To cite this version : Ferdinand, Cyrille and Alexis, Joël and Masri, Talal and Petit, Jacques-Alain and Ganza, Jean-Christophe Characterization of refractory titanium alloys welded by TIG and laser processes. (2007) In: 11th World Conference on Titanium, 03 June 2007 - 07 June 2007 (Kyoto, Japan).

Characterization of refractory titanium alloys welded by TIG and laser processes

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The use of refractory titanium alloys for the components of structure subjected to increasing temperatures is in full expansion in the air transport. Within the framework of European project HORTIA, aiming to develop and design a conduit of refractory titanium alloy helicopter by associating innovative processes and the industrial constraints, this work relates to the implementation and characterization of Ti6242 and Beta-21 S welded sheets by TIG and $C0_2$ laser processes. The determination of the mechanical characteristics in connection with the metallurgical transformations relating to the Ti6242/Ti6242, Beta 21S /Beta 21S and Ti6242/Beta21S assembly configurations allowed a rigorous comparison of the processes and studied materials. The influence of the heat treatment 600°C/8h on the relations structures/mechanical properties was also studied in order to envisage the behaviour of the assemblies under the real service use conditions.

Keywords: Refractory Titanium Alloys - TIG and laser process welding - Aeronautical applications - Structure/mechanical properties relationships

1. Introduction

The present study has been developed into the European sponsored HORTIA project (Heat and Oxidation Resistant Titanium Alloy Applications) with a direct application of the research studies on a full scale exhaust nozzle manufacturing in titanium alloys applied to helicopter engine. For effective integration of Ti6242 and Beta21S alloys into some structural components, homogeneous weld beads have been performed with both gas tungsten arc welding (GTAW) and laser beam welding (LBW) processes in order to anticipate the weld bead characteristics in the HORTIA mock-up. Laser beam welding of titanium alloys is more and more applied in the aeronautical industry especially for lightweight structures because of many advantages compared to conventional GTAW, due to highest welding speeds and high energy density. This welding process provides narrowest weld-seams, least deformations and finest grain structures which improve mechanical characteristics and ductility. To compare the welding processes and the assemblies'behaviours [1], the structures/mechanical properties relationship of the welded joints were studied.

2. Experimental procedures

Ti6242Si and Beta21S alloys were provided by TIMET Co. After rolling in the α/β field, Ti6242Si sheets are recristallized in the α/β field at 900°C during 30 min, followed by a second annealing (15 min - 785°C) to decrease the size and the proportion of β grains. The microstructure is characterised by equiaxed α grains (size approximately 20 µm), with β grains in small quantity located at the triple points of the α grain boundaries. The Beta-21S alloy sheets, with nominal chemical composition Ti-15Mo-3Al-2.8Nb-0.3Fe-0.2Si-0.13O (weight percent), were provided in the solution heat treated condition (843°C – air cooling). The microstructure includes β equiaxed grains (size 40 µm) with slight grain boundary alpha layer precipitation. The Ti6242 as well as Beta21S were assembled in homogeneous and heterogeneous configuration. Prior to welding, the samples were chemically pickled to remove any oxide layers. Autogenous, full penetration automatic GTA welds were produced with a pulsed continue currant and straight polarity, in a bead-on-plate preparation. The laser welding was initiated and developed within the Exameca company, with a CO_2 TRUMPF laser machine. The characterizations of the assemblies and base materials were carried out also after a post welding heat treatment at 600°C during 8h under argon atmosphere with and air cooling. Many former studies [2] [3] [4] showed that, whatever the process of welding, this heat treatment improves the mechanical characteristics of the weld beads of β-metastable titanium alloys while preserving an acceptable ductility.

Microhardness of the weld bead cross sections were measured along the different zones. Transversal tensile tests at room temperature were conducted on weld beads, to evaluate the tensile strength at a 10^{-3} s^{-1} strain rate. In order to define the mechanical properties of the fusion zones for each type of assembly, longitudinal microtensile tests were carried out on 3 samples. The deformation was observed under optical microscope. Following these tests, scanning electron microscopy observations of the fracture surfaces were carried out, in order to connect the mechanical characteristics to the mode of rupture.

3. Results

3.1. GTA Welding

3.1.1. Rough beads

Ti6242 GTA weld beads show microhardness values increasing from the heat affected zone (360HV), of approximately 3 mm width, until the centre of the fusion zone (400HV). This change is consistent with the increasing formation of thinner transformed β phase (lamellar α/β phase) while approaching the fusion line. In fusion zone (FZ) the Widmanstätten structure leads to an average hardness of 410 Hv. The β21S heat affected zone (HAZ) width (4.5 mm) is larger than that of Ti6242. The hardness is homogeneous along the β21S GTA weld bead with an average value of 310 Hv. The enlargement of the β grains, which was noted in optical microscopy while approaching the fusion line, does not involve significant variations of hardness. In the heterogeneous assembly, β21S base metal and HAZ hardness is the lowest, whereas the hardness in the Ti6242 HAZ is the most important. In fusion zone, hardness is overall constant with specific variations due to the composition variations in alloy elements. Low hardness, with values ranging between 315 and 340 Hv, in spite of the smoothness of the microstructure, indicates the formation of the α'' phase to cooling. Microtensile transverse tests confirm the results of microhardness tests (figure 1). All the ruptures were localised in base metal, indicating a mechanical strength of the weld beads higher than that of the base metal. The elongation at failure of the welded samples is lower than that of the base materials for identical strength. The GTA weld beads have a transverse lengthening lower than that of the base metal.

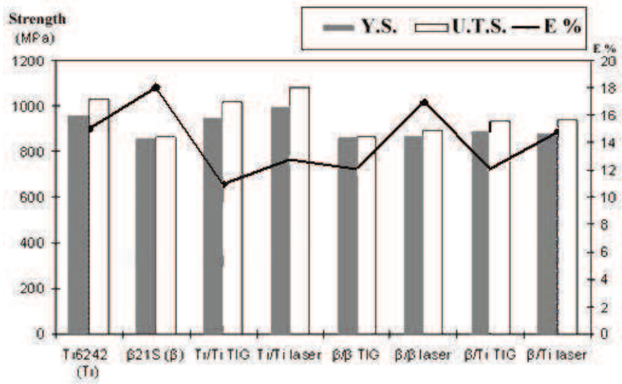

Figure 1. Transverse mechanical strength and ductility of the samples welded by TIG and laser processes.

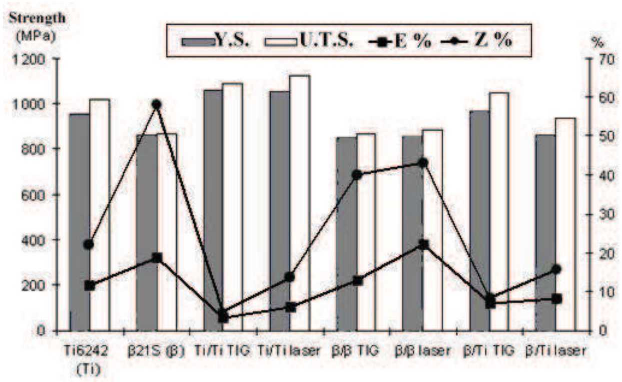

Figure 2. Longitudinal mechanical strength and ductility of the samples welded by TIG and laser processes.

The mechanical strength $Y.S_{0.2\%}$ and U.T.S of the cords in the longitudinal direction are shown in figure 2. The transgranular fracture surface of the two materials show a ductile behaviour marked by the presence of microvoids larger in β21S than in Ti6242 (figures 3 and 6).

The GTAW Ti6242/Ti6242 fusion zone made up of a α/β lamellar structure has mechanical strengths slightly higher than those of the base metal of equiaxed structure. Furthermore, the increase in the grains size and the Widmanstätten intragranular structure involve a fall in ductility. The fusion zone fracture face shows a transgranular rupture mode (figure 3a). Despite zones with a faceted fracture appearance are observed at the centre (random and discontinuous presence of α phase to the ex-β grain boundaries), the observation of equiaxed cups at a higher magnification indicates a microscopic dimple fracture. In β21S/β21S fusion zone, the increase in β grains size causes a reduction in elongation at fracture without generating changes of area reduction. This is confirmed by the dimple fracture similar to the base metal one but with larger cups (figure 3b). The mechanical strength is the same as for the base material. In mixed β21S/Ti6242 fusion zone, yield stress, microhardness, as well as elongation at failure, are equal to the average of those of the homogeneous assemblies. The fracture surface shows broad ductile zones at macroscopic scale with some faceted areas. These zones contain equiaxed cups indicating microscopic ductility (figure 3c). The rupture mode is overall transgranular with partial intergranular ruptures due to the local presence of soft α phase at the ex-β grain boundaries.

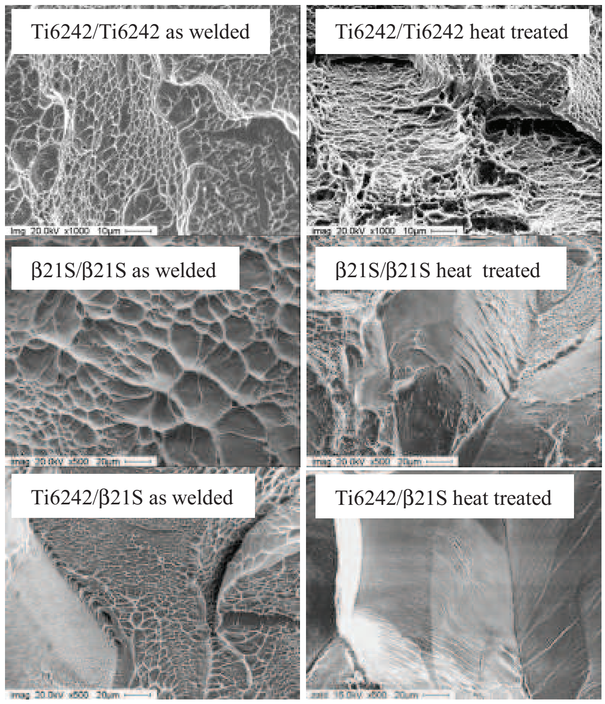

Figure 3. Fractographies of the fusion zone welded by process TIG.

3.1.2. Heat treated weld beads

As for weld joints in the as-welded condition, a continuous and progressive increase in hardness occur from the heat affected zone to the fusion zone. The heat treatment of Ti6242 does not imply any increase in hardness of the base metal in spite of the formation of transformed β phase within the previous β grains. On the contrary, average hardness in HAZ and FZ (425Hv) is slightly higher than in the as-welded condition (410Hv in ZF). This increase can be due to the ageing of α' martensitic phase present initially in small proportion in the fusion zone. The hardness increase is homogeneous in the β21S/β21S weld bead after heat treatment contrary to the as-welded weld joint. The average hardness of base metal (360Hv), HAZ and FZ (370 Hv) is associated to the precipitation of α phase increasingly fine and homogeneous while approaching the fusion line. Heat treatment of β21S/Ti6242 GTA weld beads leads to a hardness increase in fusion zone (450HV) whereas in HAZ the hardness values are the same as for the heat treated homogeneous assemblies. This can be explained by a very fine α/β phase precipitation coming from the decomposition of the α" and retained β phases. In a general way, the failure of the heat treated samples occured in base metal. The weld beads show mechanical strengths higher than base materials associated to a lower ductility. In agreement with the increase in hardness and structure transformations previously observed, the heat treatment 600°C/8h of the alloys β21S and Ti6242 involves an increase in the mechanical strength associated with lower ductility.

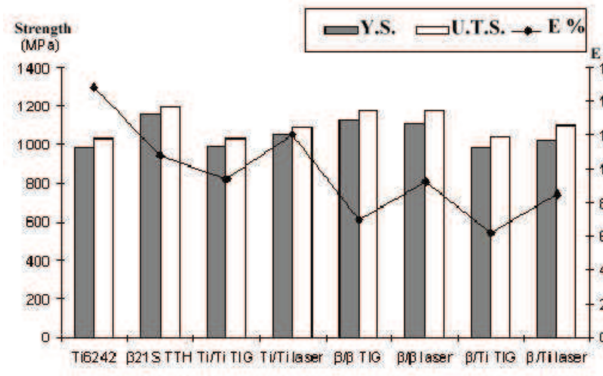

Figure 4. Transverse mechanical strength and ductility of the heat treated samples, welded by TIG and laser processes.

These variations are less marked for Ti6242. The rupture of HT Ti6242 shows a ductile surface characterized by the presence of many cups. The fracture surface of HT β21S also presents many finer cups. This is associated a brittleness with the grain boundaries which can come from the presence of phase α coarse softer than the structure of the matrix. During the tensile test, the incompatibilities of slip between the α phase with the grain boundaries and the harder matrix, involve the formation of microvoids at these joints and an intergranular rupture. Heat treated Ti6242/Ti6242 GTA weld bead has got mechanical characteristics similar to in as-welded condition but a lower ductility than the base metal.

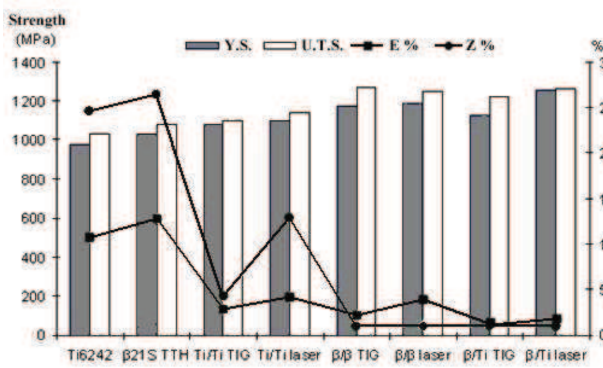

Figure 5. Longitudinal mechanical strength and ductility of heat treated cords welded by process TIG and laser processes.

The fracture surface shows facets with equiaxed and lengthened cups, indicating a transgranular ductile rupture mode, with also intergranular cleavage which is consistent with the presence of α phase at the grain boundaries (figure 6d).

After heat treatment the β21S/β21S weld fusion zone has got also mechanical strengths higher than the base metal and in as-welded condition ones, because of extremely fine precipitation of lamellate α phase. Very low ductility (Z<1%) is explained by a rupture which is carried out mainly by transgranular cleavage (presence of rivers of deformation) associated with a partial intergranular rupture, with also localised ductile zones (figure 6e). The mechanical strengths of the β21/Ti6242 weld fusion zone are similar to the β21S/β21S weld one but with lower ductility. The fracture surface highlights a purely brittle behaviour with transgranular cleavage characterized by rivers of deformation within the cleaved grains (figure 6f).

3.2. Laser welding

3.2.1. Rough beads

For homogeneous Ti6242/Ti6242 weld beads, the microstructure changes in heat affected zone involve a steady increase in hardness compared to base metal (400 to 440 Hv in ZAT and 360 Hv in base metal) and then a stabilization in fusion zone corresponding to α' acicular structure formation. Hardness in fusion zone is higher than the one of GTA weld bead of mainly α/β lamellate structure. β21S/β21S laser weld hardness shows a slight steady increase through the various zones of the bead, with an average hardness of 310 Hv in HAZ and 320 Hv in FZ. The width of the heat affected zone (1.8mm) is higher than that of the Ti6242/Ti6242 welding (0.8 mm). The hardness variations in heat affected zone of β21S/Ti6242 laser weld bead are similar to those observed for the homogeneous laser welds. The retained β phase in β21S base metal and HAZ shows the lowest hardness value whereas the α' phase in the Ti6242 HAZ has the most important one. In spite of a very fine structure, the low hardness measured in fusion zone (335-360Hv) confirms the formation of α" orthorhombic phase with weak mechanical properties, which was formed during the β phase decomposition to cooling. As for the GTA weld beads transversal tensile tests, all the laser weld beads failed in base metal, indicating the good weld beads quality (figure 1). The mechanical properties test results are given in figure 3. The α' martensitic structure in Ti6242/Ti6242 laser fusion zone involves an increase in the mechanical strength and a fall in ductility. The mechanical characteristics are higher than those of the GTA weld fusion zone, which presents more ex-β coarse grains and a mainly α/β lamellate microstructure. The fracture surface shows a faceted appearance with transgranular ductility and stripping at the grain boundaries (figure 11a). The β21S/β21S laser weld fusion zone presents better mechanical properties than the base metal and GTA weld beads ones. The fracture surface is wholly ductile and similar to base material one (figure 11b). β21S/Ti6242 weld bead fusion zone presents mechanical strengths intermediate to those of the homogeneous welds and ductility corresponding to that of the Ti6242/Ti6242 laser weld. The rupture surface presents a mainly transgranular ductile appearance with localised zones of cleavage (figure 6c).

3.2.2 Heat treated beads

The heat treatment of the Ti6242/Ti6242 laser weld bead involves a slight increase in HAZ and FZ hardness (average of 450Hv). This increase is associated with α' acicular structure transformation into fine α/β plates. The hardness variations in the heat treated β21S/β21S weld bead are not very different from those observed in GTA weld beads. Hardness increases in all the weld bead zones associated with fine α phase precipitation (average hardness of 370Hv in FZ). In heterogeneous heat treated β21S/Ti6242 weld fusion zone, hardness increases from HAZ of β21S to HAZ of Ti6242 with an hardness in the center of the FZ of 425 Hv. This variation correspond to the transformations α'' ⇒ α +β and β retained ⇒ α +β which take place through the various zones of the fusion zone. However, this hardness remains lower than that one of the Ti6242 HAZ close to the fusion zone (α' ⇒ α +β) in spite of a finer precipitation. The rupture of the welded samples in base metal shows that the heat treatment of 600°C/8h do not weaken the molten metal zone. In transverse tensile tests, the composite area (BM, HAZ and FZ) of the heat treated β21S/β21S laser assembly shows higher ductility than the HT Ti6242/Ti6242 laser weld one (figure 4). After heat treatment, the mechanical strength of the Ti6242/Ti6242 laser weld fusion zone increases to the detriment of ductility. This variation is associated with the transformation of the α' phase into very fine α/β lamellate structure.

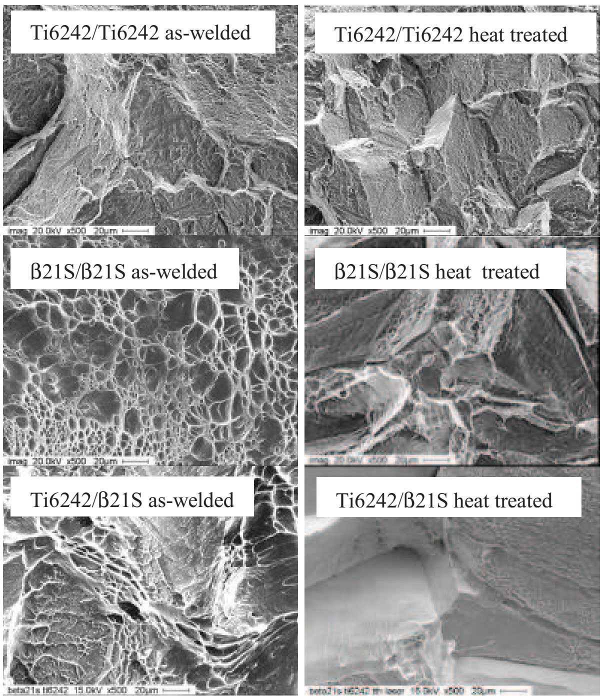

Figure 6. Fractographies of the fusion zone welded by laser process.

The fracture surface is overall transgranular and reveals plans of cleavage associated with partially intergranular ruptures. At microscopic scale, cups are observed inside the facets, indicating a rather ductile mode of fracture (figure 6d). For the β21S/β21S laser weld fusion zone, the heat treatment causes the fine and homogeneous precipitation of incoherent α phase within the grains, which increases the mechanical strength and decreases ductility by blocking the movement of dislocations. Although at a macroscopic scale, the observation indicates mainly intergranular fracture, at higher magnification the rupture surface reveals some bands of ductility (figure 6e). The heat treatment of the heterogeneous laser weld caused a fall in ductility and a rise of the mechanical strength comparable to the heat treated β21S/β21S weld fusion zone one, which is consistent with the decomposition of α'' phase in very fine α/β phase. The fracture surface presents a brittle cleavage appearance associated with intergranular rupture. Very locally, and at higher magnification, some ductile bands are observed (figure 6f).

4. Conclusion

The study of the structures/mechanical properties relationship of the GTA weld beads of Ti6242 and β21S alloys, made it possible to highlight the changes of assemblies characteristics after post welding heat treatment of 600°C/8h (under argon atmosphere). This heat treatment, used initially to stabilize the microstructure and the mechanical properties of β21S weld bead, also involved modifications of the properties of the weld bead TIG Ti6242/Ti6242 and important transformations for β21S/Ti6242 GTA weld. The mechanical tests showed that the β21S/β21S laser weld beads present a better compromise strength/ductility than the GTA weld beads, even after heat treatment. The post heat treatment accentuated the fall in ductility in the fusion zone compared to the base metal one by the precipitation of α phase. The Ti6242/Ti6242 laser welds show also mechanical characteristics higher than those of GTA welds even after heat treatment. The properties of the base metal Ti6242 are not affected significantly by the 600°C heat treatment. On the other hand this heat treatment decreases the ductility of the FZ because of the transformations of martensitic α'phase.

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