Mechanical characterization of hybrid welded titanium joints

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ABSTRACT. Fatigue behavior of hybrid welded joints made of titanium alloy grade 5 (Ti-6Al-4V) has been experimentally investigated. Fatigue data have been analyzed in order to study the influence of cord geometry (as-welded specimens have been compared with erased ones). Fatigue curves have been plotted both in terms of local strain amplitude and nominal stress amplitude. According to the WELFARE method, electrical strain gages have been bonded at the weld toe in order to measure the local strain amplitude as representative parameter of fatigue damage. Experimental results show that the fatigue strength is highly dependent from microstructural variations, and especially from defects and imperfections due to the welding process. Titanium welded joints fatigue strength is much more higher than classical materials such as steel, but internal porosity and external macro-defects, like fused material drops, definitely decrease mechanical characteristics and the fatigue life of titanium welded joints.

INTRODUCTION

Many parameters related to the manufacturing process affect the fatigue behavior of welded joints. The thermal cycle of welding makes changes in the microstructure of the material thus inducing a fragile behavior. Moreover, the thermal gradient developed during the process generates meaningful fields of residual stresses, distortions and misalignments. Finally, the global and local geometry of the weld seam modify the stress field [2]. Fatigue behavior of steel and aluminum alloy has been widely studied in the past due to the large use of these materials. Recently aerospace, automotive and naval industries have begun to use titanium alloys for applications, which require a high strength/weight ratio. Titanium alloys have the strength of the best classes of steel but a halved weight, high corrosion resistance comparable with platinum, fusion temperature near to the refractory materials and perfect biocompatibility [1]. The elevated reactivity with atmospheric gases makes the welding operation particularly delicate, but new interesting applications about the possibilities of use of welded joints have been recently developed. However a complete literature on the mechanical response of titanium joints still does not exist and also the official standards are too much recent.

The aim of the present work is the experimental study of the fatigue strength of butt welded joints made of titanium grade 5 with plate thickness of 5 mm (about 20 specimens have been tested). Fatigue curves have been plotted both in terms of local strain and nominal stress amplitude. The stress field close to the welded toe has been investigated in order to verify how the microstructure variations and the defects related to the welding process may change the mechanical response of the components. The quality and the reliability of the welding process parameters should be optimized in view of the present results.

METHODS AND MATERIALS

Butt plates welded by means of hybrid technique, that combines the laser and MIG processes, have been studied. Specimens have been obtained from plates made of titanium grade 5, welded without filler metal and without gap between the welded plates. Specimens have a nominal thickness of 5 mm, width of 40 mm and length of 348 mm.

The welding cord has orthogonal direction to the longitudinal axis of the specimen and to the direction of the applied load. Fatigue tests have been performed with load ratio R=0,1. A preliminary visual inspection has been carried out on each joint and it has shown, in some cases, the presence of macroscopic defects on the cord or close to it, like slobbers or spots of fused material.

Fatigue tests have been executed on a resonance testing machine with frequency of 80 Hz. Strain gages bonded according to WELFARE guidelines [3-4] have been used in order to measure the local strain close to the weld toe.

ANALYSIS OF THE RESULTS

Experimental results on Ti grade 5 butt welded joints are summarized in Fig. 1. It can be observed that the slope of titanium fatigue curve is very low: a local strain amplitude of 1000 $\mu\varepsilon$ indicates a fatigue strength of about $8\cdot10^5$ cycles.

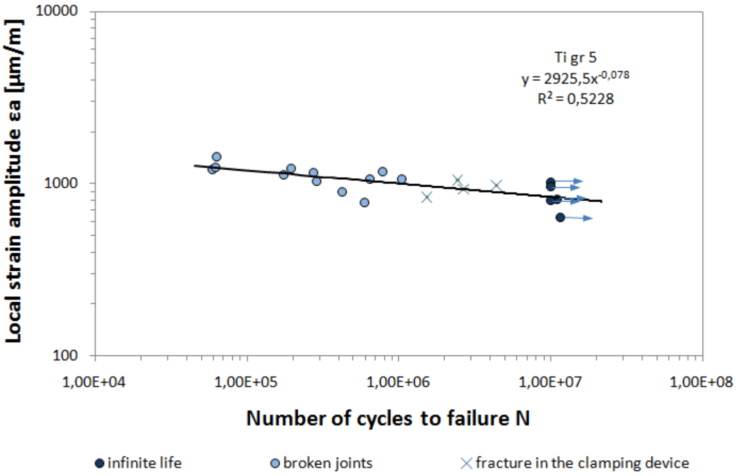

Figure 1: Fatigue curve (ε_a-N) of Ti grade 5 hybrid welded joints.

Fig. 2 shows fatigue data in terms of nominal stress amplitude. It can be observed that the slopes of fatigue curves both in terms of local strain (ε_a-N) and nominal stress (traditional σ_a-N Wöhler curve) are very similar, this indicating that local effects, in the case of titanium welded joints with respect to traditional steel ones [4-5] does not have a relevant role. Titanium welded specimens in fact have a very slight misalignment and a regular weld cord.

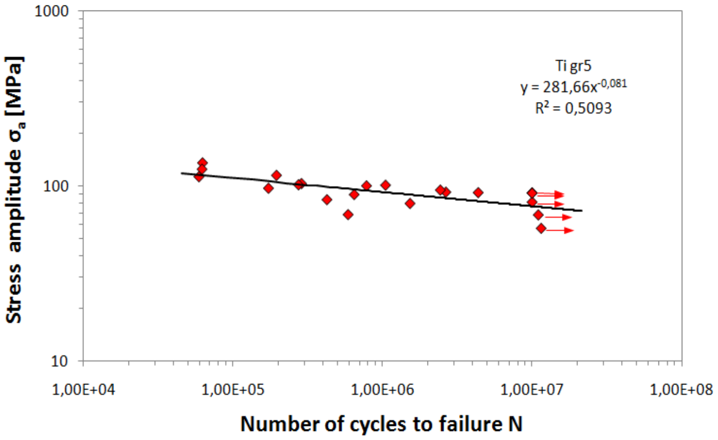

Figure 2: Fatigue curve (σ_a-N) of Ti grade 5 hybrid welded joints.

Four modalities of final fracture have been observed (Fig. 3):

- ✓ fracture due to the presence of a spot of welding near the cord;
- ✓ fracture due to inclusions or porosity inside the cord;
- ✓ fracture started from irregularities of the cord (drop or swell);
- ✓ fracture at the weld toe in absence of macrodefects.

Fracture close to the clamping device have not been considered.

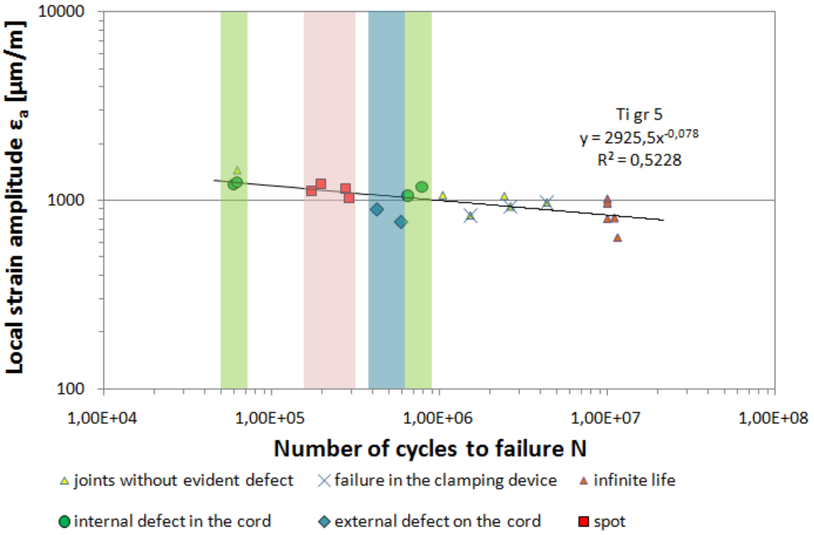

Figure 3: Kind of fracture and bands of life duration seen in the examinated specimens.

It is worthy noting that for some specimens, small superficial spots have been eliminated through filing, however that operation has not been possible for the spots of greater dimensions because of the hardness of titanium. It has been also observed that specimens without evident defects, submitted at similar level of load, and therefore at the same local strain ε_a, reach a life time higher than the ones that present defects.

Figure 3 shows that specimens with the same type of welding defect experienced a similar fatigue behavior and a very similar fracture mode.

In case of presence of spots (*Fig. 4a*) the fracture line is always parallel to the cord and perpendicular to the direction of the applied load. Observing the cross section where fracture occurred, that is in correspondence of the spot, it can be seen a different color of inside material compared with the silver gray of the remaining section, due to material alterations produced by the contact with the very hot drop of welding. Specimens with spot defects have shown in any case a fatigue life less than $3\cdot10^5$ life cycles (Fig. 3).

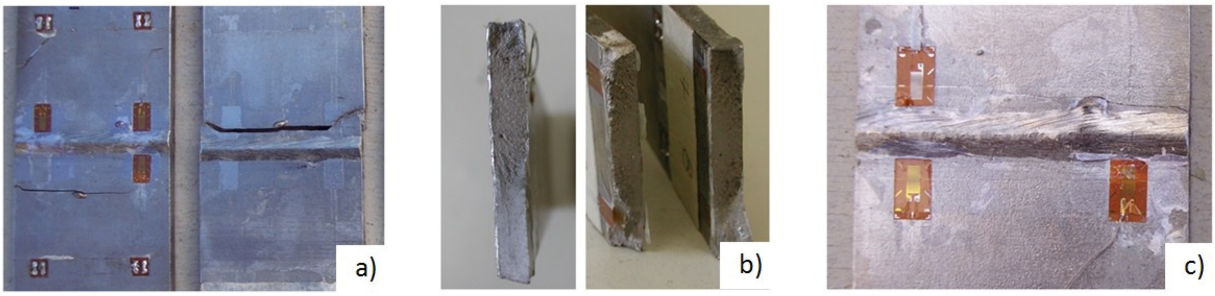

Figure 4: a) Fracture due to a spot of welding; b) Spherical cavities in the fracture section; c) Irregularities of the cord.

Fractures caused from the presence of superficial spots are absolutely unexpected, because this type of defects, very common also in steel welded joints, generally does not represent a serious risk of failure. Hypothesis have been made on the causes of an embrittlement in the zone under the spot but an analysis to the microscope and a further investigation is still necessary about this type of defect.

Inner macro-defects to the cord (Fig. 4b) represent also a weak point for welded joints. The presence of many spherical cavities of variable diameter (also till 0,5 mm) caused from an imperfect protection with gas of the fused material has been observed in many zone inside some specimens. Two different bands can be plotted (Fig 3), the first is in a range of $4 \cdot 10^4$ - $6 \cdot 10^4$ cycles and the second is in a range of $5 \cdot 10^5$ - $8 \cdot 10^5$ cycles. This might be due to different dimensions of pores or different kinds of inclusions. The decrease of fatigue strength is connected not only with the action of pores as geometric stress concentrators, but also depends on the reduction of the ductility close to the pore due to the several-times decrease in hydrogen content in it [6].

Another external macrodefect due to an imperfect welding process is the presence of a slobber on the cord (Fig. 4c). This defect is a stress concentration point from which a fracture line parallel to the cord could start and expand. This type of welding defect results to be the most dangerous (life duration of the tested joints does not exceed $6 \cdot 10^5$ cycles even if measured strain are very low).

CONCLUSIONS

Experimental fatigue data have been expressed in terms both of local strain fatigue curves and nominal amplitude of stress. It has been observed that there is a strong relation of the fatigue behavior with the quality of welding. Different type of defects have been observed and classified according to fatigue life of joints.

Welded specimens subjected to local strain amplitude lower than 1000 με have reached infinite life (number of cycles > $1 \cdot 10^7$). Spots of welding, drops of fused material and micro cavities reduce till 1/10 the number of cycles to fatigue. Probabilistic bands of fracture modes can be defined, as the mechanical response of specimens with similar defects is uniform. Therefore a coefficient representative of the defect type could be introduced in order to properly describe the fatigue strength reduction of welded joints.

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