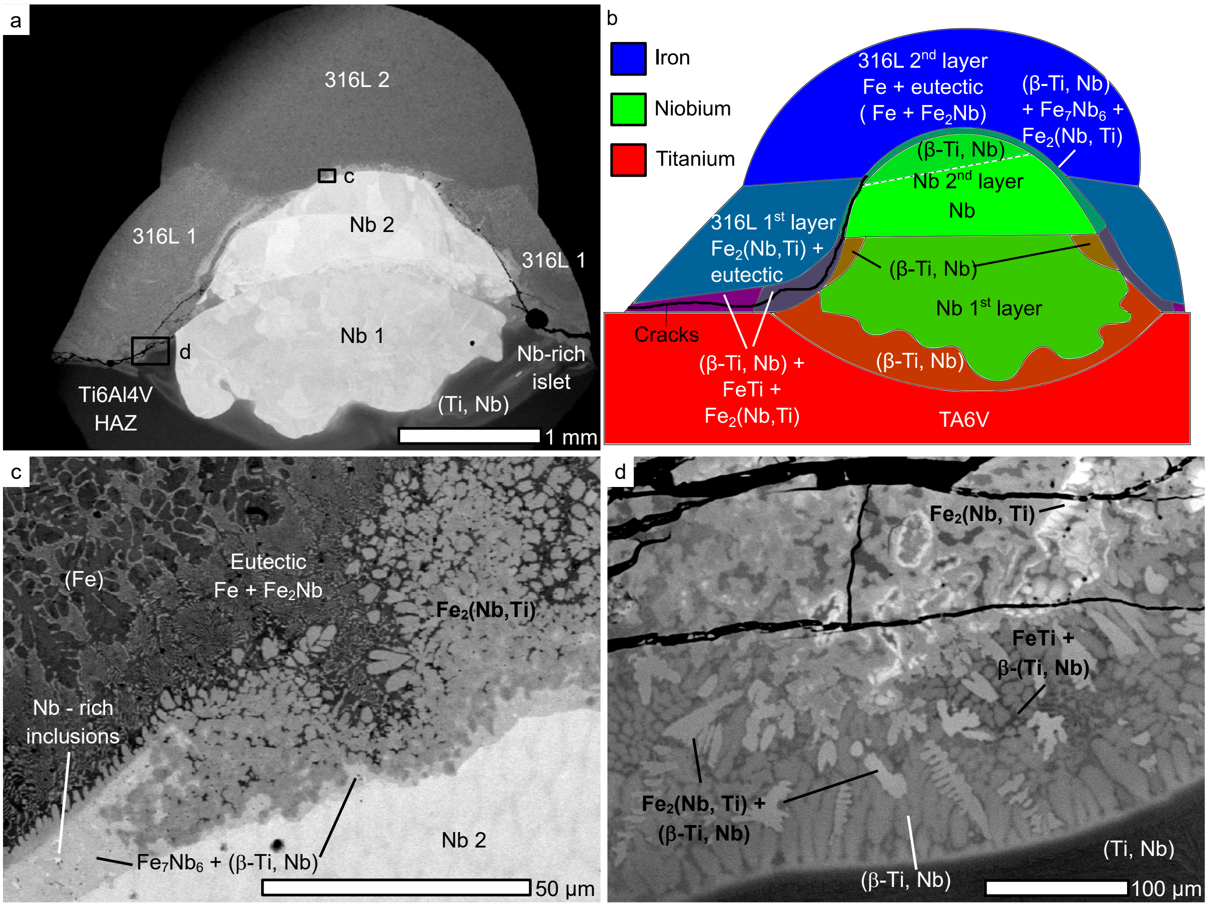

Fig. 3. Crosscut of cladded 316L/Nb/Ti6Al4V assembly: (a) general SEM view; (b) mapping of the mixing processes based on X-map and EDS; (c) reactive layer between 316L 2 and Nb 2 clads; (d) reactive layer between Ti-rich melt formed during niobium cladding and 316L 1.

Basing on these observations, it was concluded that for the production of a triple material assembly, it is preferable to clad 316L wire on the top of niobium layers previously deposited on Ti6Al4V. To create a triple assembly, two niobium layers deposited on Ti6Al4V plate were followed by two 316L layers (Fig.3a). Several crosscuts of the resulting assembly were analyzed. The map of the mixing processes based on EDS analysis is given at Fig.3b. During the deposition of the first 316L clad (316L 1), noticeable mixing zones developed next to the niobium core and Ti6Al4V substrate, and the average composition of 316L 1 clad reached 12 at. % Nb and 1-2 at. % Ti. The formation of macro-cracks was observed in the regions where 316L 1 collapsed around slightly remelted niobium clads and reacted with Ti-rich zone formed during niobium cladding. The second 316L clad (316L 2) remelted about 30% of 316L 1 and contained only 4 at. % Nb and trace amounts of Ti. Sometimes the cold cracks propagated up to Nb 2 / 316L 2 interface.

The interface between the Nb 2 and 316L 2 (Fig.3c) and the mixing zone between 316L 1 and Ti-rich melt (Fig. 3d) were analyzed. Some assumptions about the phase content and the causes of crack formation were made basing on binary phase diagrams (Lyakishev (1997)) and ternary Fe-Nb-Ti phase diagram (Shurin et al. (2006)). The first layer formed above Nb 2 clad (Fig.3c) was β-(Ti, Nb)+Fe_7Nb_6 eutectics with minor Nb-rich inclusions. At some places it was quite thin and followed by a large ramified layer of Fe_2(Nb,Ti). The surrounding 316L 2 clad was composed by Fe-rich dendrites and Fe+Fe_2Nb eutectics. The width of reactive layer was quite important (up to 50 µm), but it did not show excessive cracking. On the other hand, in the mixing zone between 316L 1 and Ti-rich melt (Fig. 3d), which contained Fe_2(Nb,Ti), FeTi and β-(Ti, Nb) phases, severe crack formation was observed. This can be attributed to a higher thermal stress near the Ti6Al4V substrate, due to the mismatch in thermal expansion coefficients of used materials, and to a harmful contribution of FeTi. These cracks were propagated down to the next layer composed by β-(Ti, Nb) cells, rare dendrites of Fe_2(Nb,Ti) and intergranular FeTi, however, they did not penetrate into the underlying (Ti, Nb) melt. The rest of 316L 1 clad was composed by Fe+Fe_2Nb eutectics and Fe_2Nb dendrites and was free from cracks. Therefore, it can be concluded that the cladding of first 316L layer is critical for the quality of this triple material assembly: the collapse of 316L down to the Ti6Al4V should be avoided through the creation of higher Nb multipass clad and by further optimization of operational parameters of 316L wire deposition.

4. Conclusions

The feasibility study demonstrated the possibility to produce good quality niobium clads on Ti6Al4V substrate, due to the absence of brittle phases in Ti-Nb system. The cladding of niobium wire on 316L plate was related with excessive melting of the substrate due to the important mismatch in melting points and the accumulation of brittle phases producing cold cracks. Therefore, for the creation of triple 316L/Nb/Ti6Al4V assembly it was necessary to clad niobium wire on Ti6Al4V and then add 316L wire, and not otherwise. The produced assembly presented a complex microstructure and suffered from local crack formation in the areas where the 316L clad collapsed on the sides of niobium clad and entered in contact with Ti-rich melt. The difference of thermal expansion coefficients induced the cracks along Ti-rich zones with accumulated Fe_2(Nb,Ti) and FeTi phases. Therefore, for the improvement of such triple assembly, it is recommendable to avoid all contact between Ti6Al4V plate and the 316L clad by the increasing of Nb clads height or by the limitation of fluidity of first deposited 316L layer.

Acknowledgements

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