

Correlation between road public usage and experimental fatigue curves on brazed heat exchanger

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Abstract

This document presents the results concerning fatigue resistance of aluminium mock-ups composed of the tube and the header of car thermal exchanger. Because it is necessary to take into account the geometry of the exchangers (crack at the tube-header brazing joint level) to define the fatigue damage mechanism and the mechanical properties, a prototype dye was created to perform the fatigue test on complex assembly. This study shows the Wölher curves at the crack initiation compared with that of the complete torn-off of the mock-ups and the influence of temperature (-30°C, 20°C, 120°C). A metallographic analysis coupled with EBSD analyses is proposed to understand the crack path and a SEM study shows the propagation mode on a tube. Comparison with road public usage was finally performed.

Introduction

Environmental and economic constraints are pushing for a constant weight reduction of the aluminium exchangers for cars, hence leading to a downgauging of the materials. This thickness reduction locally induces a stress increase which can lead to rupture due to a fatigue phenomenon. Moreover, new antipollution norms and coolant replacement by CO₂ lead to a high level of pressure and temperature which can reach 30 MPA and 275°C. Therefore, critical conditions are reached regarding the use of aluminium.

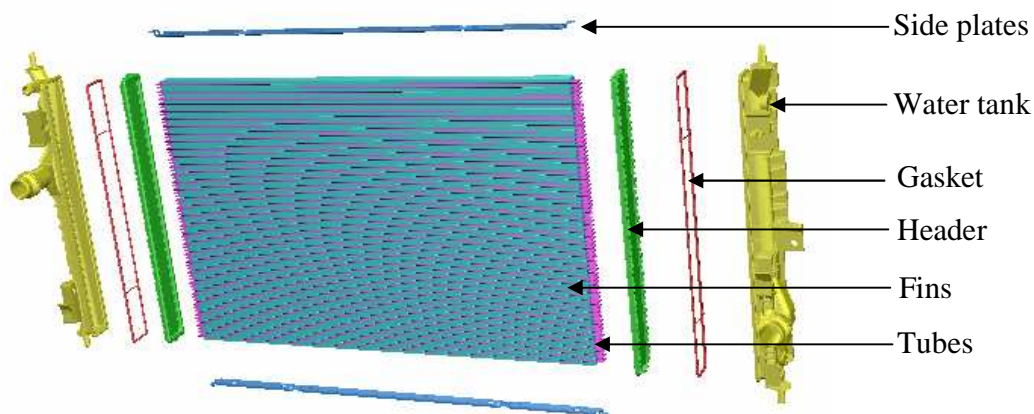


Figure 1: Structure of a brazed exchanger

The main failure mode of the exchanger results from thermomechanical phenomenon which is induced by transient differential thermal dilatation of the exchanger components. Even if the corrosion phenomenon is still an important research subject to maintain high life expectancy of the materials, the limiting factor is now the exchanger resistance to fatigue solicitations.

All thermal car exchangers have the same type of structure based on two technologies: tubes or plates. These tubes or plates are linked by headers and fins as we can see on Figure 1. Tubes ensure the coolant liquid passage, fins increase the exchange surface with air temperature, headers allow coolant distribution in the tubes or plates and side-plates give core mechanical rigidity.

Understanding fatigue mechanisms is the main point for Valeo in order to optimize life expectancy of the exchangers. The objective here was to perform some fatigue tests on complex samples composed of a tube and a header part and to reproduce the failure mode observed on exchangers (rupture at level of tube-header joint). The first challenge was to create a universal fixture allowing us to perform these fatigue tests at different temperatures on the mock-ups. The second challenge was to find a protocol to follow the crack initiation and not only the complete rupture of the tube. Indeed, a failure on an exchanger is not represented by the tube being completely torn-off (which never happens) but the moment when the crack is just on the rim of the tube. In order to study the rupture phenomenon at the grain level, electrochemical attacks and optical microscopy have been performed. We performed some Scanning Electron Microscopy (SEM) analyses to determine the direction of the propagation and some Electron Back Scattered Diffraction (EBSD) analyses to observe the crystallographic system as a function of temperature.

Experimental procedures

1) Materials used and universal fixture conception

The system studied is composed of a tube and a header (Fig 2-b). The tube is a 3 co-rolled aluminium alloy (4XXX, 7XXX, 3XXX alloys, total thickness 0,27mm, Fig 2-a) and the header is a 2 co-rolled aluminium alloy (4XXX, 3XXX alloys, total thickness 1,5mm).

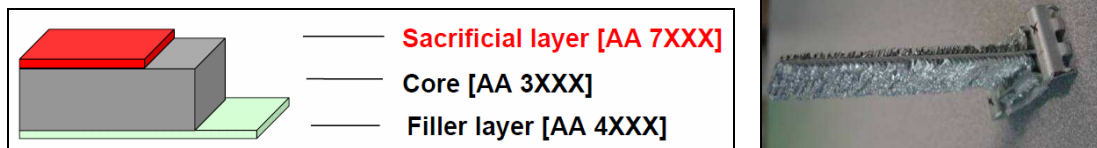


Figure 2: a- Material used to represent the tube, b- Sample tested composed of a tube and a header part

A prototype fixture (Fig 3) has been especially created for this study to allow us to perform a fatigue test on the mock-ups (tube+header) and a complete protocol has been done to obtain reliable results.

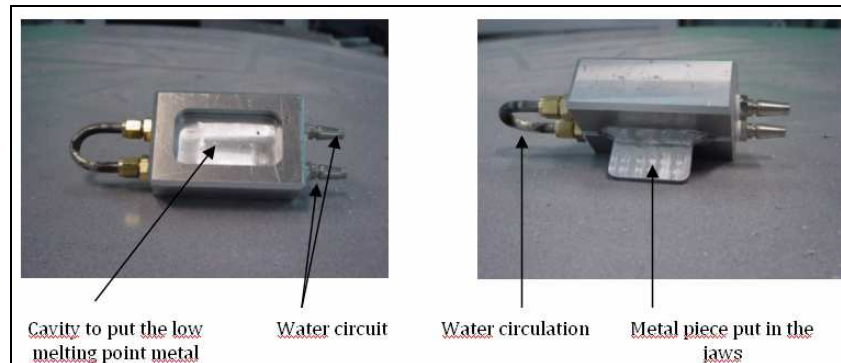


Figure 3: Universal fixture for fatigue tests

The Wölher curves (with crack following or at final rupture) have been performed during constant stress amplitude, stress at different temperatures to understand the influence of this parameter ($R=0,1$, $f=30\text{Hz}$, $T= -30, 20, 120^\circ\text{C}$).

2) Preparation samples

Mocks-ups were sampled on a complete heat-exchanger and cut with a band-saw to obtain a single tube and a header part. In order to follow the initiation of the crack (when the tube is leaking), we filled the tubes with a coloured liquid and monitored the fatigue test with a webcam (fig 4).



Figure 4: Following of the crack

For microscope observation or EBSD analyses, all samples have been embedded and polished up to OPS. In order to observe the microstructure, an HBF4 (tetrafluoroboric acid) attack was performed on samples.

Results

Figure 5-a presents Wölher curves at room temperature, -30°C and 120°C for a complete rupture (tube completely torn-off of the header). First of all, fatigue test on mock-ups allowed us to obtain a very high reproducibility of the result ($0,9 < R^2 < 0,98$). As we can see, fatigue resistance on mock-ups is better at low temperature in comparison with those at room temperature or at 120°C .

This phenomenon is observed on aluminium fatigue samples [1] and linked to the mechanical property modifications as a function of temperature (decreasing of the Young modulus and yield strength with an increase in temperature).

Same type of results was observed at rupture initiation (Fig 5-b).

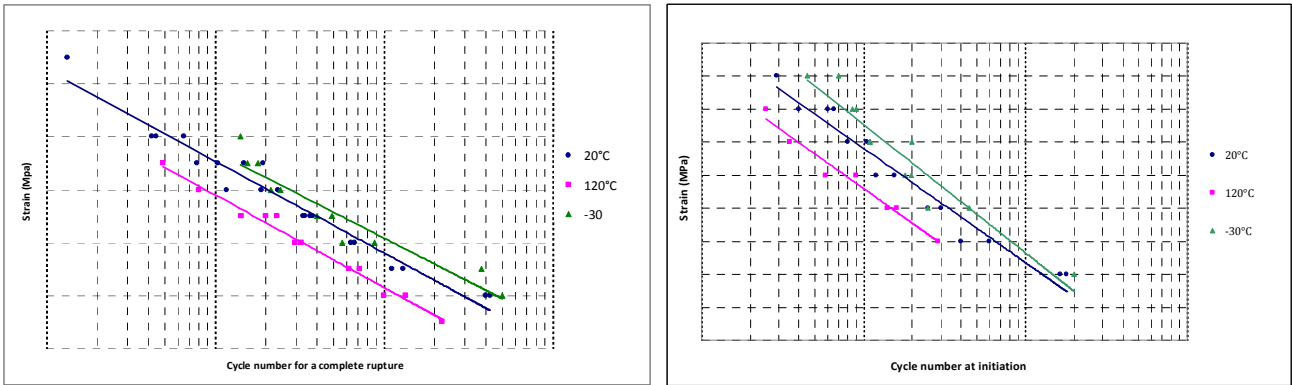


Figure 5: a- Wöhler curves at final rupture, b- Wöhler curves at initiation of the rupture

The parallelism between curves on figure 5-a and figure 5-b indicates a proportional relationship between the initiation of the rupture and the final rupture. Indeed, if we study the Basquin coefficient, we can observe some very similar values for each temperature (Fig 6-a). The temperature does not affect the propagation mode: initiation of the rupture appears systematically at 40% of the total life expectancy of the tube (Fig 6-b).

Température (°C)	-30	20	120
1/b (fissuration)	5,8	6,3	6,4
1/b (rupture)	6,2	6,5	6,7

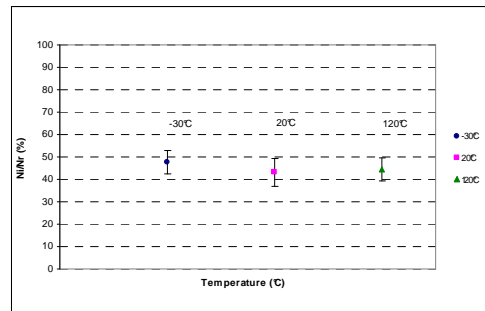


Figure 6: a- Correlation between Basquin coefficient as a function of temperature for final rupture and initiation of the crack, b- Proportional coefficient between the cycle number at rupture initiation and final rupture

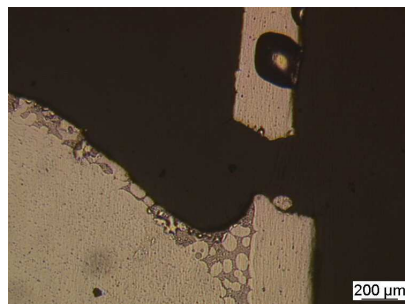
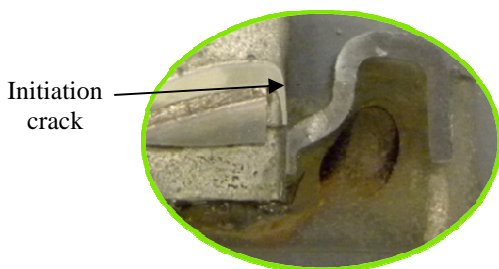


Figure 7: a- Localisation of the crack on the tube, b- Cross-section of the tube-header joint, c- Tube microstructure

Figures 7-a and 7-b present the failure mode after a fatigue test on a mock-up. This reproduces perfectly what happens on a car. The study of the microstructure shows (Fig 7-c) an intergranular crack in the residual clad then a transgranular crack in the core.

Figure 8 shows the misorientation of the grains on the initiation area of a 20°C sample.

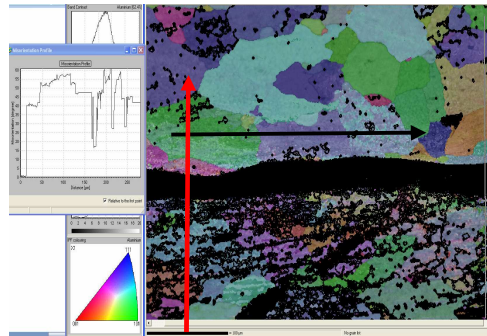


Figure 8: Misorientation of the grains in the initiation area of a 20°C sample (X250)

First, all the samples show the same grain size distribution. There is no change of the grain size cause to either the temperature or the strain of the test.

For all the samples, the measures of the misorientation between grains along profiles have been performed. These profiles have been measured on either side along the crack (see on Figure 8, the black arrows) and perpendicularly of the crack propagation direction (see the red arrows on Figure 8).

It has been shown that intergranular and transgranular crack propagation behaviors can both exist in an aluminum alloy [1], [3]. The same kind of propagation behavior is observed in all the samples studied; the temperature and the stress of the tests have no impact on the crack propagation behavior.

One can observe that the mean misorientation along a side of the crack is lower than the mean misorientation between two grains on either side of the crack. That means that the propagation of the crack occurs preferentially between two grains (or sub grains) showing a high misorientation.

Figure 9 shows some sample results. Moreover, we can see that the difference between the misorientations of adjacent grains on the same side, and two grains on either sides of the crack, is higher on the crack end area than on the initiation area. The misorientation between two grains on either sides of the crack is higher on the crack end area than on the initiation area.

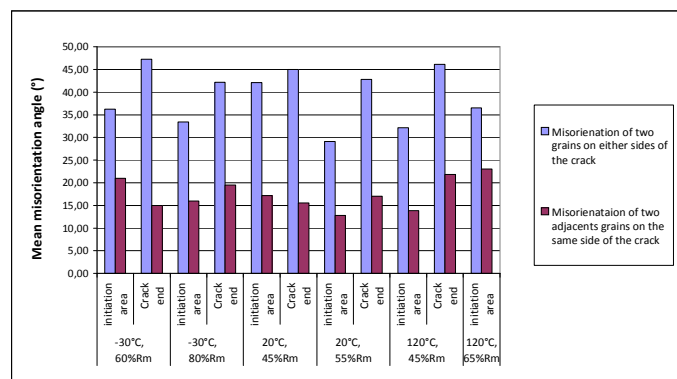


Figure 9: Misorientation of the grains around the crack for some samples

The misorientation between two adjacent grains could be linked to the grain boundary energy [4], [5], [6], [7]. The higher the misorientation between two grains, higher the probability of the crack propagation between these two grains.

Figure 10 presents the propagation mode of the crack observed by SEM. Three characteristic areas were systematically observed on our mock-ups: stable propagation (green, fig 10-a), mixed area (blue, fig 10-b) and final brutal rupture (orange, fig 10-c).

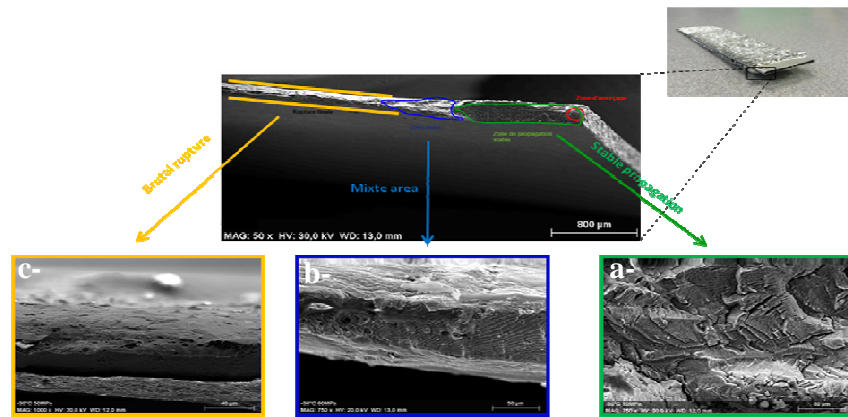


Figure 10: SEM observation of rupture morphology, distinction between the different areas: a- stable propagation, b- mixed area and c- brutal rupture

The first area is characterised by a smooth area where some fatigue Lüders bands can also be observed. These bands show the stable propagation of the crack on this area. The second one, is named mixed area because the fatigue bands are present with a lot of dimple typical of a ductile rupture. We have to notice that the transition between the stable propagation and the mixed area induces a modification in the direction of the fatigue bands. Therefore, if the fatigue bands classically show the propagation direction in the stable propagation, a rotation of 90° on the fatigue bands is observed in the mixed area. This phenomenon has also been observed on thin fatigue samples with the same tube materials [8] and was explained by “Flat-to-Slant” rupture morphology. Finally, the third surface area of brutal rupture is only composed of dimples and depends on the stress applied, the higher the stress and the bigger the area.

Figure 11 shows the different rupture morphology observed as a function of temperature. Grey areas represent the final rupture, green arrows show the propagation direction and red areas are the mixed areas. Rupture initiation systematically appears on one external side or two sides of the round of the tube and propagates to the internal tube face. It confirms the fact that the brutal rupture areas improve with an increase in stress.

We can logically expect that the rupture should happen from two sides of the tube because we perform symmetric tensile solicitations but we suppose that a microstructural or geometrical defect or a incorrect parallelism of the sample can promote the initiation of the crack on a side.

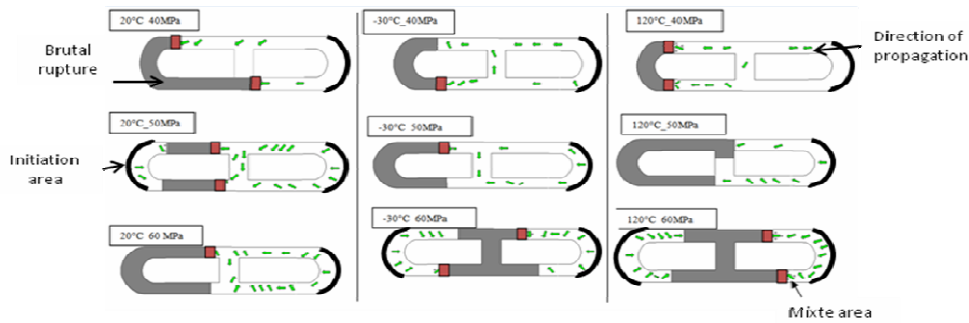


Figure 11: Summary of the rupture morphology observed as a function of temperature

Comparison with road public usage

The aim of the comparison between road public usage and bench is to establish a test specification to validate the component on accelerated tests. In this way, we use an equivalent fatigue damage approach.

First, we instrument the failure area of the component of strain gages.

This instrumentation allows us to build the real fatigue curve of the component on bench.

In deed, the test is pushed up to failure on bench with gage measurement in parallel. All failure modes are similar to the sample fatigue test (Figure 7.a). We confirm the Basquin's coefficient of 5 for heat exchangers in aluminium in the range 10.000 cycles to 500.000 cycles. This point is correlated with samples fatigue already seen above.

Second, the vehicle is equipped with the exchanger instrumented. The road public measurement can be done on road in extreme conditions, either in cold country (ie : Arjeplog in Sweden) or in windtunnel.

Following a rainflow counting coupled with the real fatigue curve, the damage is assessed. The comparison between the damage on bench and vehicle gives us the real target to achieve on bench. In order to take into account all uncertainties and assumptions of this approach, a safety factor is applied on the specification. This statistical coefficient comes from a strength-stress method.

Conclusion

This is the first time that fatigue tests were performed on thermal car exchanger mock-ups.

Wöhler curves showed that an increase in temperature (-30, 20, 120°C) significantly decreases the fatigue resistance. There is a relationship between the initiation of the crack (thickness of the tube) and the total tearing-off of the tube: initiation systematically appears at 40% of the total rupture. This relation does not depend on the temperature.

The microstructure analysis shows that crack is intergranular in the clad and transgranular in the core.

The EBSD analyses show that a higher misorientation between grains on either side of the crack is observed. This misorientation is higher than the misorientation of adjacent grain along one side of the crack.

According to these observations, the higher the misorientation between two grains, the higher the probability of the crack propagation.

Three characteristic areas were highlighted by SEM: stable propagation characterised by fatigue bands, mixed area composed of dimples and fatigue bands perpendicular to propagation direction and final brutal rupture with neck-in and dimples.

Finally a correlation was done between radiator test on bench and fatigue test on tube-header system: Basquin coefficients are very close to each other (Figure 12).

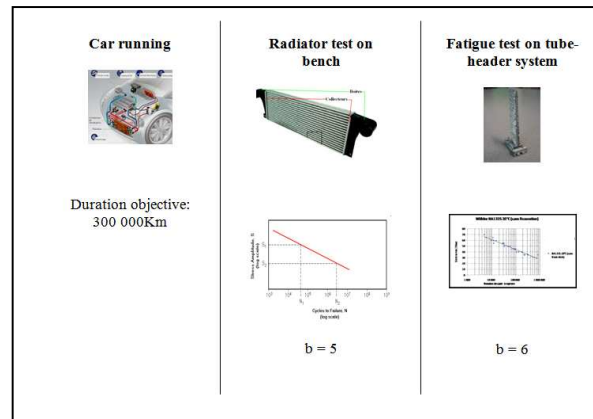


Figure 12: Comparison between radiator test on bench and fatigue test on tube-header system Basquin coefficients

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