DURABILITY, DAMAGE TOLERANCE AND ENVIRONMENTALLY ASSISTED CRACK PROPAGATION CHARACTERISTICS OF A TIG WELDED TITANIUM ALLOY

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Abstract

The paper presents the main results of a collaboration between the Department of Aerospace Engineering of the University of Pisa and Alenia Aerospace, for the evaluation of damage tolerance and fatigue behaviour of TIG welded Ti-6Al-4V sheets. Particular care was paid to the assessment of corrosive environment effects, since the most significant applications are in space vehicle tanks. Residual stresses were also evaluated, in order to analyse more appropriately the results of all the tests. Resistance of welded panels to fatigue crack growth is comparable to the one of the base metal, being penalised only for cracks growing orthogonally to the weld bead, that are influenced by the residual stresses field. The environment has a significant effect on fatigue crack growth, but the resistance to stress corrosion cracking is very good. Durability characteristics of welded butt joints are also good. No particular environment effect is appreciated on durability.

1 Introduction

Since their appearance on the market, at the beginning of the 50's, titanium alloys have found increasing application in various engineering fields as a consequence of their high specific strength, high resistance against corrosion phenomena, good resistance to oxidation up to medium temperatures, high fracture toughness and good fatigue resistance. Titanium alloys are extremely reactive with oxygen and the corrosion resistance strongly depends on a surface film of TiO_2, that is stable, tough, protective and well-anchored to the substrate. This surface oxide film is formed almost immediately, when exposing fresh titanium to air or a humid environment and continues to grow even after years, [1].

Titanium alloys can be welded, generally with good results: welded titanium alloys have shown reliable properties also in hostile environments, [2], because the same passive film forms also on welded joints, despite variations in the microstructure. Titanium reactivity with oxygen, nitrogen, hydrogen, carbon, refractory materials and metals is such that welding of titanium alloys is possible only if external elements can be excluded from the molten material. For this reason, standard procedures usually applied for good quality welding are exaggerated for titanium alloys, such as component cleaning and clamping set-up, use of high purity gas, etc. Therefore, welding in inert atmosphere or, preferably, under vacuum is necessary.

As for all the other materials, also for titanium alloys the welding technology opens new problems, such as introduction of residual stresses and defects, together with micro-structural modifications. These aspects must be investigated for every case.

This paper refers to a collaboration between the Department of Aerospace Engineering of the University of Pisa and Alenia, Aerospace Division, and is focused on the characterisation of defect propagation resistance, under static and fatigue loading, of Ti-6Al-4V alloy, welded with the Tungsten Inert Gas (TIG) process. This material is commonly used for the manufacturing of tanks for space vehicles.

The investigation has been completed by the study of the behaviour of welded Ti-6Al-4V in hostile environments.

2 Tests and experimental set-up

2.1 Materials

The experimental activity was carried out on TIG butt-welded Ti-6Al-4V panels. The welding technique was the “Direct Current Electrode Negative”, using helium as torch gas and argon as backing gas. The filler metal was a wire, ϕ=1.8 mm, of Ti-6Al-4V. The joint faces and the surrounding area were cleaned before welding by M.E.K. and pickled in an aqueous solution of hydrofluoric acid and nitric acid. Dimensions of the panels were 200 x 500 mm, 1.6 mm thick. The investigation studied both the case of a crack growing orthogonal to the weld bead and the case of a crack growing parallel, along the weld bead (in the Heat Affected Zone, HAZ, or in the centre of the bead). Tests were also carried out on panels subjected to a heat treatment for residual stress relieving. For comparison, reference data was obtained from tests on the base metal.

The panels with longitudinal welding were affected by a considerable out-of-flatness, with a shape similar to a saddle; the peculiarity of this state of deformation was such that there were two stable equilibrium configurations, and that small forces, even applied by hand, were sufficient to switch from one configuration to the other. Fig. 1 shows the typical measures of this deformed state. As a consequence, the fatigue crack propagation tests were carried out on this type of specimen by stabilising the lateral edges with stiff guides. In this way, the cyclic out-of-plane displacements of the panels under axial fatigue loading was avoided, at least in part. Otherwise, a cyclic bending would have been superimposed on such axial loading, making analysis of the results extremely difficult and uncertain. The stress relieving treatment had positive effects also on this aspect: the relevant panels were almost flat.

The initial artificial defect was a surface flaw, as for instance shown in Fig. 2, because this is representative of the most common type of weld defect. Fig. 2 also shows some details of a weld bead: it is quite wide, approximately five times the thickness. This fact means that the welding process introduced a large heat quantity, with the consequence of an increase in the grain size. Grains could be distinguished also by the naked eye on the as-welded specimens, Fig. 2c, while in the base metal the grain size is very fine: typically, it is about 0.01 mm in the rolling direction and even smaller in the other directions.

The weld bead had a very regular cross section, Fig. 2d, without undercuts and with a large radius at the weld toe. After Keller etch attack, grains were clearly visible also in the cross section.

2.2 Experimental set-up

A servohydraulic fatigue machine of the maximum capacity of 200 KN was utilised for the crack growth tests, as well as for pre-cracking the specimens for the stress corrosion cracking tests. To perform this type of test, a special loading frame was built, capable of applying a maximum load of 200 KN (this was the limit of the load cell) by means of a bolt system acting on a Belleville spring group. This loading frame proved very efficient, much more than a traditional hydraulic machine, since tests with duration up to six months had to be carried out. The configuration of the machine was such that two specimens could be tested, loaded in series, at the same time. As far as the corrosive environment is concerned, tests were carried out in isopropyl alcohol and in salt water.

During the tests, the defect dimension was measured by means of an optical microscope, 10÷70 X, mounted on a sliding block, coupled with a measuring system capable of appreciating a 0.01 mm displacement.

Durability tests were also carried out on traditional butt welded coupons, by using a servohydraulic machine, of the capacity of 50 KN.

3 Test results and discussions

3.1 Residual stresses in welded joints

It is well-known that the welding process introduces in a joint a system of residual stresses, that can sometimes be of considerable intensity: in steels, the maximum tensile residual stress, acting along the weld bead, is typically about the yield stress of the material. The strength and behaviour of a welded structure cannot be discussed without considering such a stress system. For this reason, the residual stresses in a panel were measured; this information was particularly useful for analysing the results of the other tests performed.

The residual stresses were measured by means of the relaxation technique, a very simple method, that is of a destructive nature. Some strain gauges were bonded on the specimen and zeroed; by sectioning the panel, the relaxation of internal residual stresses occurs. The readings of the strain gauge are the opposite of the original strain field. The results obtained are shown in Fig. 4, where the longitudinal stress (acting in the bead direction) is reported as a function of the distance from the bead axis itself. The results (open symbols and dashed best-fit curve) show some anomalies; in particular, the stress does not tend to zero as the distance from the weld bead increases and besides the diagram resultant, that should be nil for equilibrium reasons, is clearly unbalanced on the compression stress side. The explanation for this is the initial deformation of the welded panels, produced by an internal stress system (see Fig. 2), in which also a bending component is present and that influenced the strain measurement. The bending component can be approximately evaluated imagining the sheet subjected to a uniform bending moment such as to produce the displacement measured in the centre. Simple computations show that such a bending moment induces stresses of about 60 MPa in the centre of the panel. The experiments show that the longitudinal stress tends to a value of about 45 MPa, a value not too far from the above mentioned-one. Therefore, the shape of the panels was the cause of the observed anomalies. If the bending component is subtracted from the measurements, the points and diagram shown in Fig. 4 (solid symbols and continuous best-fit curve) are obtained. The new results are much better than the previous ones, in terms of global equilibrium. This observation was confirmed in a second test, in which two strain gauges were bonded back to back in the centre of the panel: the measured bending strain was in accordance with the estimated value.

The maximum stress evaluated at the centre of the weld bead was about 260 MPa, a low value if compared with the yield stress of the material, that is about 920 MPa. As previously pointed out, the maximum residual stress that can be measured in steels is about the yield stress, while in light alloys values of about half the yield stress are commonly found. In this case, the value is about one quarter the yield stress; this is a further advantage of titanium alloys over other metallic materials.

3.2 Fracture toughness

Fracture toughness was measured on two welded panels by introducing a through crack in the HAZ. In both tests, a stable subcritical crack growth was observed, starting from K values of about 95 and 102 MPa√m, while for both panels the final failure occurred for K = 116 MPa√m (this value was computed on the basis of the initial crack length). It was not possible, due to shortage of material, to carry out similar tests on the base metal, but some reference values are available in the literature. In [3], for a 1.27 mm thickness, a stable crack growth was observed for K values higher than 150 MPa√m, while collapse occurred for 180 MPa√m. From these results, it can be concluded that the welding process causes a considerable reduction in the material fracture toughness. The results obtained, useful for design purposes, were also utilised for preparing the stress corrosion cracking tests, described later on.

3.3 Fatigue crack growth (in air)

The results of the fatigue crack propagation tests carried out in air are reported in the classical da/dN vs. ΔK form. Due to the difficulties in measuring the growth in the thickness direction, the results are relevant only to the phase when the defect had become a through crack. For the sake of clarity, even if all the tests had been at least duplicated, in the figures only the results of one test per group is shown, in order to have clearer indications about the comparison between different test conditions.

Fig. 5 shows the results of the tests carried out on the base metal for two different values of the stress ratio R, Smin/Smax. As commonly observed, the growth rate increases with R. In Fig. 6 a comparison is made between the average curve of the base metal, R=0.1, with the results of the tests where the defects grew parallel to the weld bead (initial defect in HAZ or at the bead centre). The comparison shows a small decrease of the propagation rate in the welded joints, compared to the base metal; the same result was observed also in other titanium alloys, see for instance [4]. The results from thermally stress relieved specimens are fully comparable with those of the as-welded specimens; this last finding is a consequence of the lack of significant residual stresses in that direction, i.e. parallel to weld bead.

The results of the tests carried out on the base metal, for R=0.1 and 0.5, are compared with the corresponding results from longitudinal weld specimens, as-welded and after stress relieving, in Figs. 7 and 8, respectively. In as-welded specimens, the growth rate does not depend on the stress ratio; a possible explanation is as follows. The R=0.1 tests were carried out with a Smax equal to 100 MPa, while for the R=0.5 tests a value of 160 MPa was used. The stress ratio is only nominal (R_{nom}), it is referred to the applied mechanical load, but should be modified to take the effective stress (applied and residual) at the defect tip into account. If we consider that a residual stress of about 260 MPa was measured in the weld bead, the effective stress ratio (R_{eff}) for the two tests is

$R_{nom}= 0.1 \Rightarrow R_{eff} = (10+260)/(100+260)=0.75$

and

$R_{nom}= 0.5 \Rightarrow R_{eff} = (80+260)/(160+260)=0.81$

respectively. Therefore, as a consequence of the presence of residual stresses, the effective stress ratio increases and the differences between the two nominally different test conditions almost vanish. As the crack length increases, the tip is surrounded by a residual stress field of minor intensity; so, for equal nominal ΔK, the differences in crack propagation rate, with respect to the base metal, diminish. Fig. 8 shows the results relevant to the stress relieved specimens, that exhibit a lower growth rate in comparison with the as-welded specimens and the stress ratio becomes again significant, even if to a minor extent with respect to the base metal.

Finally, in both diagrams in Figs. 7 and 8, an increase in crack growth rate is observed for R=0.5 when ΔK becomes greater than 30 MPa√m. This effect is simply due to the fact that the effective maximum cyclic K is approaching the material toughness.

From all the results, it can be concluded that the crack growth resistance of welded joints is very good. The stress relieving treatment, in addition to a substantial improvement of this property, has also a beneficial effect on the specimens’ shape, since lower deformations are present.

3.4 Stress corrosion cracking behaviour

Even if titanium and its alloys are materials with a reputation of a high resistance to corrosive environments, they can be susceptible to stress corrosion cracking when an appropriate combination of stress, metallurgical history and environmental factors occurs [5]. In the literature, many results are available about tests carried out on several metals in different environments; welded joints behave, from this point of view, as different alloys, because different microstructures are obtained, as a function of the welding process and of the welding parameters, with a consequently different degree of susceptibility to stress corrosion. For this reason, specific tests must be performed as a support to the qualification programme of the welding procedure.

In this research programme, six stress corrosion cracking tests were carried out: four specimens with longitudinal weld bead have been tested, two as-welded and two stress relieved, and two specimens with transverse weld, one with the initial defect in HAZ and one in the centre of the weld bead. After the introduction of the artificial defects, by means of a small diamond mill, a natural crack was nucleated by applying fatigue loading. The test environment, immersion in isopropyl alcohol, was suggested by the European Space Agency; it is commonly used to clean tanks and is suspected of promoting stress corrosion cracking in titanium alloys. Also some comparative tests were carried out, using the classical 3.5% NaCl water solution as an aggressive environment. No particular differences were observed between the effects of the two environments.

The six specimens were tested in pairs, using the set-up previously described. The execution of this small test programme required in all 437 days.

The loads to be applied in each test were defined on a tentative basis, starting with a relatively low load, equal to 70% of the measured fracture toughness. This is a starting value better than the values suggested in various design manuals: for instance, ESACRACK manual, [6], reports a conservative value of K_{ISCC}, for various forms of Ti-6Al-4V, equal to 44 MPa√m. The load every two weeks was slightly increased, if no growth was observed in that period.

All the welded panels exhibited a very high resistance to stress corrosion cracking: only for K greater than 100 MPa√m was it possible to observe a crack propagation. Such a value is within the scatter band relevant to the data available in the literature, [3], where a wide range, from 33 to 115 MPa√m, can be found for the base metal, while the range reduces for welded metal to 68÷102 MPa√m. The observed value falls in the high region of this range.

As an example of the results obtained, Fig. 9 shows the evolution of a defect in a test carried out on a transversely welded specimen, with an initial defect in HAZ. The observed K_{ISCC} was 104.5 MPa√m. The initial total crack length was 42.65 mm; after 123 test days since the beginning of growth, it was 43.455 mm, with an average growth rate, at each tip, of 3.27 x 10^{-3} mm/day. Such a value is quite small, compared with the high stress intensity factor.

3.5 Fatigue crack propagation (in a corrosive environment)

The high stress corrosion cracking resistance suggested the study of fatigue crack propagation in a corrosive environment, immersion in 3.5% NaCl water solution. A special box, with glasses to allow the crack length optical measurement, was mounted on the specimen; the 3.5% NaCl water solution was continuously circulated inside the box. The load frequency was reduced in these tests to 2 Hz, to increase the effect of the corrosive environment.

Fig. 10 shows the results obtained, for two values of the stress ratio, 0.1 and 0.5. In this case, the aggressive environment has a large effect on the growth rate, even if titanium alloys do not suffer corrosion problems. This statement is valid only if no defect is present, as shown by the present results and by similar data available in the literature, [7].

3.6 Durability

The test programme was completed by performing traditional fatigue tests. Due to the very low number of launches for each tank structure, the study of the fatigue behaviour is more of academic interest rather than useful for industrial purposes. Butt welded specimens were tested under a Constant Amplitude loading, with a stress ratio R=0.1. The tests were carried out in air and in a corrosive environment (a soaked sponge, saturated with 3.5% NaCl water solution, was applied to the specimen central section). The results obtained are shown in Fig. 11, together with reference results of the base metal, on the same nominal material [8]. It is very difficult to draw a best-fit line through the results of the welded specimens; it seems as if the phenomenon had an on/off level, and therefore the line shown was drawn in a qualitative manner, including also the run-outs. Anyhow, the slope of the S-N curve of the welded material is not substantially different from the one of the base metal. This can be considered an index of the good quality of the welding process, because usually S-N curves of welded joints are characterised by a much steeper slope than the base metal, similarly to what happens for a stress concentration. The results obtained show that the fatigue strength of titanium welded joints is about 50% of the one of the base metal.

A second observation is relevant to the corrosive environment, that seems to have a negligible effect, if any, on the fatigue strength; this confirms, once more, the high resistance to hostile environments of titanium alloys, even welded.

The last point worthwhile being discussed is relevant to the defects, typically a serious problem for most welding processes. Obviously, being space structures, the welded joints were of very high quality and the optimisation of the welded process could ‘a priori’ exclude the presence of large defects; anyhow, all the joints were X-ray examined. On the contrary, small defects, in the form of pores, are practically unavoidable, even in high quality welded joints. In Fracture Mechanics tests, the initial artificial defect is largely dominant, in comparison with possible small defects; therefore, in such tests, porosity is of no consequence. In the case of fatigue tests, the situation is completely different: small defects can promote early crack nucleation. As a matter of fact, in the present research, in accordance with what usually occurs in welded joints, most of the failures were located in the HAZ, at the bead toe, i.e. in the base metal. Only in one case, the crack nucleated (and propagated) inside the weld bead; subsequent fractographic investigation revealed the presence of 3 pores, the largest of which had a diameter of about 0.26 mm, Fig. 12. The result of this test, indicated with the “P” label in Fig. 11, is not too far from all the others.

Pore cracking in titanium weldings was the object of many investigations in the last decades, with particular attention being paid to the effect of pores on the joint strength, the pore formation process and the gas content in the pores themselves. In some cases, pores, even if of small dimensions, have been the source of big problems. For instance, [9] describes the investigations carried out on two welded spherical pressure vessels made of Ti-6Al-4V, used in the Space Shuttle to store helium, that leaked prematurely in service due to cracks emanating from weld porosity. X-ray inspection revealed the presence of about 80 pores in each vessel, in the range 0.25-1 mm.

The number of available results is very low for the present investigation (exactly 9), and too small to allow us to draw conclusions about the effect of porosity on fatigue strength of welded joints. Anyhow, most of the failures were at the bead toe, where porosity is absent.

4 Conclusions

A test programme was carried out to investigate the durability and damage tolerance behaviour of TIG welded Ti-6Al-4V, under different load and environment conditions. The research was carried out within a collaboration between the Department of Aerospace Engineering of the University of Pisa and Alenia, Aerospace Division, that utilizes this material and process for the manufacturing of space vehicle tanks. The tests were carried out on as-welded panels, on stress relieved panels and, for comparison, also on base metal.

From all the results obtained, it can be concluded that the resistance of welded Ti-6Al-4V joints to the fatigue propagation of a defect is very good; only in the case of a crack growing orthogonal to the weld bead the growth rate was superior to the one of the base metal, due to the significant contribution of tensile residual stresses. Stress relieving treatment not only improves this performance, but also reduces the out-of-flatness of the specimens.

Under sustained load conditions, in a corrosive environment (immersion in isopropyl alcohol), crack growth occurred only for K higher than 100 MPa√m. An average growth rate of about 3.2 x 10^{-3} mm/day was observed. If we consider that in the fracture toughness tests carried out in air a crack growth onset was observed at 95 and 102 MPa√m, it can be concluded that resistance to stress corrosion cracking of the weld material is very high. Notwithstanding this high resistance, fatigue crack growth is strongly influenced by a corrosive environment.

The fatigue strength of welded butt joints of Ti-6Al-4V, compared with the one of the base metal, shows a reduction of about 50% in stress, and a similar slope of the S-N curve. Most of the failures originated in HAZ, showing a low content of defects in bead and therefore a good quality of the welding process. The exposure to a corrosive environment does not seem to have significant influence.

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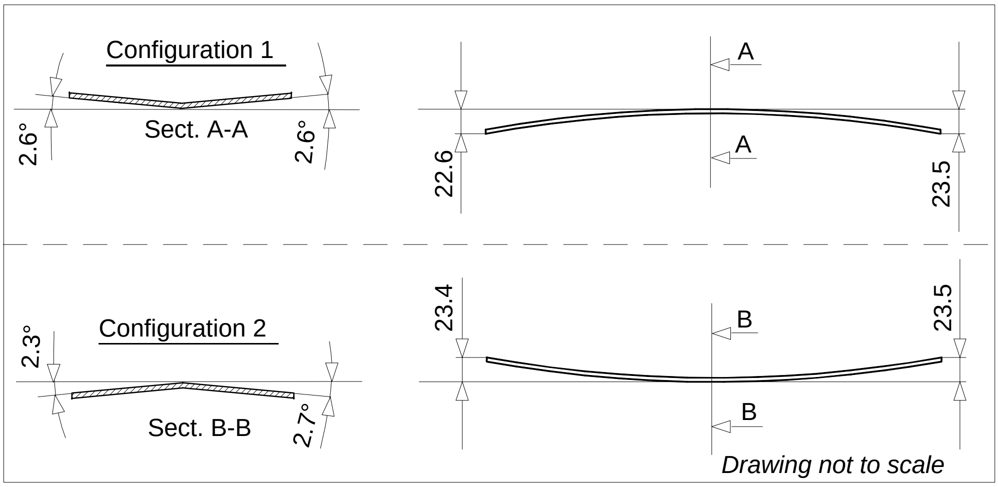

Fig. 1 – Initial deformations measured in a longitudinally welded panel (as-welded).

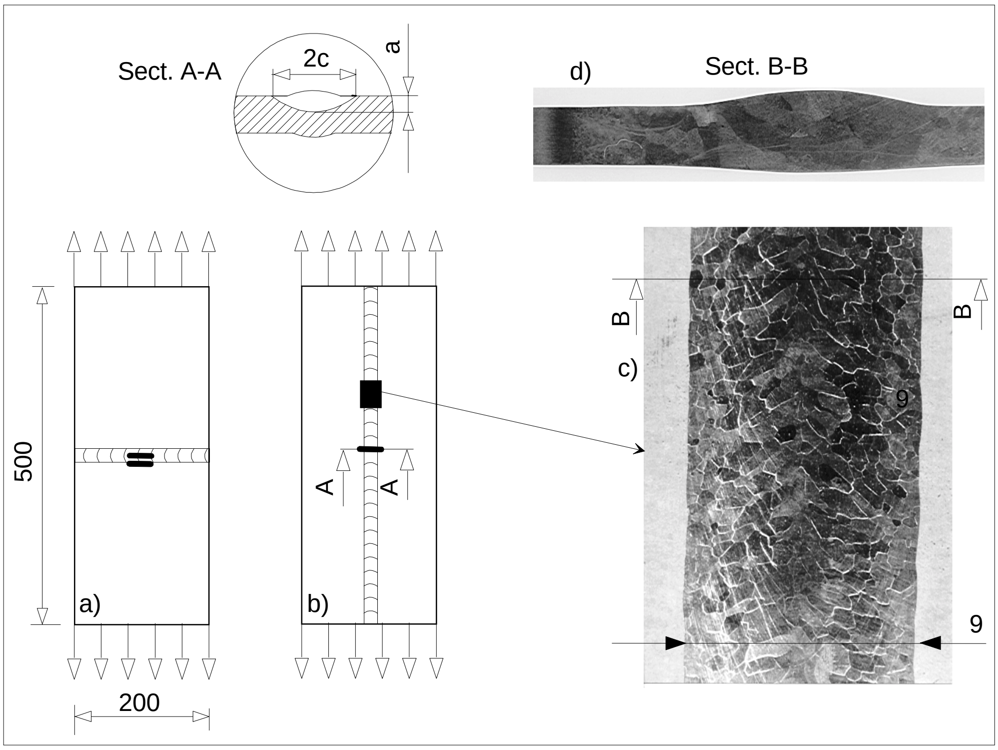

Fig. 2 – Specimen geometry and details of a weld bead.

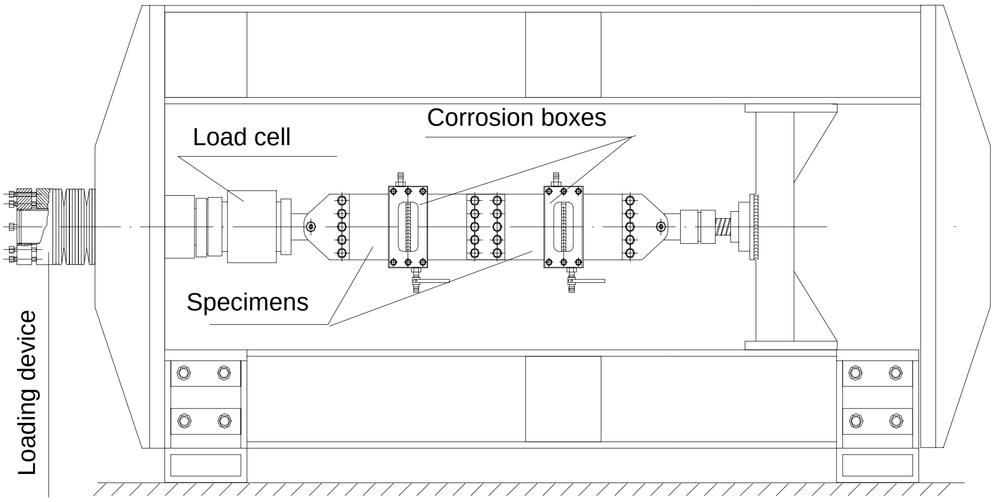

Fig. 3 – Experimental set-up for stress corrosion cracking tests.

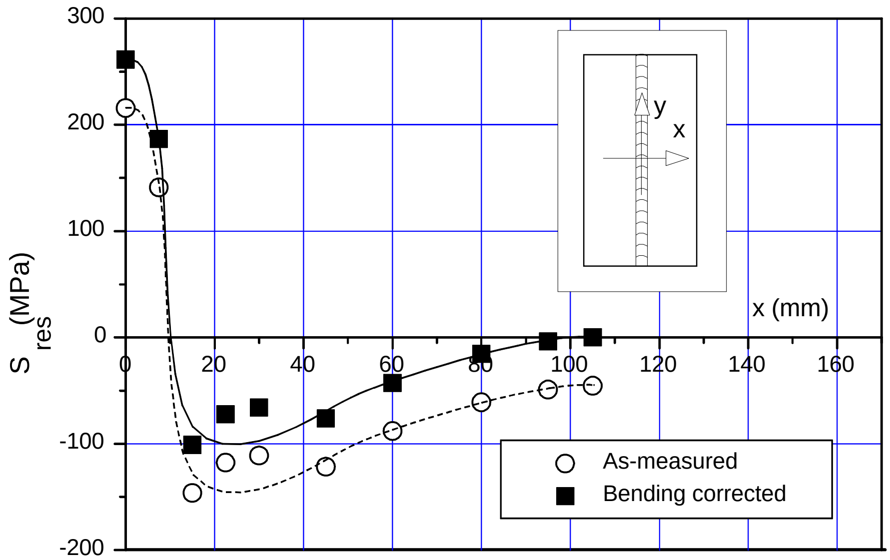

Fig. 4 – Residual stresses measured parallel to a weld bead.

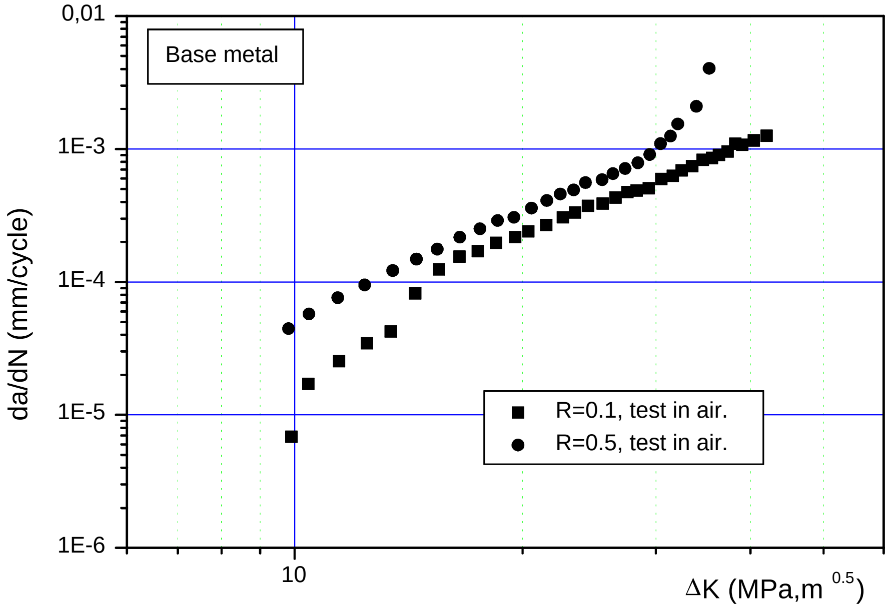

Fig. 5 – Fatigue crack growth rate in Ti-6Al-4V.

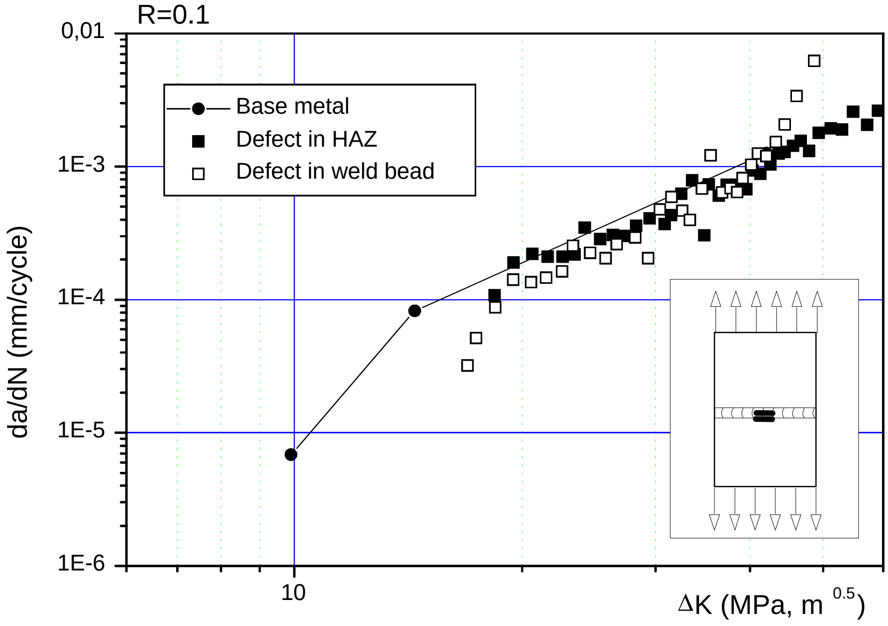

Fig. 6 – Fatigue crack growth rate in as-welded Ti-6Al-4V. Direction of growth parallel to the weld bead.

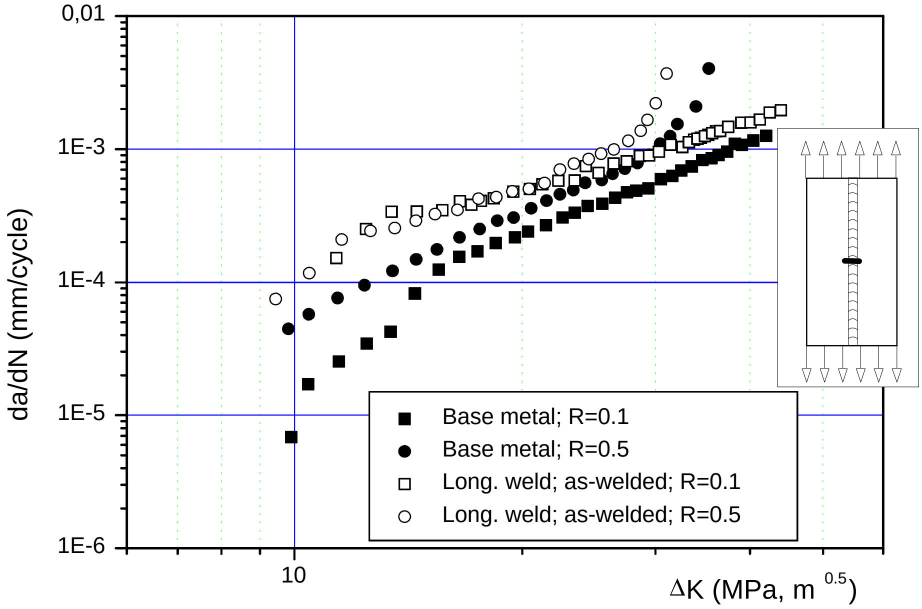

Fig. 7 – Fatigue crack growth rate in as-welded Ti-6Al-4V. Direction of growth perpendicular to the weld bead.

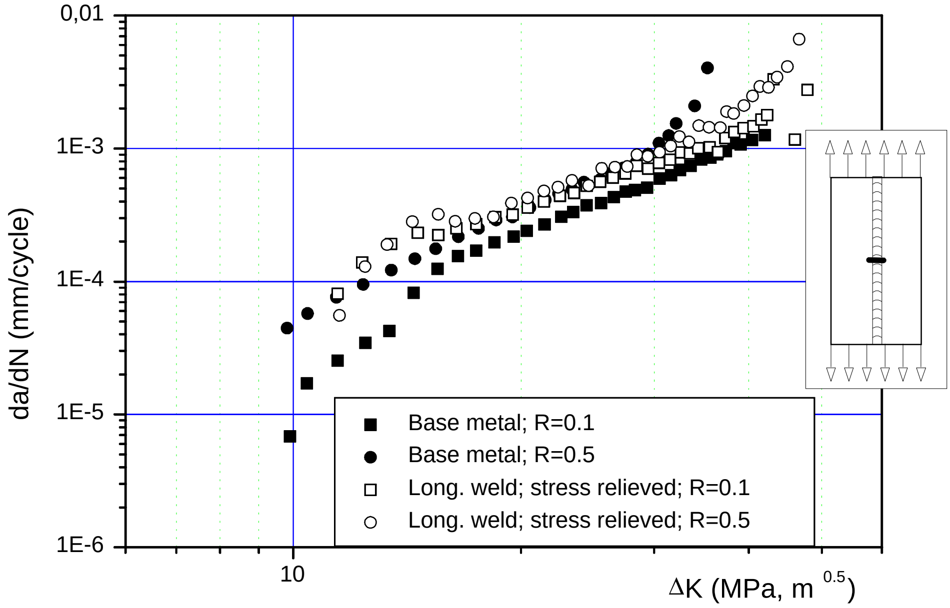

Fig. 8 – Fatigue crack growth rate in welded Ti-6Al-4V after stress relieving. Direction of growth perpendicular to the weld bead.

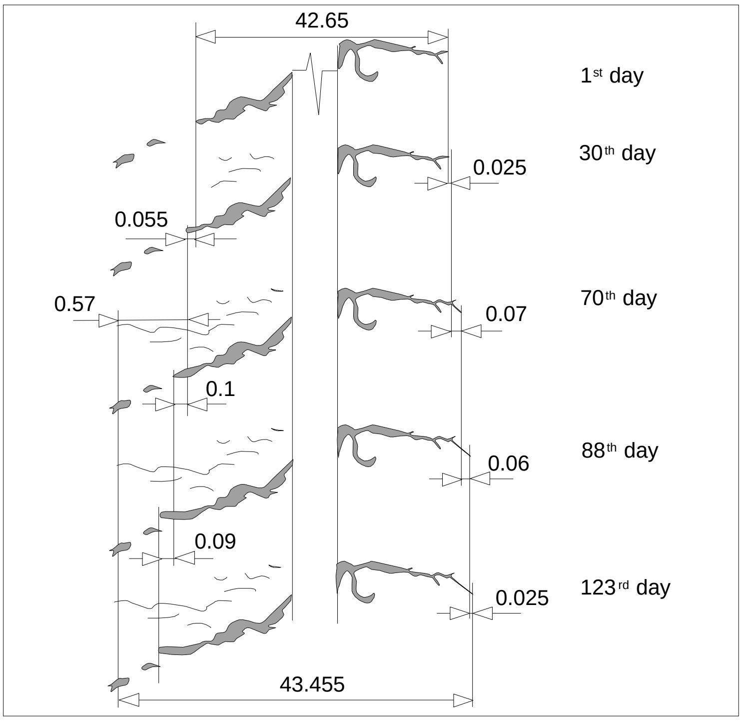

Fig. 9 – Example of defect growth for stress corrosion in welded Ti-6Al-4V. Defect in HAZ.

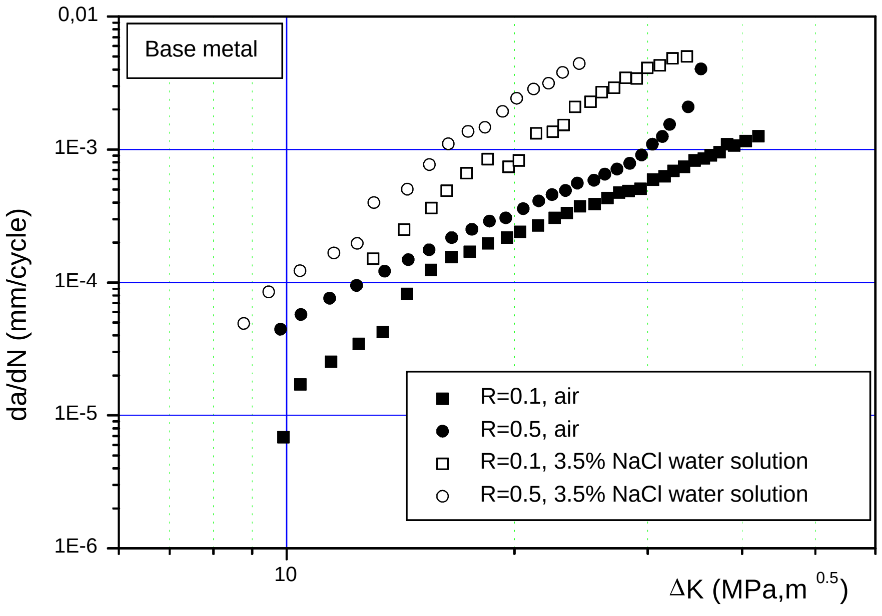

Fig. 10 – Fatigue crack growth rate in Ti-6Al-4V, in air and in 3.5% NaCl water solution.

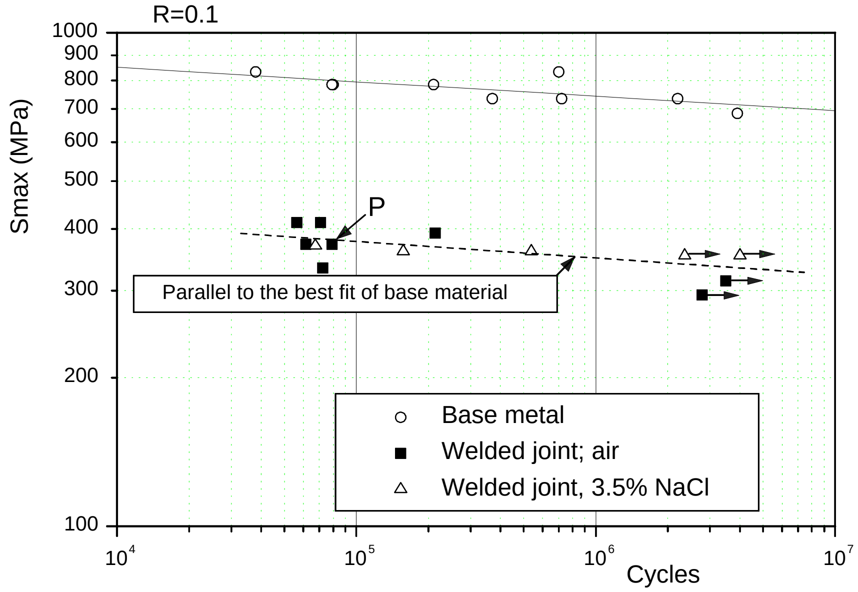

Fig. 11 – Fatigue behaviour of welded butt joints compared to base Ti-6Al-4V, R=0.1.

Fig. 12 – Defect in weld bead.