MELTED ZONE MORPHOLOGY BY LASER WELDING OF TI-6AL-4V WITH X5CRNI18-10

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Abstract
Welding of dissimilar materials using high energy sources like Nd-YAG laser operated in continuous or pulsed mode presents applicative and scientific interest determined on the one hand by the localized energy contribution introduced in pieces and on the other hand by the high cooling speeds (short thermal cycle) which influences the kinetics of phases formation during solidification and the solid state transformations. The behavior by welding of these materials is often limited by the large differences of thermo-physical properties and chemical nature (solubility, formation of fragile phases, oxidation, etc).

The present paper aims the understanding of the mechanism which occurs by the mixing of the titanium alloy with the stainless steel using as intermediate layer a copper foil to obtain a laser weld joint with acceptable mechanical properties.

The particularities of the welded joints consist of low absorption coefficient of radiation by the solid metallic material and of the multiple reflection phenomena that occur in vapor capillary, which position, penetration and geometry determines the melted materials proportions and their mixing degree.

In this way, the melt zone is characterized both at macroscopic level in order to highlight the crucial role of the welding process and of the parameters on its morphology and on the chemical elements distribution, and at microscopic level to locate and identify the microstructure types formed during solidification.

Multiple observations, revealed by the used investigative techniques, have led to scenario hypotheses which permit the explaining of the chemical heterogeneity origin manifested in the melted zone.

Keywords:
laser welding, heterogeneous joints, microstructure, SEM-EDX chemical analysis.

1. INTRODUCTION
The fusion welding of the materials Ti-6Al-4V + X5CrNi18-10 can not be done directly because after the molten bath solidification are formed fragile intermetallic phases between Fe and Ti which can lead to cracking phenomena. In addition, intense oxidation phenomena of the titanium can occur if the protection of the molten metal bath is weak [1].

Therefore, laser welding technique was chosen using a continuous operation Nd-YAG apparatus and in order to reduce the proportion of unwanted intermetallic phases a copper foil, with the thickness of 600 μm, was intercalated between the two base materials for the minimization of the metallurgical incompatibilities specific to the heterogeneous joints.

2. EXPERIMENTS
The used Nd-YAG laser has a beam diameter of 200 μm and an argon gas protection system on both sides of the weld, the gas flow during the experiments was 15 liters/min.

For making butt joints with acceptable mechanical properties, one attempted to modify the chemical modification by adding in the molten bath of a copper foil. This metal is metallurgical compatible both Ti-6Al-4V and X5CrNi18-10 materials.

The laser beam position was shifted to the joint plan by 0.4 ... 0.6 mm on the stainless steel.
The used sheets had a thickness of 2 mm, and the welding process parameters were varied in range of the following limits: laser beam power, 3000 ... 4000 W, welding speed, 2 ... 3 m/min., linear power, 80 000 ... 120 000 J/m. The width of the molten bath was about 1...1.2 mm.

3. MACROGRAPHIC ANALYSIS

The copper used as intermediate layer acts as a thermal barrier for Ti-6Al-4V which limits the formation of intermetallic phases between Fe and Ti. Since the laser beam was shifted with the stainless steel, it is causing a meltdown mainly of it and the copper having good thermal conductivity will help the heat transfer to the liquid metal bath.

Figure 1a, b presents two images of the welded joint cross section observing that the weld is located in the stainless steel and the titanium alloy helps only slightly to its formation. At lower values of the linear energy one shows the formation of pores in weld (Fig. 1b).

![Fig. 1 Macrostructure of the welded joints: a- E_l = 80 000 J/m; b- E_l = 60 000 J/m](image)

4. TENSILE TESTS

Table 1 summarizes the results of the static tensile tests of the welded joints for two values of the linear energy. Breaking of the welded specimens occurred in an area closer to the titanium alloy.

The three base materials that have participated at the formation of the molten bath had the following values of the tensile strength:

- stainless steel, Rm = 632 N/mm²;
- titanium alloy, Rm = 1041 N/mm²;
- annealed copper, Rm = 210 N/mm²

<table>
<thead>
<tr>
<th>Linear energy, E_l, J/m</th>
<th>Experimental values, R_m, N/mm²</th>
<th>Average, R_m, N/mm²</th>
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<tbody>
<tr>
<td>80 000</td>
<td>319</td>
<td>328</td>
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<tr>
<td>60 000</td>
<td>289</td>
<td>268</td>
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<td>254</td>
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The microfractography of the adjacent area to the titanium alloy is shown in Fig. 2a, and to the stainless steel is shown in Fig. 2b.

The results of these tests show that the addition of copper in the molten bath causes a decrease in mechanical strength of the welded joints; the phenomenon being more pronounced by porous specimens and the breaking has a predominantly ductile character on both surfaces in contact.

![Fig. 2 The microfractography image of the tensile samples: a – adjacent area of the Ti alloy; b – adjacent zone of the stainless steel](image)

5. MICROGRAPHIC EXAMINATIONS, HARDNESS MEASUREMENTS AND XRAY DIFFRACTION ANALYSIS

To understand the mixing mechanism of the materials involved in obtaining of the weld, it has been approached some concepts concerning the dynamic of the capillary formation (Fig. 3) during the welding operation.

The dynamic effects which are generated by the laser-material interaction are very important, they occurring in very short time (order of milliseconds) and on very small sizes (order of millimeters).

a. Initiation of capillary

If the surface of a metallic material is irradiated by a laser beam (specific power being about $10^6$ W/cm$^2$), a part of the beam is reflected and another part is absorbed. Energy flow being often very high; the conduction can no longer ensure the evacuation of the transmitted energy. Consequently, the irradiated material melts and then the liquid evaporates itself. Vapor expansion generates a recoil pressure on the surface of the molten bath, which will create a depression and therefore decrease of the liquid thickness. Liquid-vapor interface is controlled to the interior of the material, facilitating the penetration of the laser beam inside the sample. Thus, there is an evacuation of the liquid to the bath edges. Accumulation of the fluid around the capillary produces the heating of the adjacent area and thus the widening melted zone (Figure 3).

b. Development of the capillary

During this phase, the incident energy which was incorporated will be partially redistributed in capillary by multiple reflections on the walls.

Such of phenomenon favorites the capillary penetration in the material, its growth being conditioned by:

- maintenance of the material vaporization (multiple reflections);
- a recoil pressure high enough to take the effects of surface stresses.
During the welding process, evaporation phenomena are partly responsible for the geometric evolution of the capillary. In the capillary background the recoil pressure pushes and directs the fluid along the capillary walls. The liquid is directed to the workpiece surface by convective motions, creating a vortex, a liquid crown which surrounds the capillary surface (Fig. 3).

c. Capillary filling and solidification

When the laser irradiation stops, the material does not receive energy anymore so that it can lead to rapid closure of the capillary and therefore a certain amount of vapor will remain included in it.

By cooling the melt, the solidification of the base material will occur based on conductive (in liquid and solid material) and convection (in the moving fluid) phenomena.

The microstructure resulted after solidification is extremely complex. Due to small volumes of molten material and of the high cooling speeds, the phenomena of microsegregation and fragile phases formation will be limited.

In Fig. 4 ... 6 are shown some typical microstructures of the welded joints which showed the highest values of the static tensile strength.

- the dark area on the interface Ti-6Al-4V and welding consists mainly of Cu$_2$Ti phase and a small proportion of FeTi phase (Fig. 4)
- stainless steel inclusions as polygonal shaped in the hardened Cu area by precipitation of some Fe$_2$Ti phase particles (Fig. 5);

- interface between the central zone of the weld and the adjacent molten stainless steel area has a heterogeneous microstructure with molten steel drops built-in hardened Cu with phase particles Fe$_2$Ti and Cu splashes in the mass of the steel (Figure 6);

- weld seam near the stainless steel is composed from a solid solution of Cr, Ni and Cu dissolved in Fe (Fig.6) with extremely fine dispersed particles of secondary phases.

Explaining of the complex weld morphology is based on specific phenomena of rapid solidification process. Since Ti has the highest fusion temperature (1725 °C), initiating of solidification occurs on the interface between Ti-6Al-4V and molten bath.

The second area which begins to solidify itself is the melted zone of stainless steel (melting point of Fe = 1538 °C), with round or polygonal islands from the center of Cu, due to its limited solubility in Fe.

The high Cu concentration beside its gamma type character and the high cooling speed stabilizes Fe$_\gamma$ to room temperature.

According to Fe-Ti equilibrium diagram at 1427 °C is initiated Fe$_2$Ti phase formation and at 1317 °C the FeTi phase appears at the edge of the nodular inclusions, on the interface between Ti alloy and the molten bath and also in the liquid rich Cu areas.

Then, begin the solidification of the Cu rich zone of the weld. The solubility of Fe in Cu is about. 4% at a temperature of 1100 °C and by rapid cooling the diffusion is slowed and therefore the hardness of that welded zone will increase.

For the Ti-Cu equilibrium diagram result that at the 1005°C is formed the Ti$_2$Cu phase and at 982 °C begins the precipitation of TiCu phase.

The scanning electron microscopy investigation of the local chemical composition of a weld zone between the Cu foil and the Ti alloy (Fig.7) confirms the role accomplish by the Cu presence by limitation of the diffusion phenomena of Fe, Cr and Ni in the Ti alloy and also of the Ti diffusion in austenitic stainless steel.

In addition, the shifting of laser beam position to the stainless steel minimize the mixing of the three materials, and the Cu low absorption coefficient of the laser wavelength leads to the formation of enriched stainless steel welds.
The X-ray diffraction (Fig. 8) permitted the identification of all phases present in welding and confirm the formation of these.

![X-ray pattern of the heterogeneous weld Ti-6Al-4V+Cu+X5CrNi18-10](image)

**Fig. 8** X-ray pattern of the heterogeneous weld Ti-6Al-4V+Cu+X5CrNi18-10

6. **CONCLUSIONS**

Using of a copper foil, with the thickness of 600 μm, as intermediary layer occurs by reducing the proportion of FeTi and Fe₂Ti intermetallic phases and the formation of TiₓCuᵧ phases is compensated by high ductility and toughness of Cu which leads to acceptable strength characteristics.

The laser beam shifting on the stainless steel limits the participation of the Ti alloy at the weld formation, and the Cu low adsorption coefficient by the laser beam causes the formation of a high stainless steel enriched weld.

**ACKNOWLEDGEMENTS**

This work was partially supported by the strategic grant POSDRU/1.5/S/13 project ID 6998/2008, cofinanced by the European Social Fund – Investing in People within the Sectoral Operational Program Human Resources Development 2007-2013, and Grant No. 166/05.10.2011, PN-III-PCE-2011-3-087 Exploration System for Optimization of Shape Memory Actuation in Compositional Spreads

**LITERATURE**


