Fatigue Crack Growth in Re-welded AISI 4130 High Strength Steel

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ABSTRACT: *All over the world the flight safety has been the main concerns of aeronautical authorities. Structural failures during flight are usually attributed to fatigue of materials, project errors or aerodynamic overloads. Nowadays, fatigue is the most important consideration of project and operation in both civil and military aircrafts. From small aircraft (<20 kN) the most solicited component is one that support the motor. This component contains a complex geometry, made of different welded tubes from several angles. It has the function of supporting the aircraft motor, besides maintaining fixed the nose landing gear in another extremity. As a result, fatigue cracks are always observed at the weld sites. After successive welding repairs, they are frequently retired of operation. Therefore, it is extremely important to determine the effects of welding repairs on the structural integrity of this component. The aim of this study is to analyze the effects of successive TIG welding repairs on the structural integrity of the AISI 4130 aeronautical steel through fatigue crack propagation tests located in base material, heat affected zone - HAZ - and weld metal (the original one and that re-worked). Increase of the fatigue crack propagation was observed in both HAZ and re-welded material. The results were associated to their microhardness and microstructure variation.*

INTRODUCTION

Fatigue in aircrafts has been subject of extensive investigation since 1950, after the accident with the English model “Comet” [1]. Many fractures of materials are caused by fatigue due to inadequate project, or notch produced during manufacturing or maintenance operations of aircraft [2]. Maintenance operation errors, specially, are responsible for serious safety problems and fatal accidents [3]. During flight an aircraft is subjected to complex loads from varied frequency and magnitude. Nowadays, aircraft projects are a result of extensive research toward increase in their service life. It is well know that 90% of structural failures of a component submitted to cyclic loads are attributed to the fatigue process. The support of aircraft motor is an high responsibility component and its fracture can be fatal. This component is made from AISI 4130 steel, welded by TIG process. Previous studies on 157 components that support motors of the T-25 Brazilian aircraft indicate that all fractures are located at welding sites. For this reason, aeronautical requirements are extremely careful and restrictive. However, this component is frequently submitted to welding repairs after cracks are detected. So, becomes extremely important to determine the welding repair effects on structural integrity of this component. The aim of this study is to analyze the effects of successive TIG welding repairs on the structural integrity of the AISI 4130 aeronautical steel through fatigue crack propagation tests located in base material, heat affected zone - HAZ - and weld metal (the original one and that re-worked). Increase of the fatigue crack propagation was observed in both HAZ and re-welded material. The results were associated to their microhardness and microstructure variations.

EXPERIMENTAL PROCEDURE

Material

The material used in this study was AISI 4130 steel plate, with 1,58 mm thick, and the chemical composition in weight percent was: 0,32C; 0,28Si; 0,58Mn; 0,91Cr; 0,18Mo; 0,013P; 0,008S; Fe in balance.

From the mentioned material, samples were prepared for tensile and fatigue crack propagation tests, with and without welding. The hardness of the base material in the "as received condition" was 60 HR_A.

Welding procedure

TIG welding process was performed according to the EMBRAER[❶] NE 40-012 TIPO I standard, using commercial protective argon gas (99,95% purity). The welding process was made with metal of addition AMS 6457 B - Turballoy 4130. The root weld was 0,6 mm approximately. A SQUARE WAVE TIG 355-LINCON equipment was used. All the welding parameters were controlled, and the principal ones are indicated in Table 1. The welding direction was always transverse to that of the lamination one of the plate. Before welding process, samples were fixed in a device (backing bar) to avoid contamination of the weld root and, so the introduction of pores. Afterwards, they were cleaned by chlorinated solvent for oxide removal. After the welding process, none subsequent heat treatments for tension residual stresses relief or grinding machining of the weld metal were performed, in order to simulate the real condition of the original

[❶] Brazilian Aeronautical Industry.

aeronautical structures. As a consequence of thin plates, only a single-pass of welding was required. All the welded specimens were submitted to X-ray inspections to guarantee the absence of significant defects in the weld metal.

Table 1: TIG welding parameters.

DESCRIPTION	PLATE #1,58
WELDING POSITION	PLANE
WELDING VOLTAGE	12 V
WELDING CURRENT	75 A
WELDING SPEED	192 mm/min
FLOW RATE	5 L/min
HEAT INPUT	28 kJ/cm
PRE HEAT	100 ^{o}C
FILLER METAL DIAMETER	1,6 mm

Monotonic tests

For monotonic tensile tests, specimens were prepared according to ASTM E 8M. The tests were performed on a servo-hydraulic MTS test machine with 0,5 mm/s speed of deformation, and pre load equal to 0,1 kN. The following specimens were tested:

- smooth specimens - 1,58 mm thick (TBM)[2];
- specimens - 1,58 mm thick, welded at the central region (TWM)[3];

Fatigue crack growth tests

For the fatigue crack growth tests, specimens were prepared according to ASTM E 647, following the LT directions. The tests were performed on a servo-hydraulic machine upon a sinusoidal load, at room temperature, constant amplitude, load ratio R = 0,1 and at 10 Hz frequency. The specimens were subdivided in three groups:

- GROUP I → specimens with central crack (Fatigue B. Material - FBM);
- GROUP II → specimens with central crack located in the weld metal – both original and re-worked - (Fatigue Weld Metal - FWM);
- GROUP III → specimens with central crack located in the HAZ – both original and re-worked - (Fatigue HAZ - FHAZ).

The central notch, necessary to generate the fatigue pre crack, was performed in accordance to ASTM E 647, by electrical discharge machine (EDM). The maximum test load applied was 11,7 kN (200 MPa) approximately for all specimens.

[2] Tensile specimen of Base Material.
[3] Welded Tensile specimen.

The re-welding process was made by removing the original weld metal of the non-tested specimen through a rotate pneumatic grinding machining at 22.000 rpm. An optical microscope containing a graduate scale of 0,01 mm was used to observe and measure the fatigue crack propagation.

Metalographical and microhardness analyses

The etching was made by Nital 5%, applied during 20 seconds.

Vickers microhardness measurements were performed by using a 1 N load. Measurements were obtained at 0,0254 mm intervals throughout regions under analyses (base material, HAZ and weld metal).

RESULTS AND DISCUSSION

Chemical analysis of the weld metal.

The chemical composition of the weld metal in weight percent was: 0,30C; 0,50Mn; 0,004P; 0,003S; 0,25Si; 0,179Mo and 0,042Cu.

The chemical composition of the weld metal is similar to the specified for the base material. Chemical elements as Oxygen and Nitrogen, indicators of contamination of the weld metal during the process, were not found.

Monotonic tests

Table 2 presents the result of the monotonic tensile tests of smooth and welded specimens.

Table 2: Characterisation of AISI 4130 steel.

MONOTONIC TESTING - AISI 4130 STEEL			
GROUP	**YIELD STRESS 0,2% (MPa)**	**MAX. STRENGTH (MPa)**	**ELONGATION (%)**
TBM	730,5±33,7	826,5±12,8	9,5±1,1
TWM	686,3±6,5	791,4±6,9	4,8

All welded specimens fractured exactly between HAZ and base material, despite any stress concentration originated in the weld toe. This means that the influence of the microstructural changes between base material and HAZ is more significant on tensile strength than the geometric modifications caused by the welding process. By analysing the results presented in Table 2, one can observe decrease of ductility, yield tensile stress and ultimate tensile stress after TIG welding process. However, in both cases, the relationships between the yield tensile stress and maximum tensile stress (σ_{ys}/σ_m) was around 0,88.

Fatigue crack growth tests
Figure 1 presents the *a x N* curves of all specimens cited.

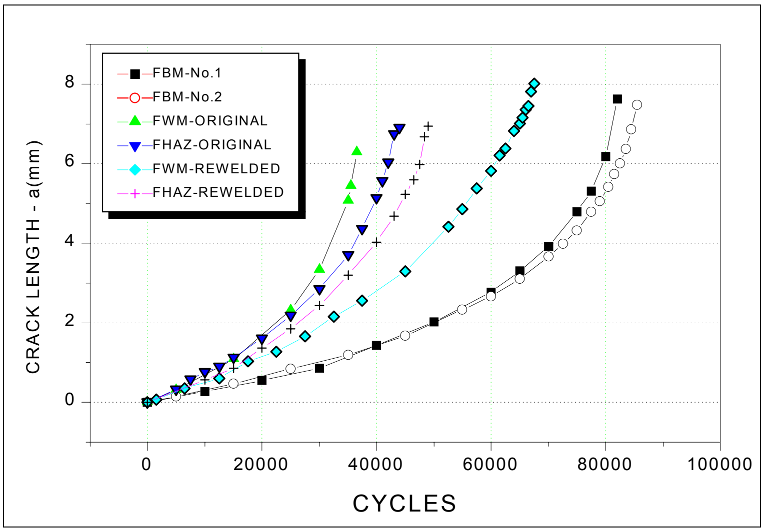

Figure 1: Fatigue crack propagation test results

On original welding, one can see that the crack propagated faster in the weld metal, followed by HAZ and base material respectively. However, differences between fatigue crack growth in both HAZ and weld metal was minimum. These results are related to microhardness and microstructure changes observed in the three analysed areas. Table 3 presents the microhardness results obtained.

Table 3: HV Microhardness values.

AREA	ORIGINAL WELD METAL	RE-WORKED WELD METAL
BASE MATERIAL	267.7 ± 16.4	285.5 ± 15.8
HAZ	362.9 ± 55.7	373.4 ± 22.8
WELD METAL	573.2 ± 69.8	507.5 ± 47.4

It is well known that the crack propagate faster in harder material due to smaller dimension of the plastic zone size at the crack tip.

On the other hand, from Figure 1, an important recuperation on fatigue crack propagation strength is observed in the same sites due to re-welding, despite to higher microhardness value presented. It is well known that properties of weldments are also greatly affected by the weld microstructures, mainly in low alloy steel welds. Figures 2 and 3 present the microstructures of base material, HAZ and weld metal (original and re-worked).

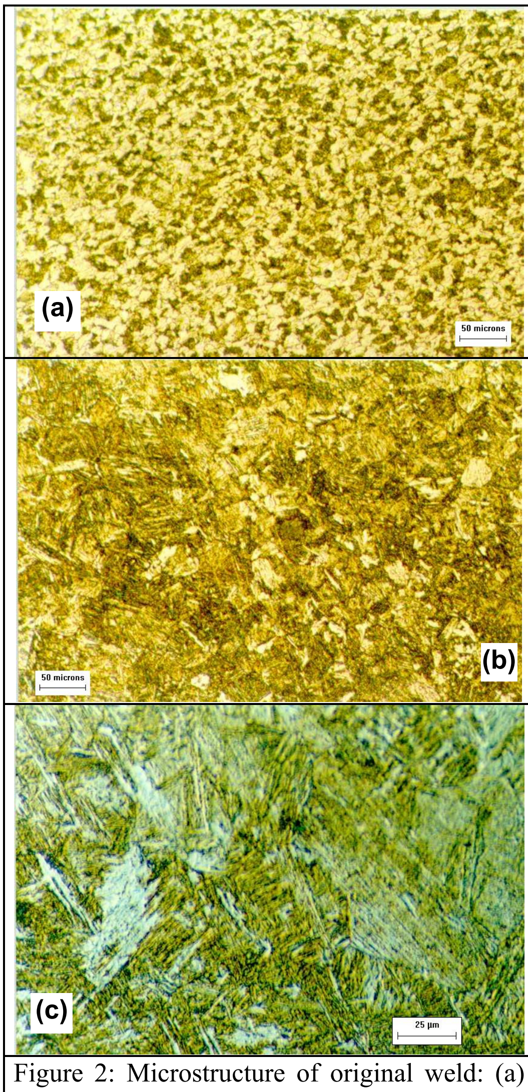

Figure 2: Microstructure of original weld: (a) base material; (b) HAZ; (c) weld metal.

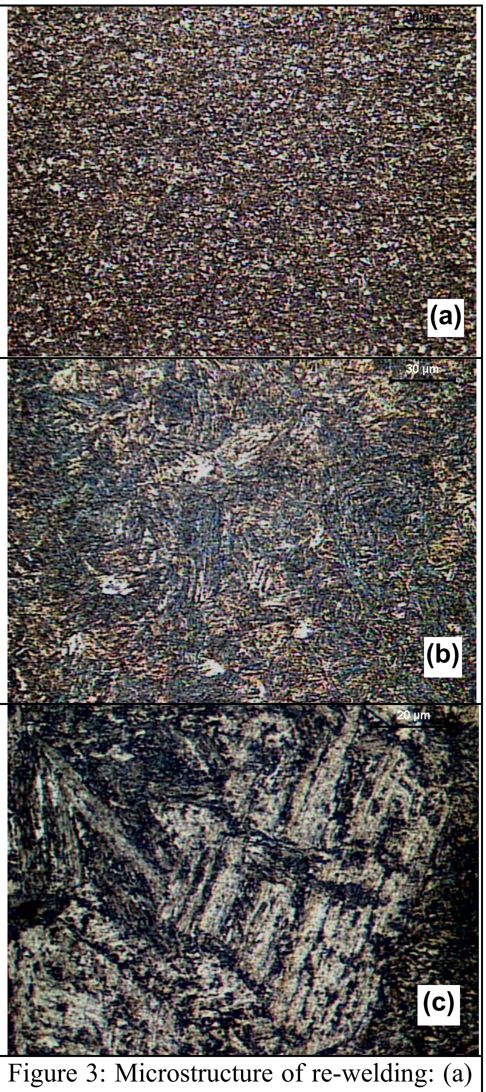

Figure 3: Microstructure of re-welding: (a) base material; (b)HAZ; (c) weld metal.

From Figure 2(a), one can see that the base material contains a microstructure of fine grains, formed by ferrite and perlite. So, the fatigue crack will find larger resistance to propagate through the ferrite and perlite grains due to the microstructural barriers offered. From Figure 2 (c), it is possible to observe the heterogeneous microstructure of the weld metal, which is formed basically by un tempered martensite, acicular ferrite (AF), primary ferrite (PF) and ferrite side plate (SPF), developed in several crystalographic plans due to the cooling speed. Finally, the HAZ (Figure 2(b)) presents a dense microstructure, also formed by untempered martensite, primary ferrite and acicular ferrite, however containing smaller grains comparatively to the weld metal.

From Figure 3(a), one can see that the base material contains a microstructure of fine grains, formed by ferrite and perlite, as well. However, both HAZ (Fig. 3(b)) and weld metal (Fig. 3(c)) present a microstructure formed by tempered martensite, which is caused due to high cooling rate and by the original structure. The effect of the microstructure on the fatigue crack growth of various steels has been reported by several investigators [4], who concluded that tempered martensite has a higher resistance to the crack propagation.

With the obtained results the "*C*" and "*n*" constants were determined for the three mentioned areas (base material, HAZ and weld metal) by using the equation of Paris and Erdogan [5].

$$\boxed{\frac{da}{dN} = C(\Delta K)^n} \qquad (1)^{❹}$$

Table 4 presents *C* and *n* values obtained.

Table 4: *C* and *n* values.

GROUP	C	n
FBM – Nº 1	1,941E-10	1,593
FBM – Nº 2	2,722E-10	1,471
FWM	9,637E-10	1,331
FHAZ	1,533E-09	1,174
FWM – RE-WELDED	2,608E-09	0,954
FHAZ – RE-WELDED	1,014E-09	1,305

Figure 4 gives the *da/dN* values of the base material, weld and re-weld specimens in the ΔK range from 18 to 39 MPa√m, where the crack direction was perpendicular to the loading axis.

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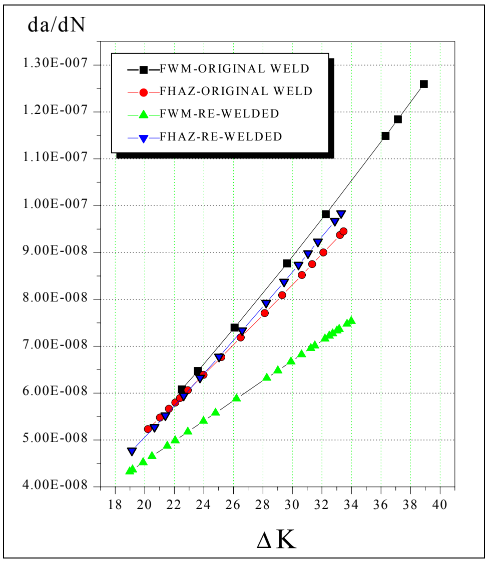
❹ da/dN → fatigue crack growth rate;
C and n → constant of material;
ΔK → stress intensity factor range.



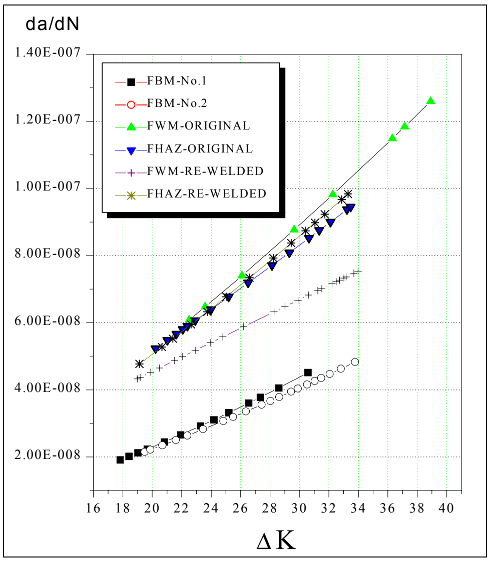


Figure 4: *da x dN* curves from all the mentioned conditions.

Figure 4 reveals that the original welded specimen has a faster *da/dN* than all other conditions. On the other hand, it is clear that the re-welding effectively retarded the crack propagation into the weld metal. However, in relation to both HAZ, the behaviour were similar.

It is well known that the residual stresses are present in welded components [6] and have great effect on fatigue crack growth [4]. However, these effects were not treated here. Chiarelli et al [7] verified, in studies realized in Faith 510 D1 steel, the same behaviour of the fatigue crack propagation both in the base material and in the HAZ. El-Batahgy, Abdel-Monem [8] in studies realized in St.37 (mild) steel and St 50 (high strength) steel, found that the fatigue strength of HAZ was higher than that of base material. The author attributed this results to the microstructural variations induced by the welding process. On the other hand, studies developed by Tsay, L. W., *et al* [9], on D6AC high strength steel welded by electron beam process indicated the same tendency observed here, i.e., the fatigue crack also grew faster in the weld metal. However, after post welding heat treatment the fatigue crack growth in the weld was lower than base material.

CONCLUSIONS

In the present paper the following conclusions may be drawn:

1. The TIG welding process reduced the ultimate tensile strength, as well as the yielding tensile strength and the ductility of the AISI 4130 steel.
2. Fatigue crack in weld metal grew faster in relation to HAZ and base material. However, the crack propagation was faster in relation to the former.
3. Base material presented larger resistance to fatigue crack propagation. This behaviour was associated to lower microhardness values and microstructure constituted by fine perlite-ferrite grains.
4. TIG re-welding process induced microstructural and microhardness changes on the weld metal and improved its strength to the crack propagation.
5. TIG re-welding did not improve the fatigue crack propagation of the HAZ.

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REFERENCES

1. Payne, A. O. (1976) *Engineering Fracture Mechanics*. **8**, 157.
2. Goranson, U. G. (1993) *International Journal of Fatigue*. **19**, S3.
3. Latorella, K. A. and Prabhu, P. V. (2000) *International Journal of Industrial Ergonomics*. **26**, 133.
4. Wei, M.Y. and Chen, C. (1994) *Scripta Metallurgica et Materialia*. **31**, 1393.
5. Paris, P. and Erdogan, F. (1963) *Journal of Basic Engineering, Transactions of the ASME*. **85**, 528.
6. Chiarelli, M., Lanciotti, A. and Sacchi, M. (1999) *International Journal of Fatigue*. **1**, 1099.
7. Abdel-Monem El-Batahgy (1994) *Materials Letters*. 21, 415
   Tsay, L.W., Chung, C.S. and Chent, C. (1997) *International Journal of Fatigue*, **19**, 25.