EFFECT OF TEMPERATURE ON FATIGUE CRACK BEHAVIOUR IN DIFFERENT ALLOYS

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Abstract. This paper deals with the role of temperature in the behaviour of fatigue cracks in different alloys used in the aircraft industry. Three different alloys were studied: an aluminium alloy (Al 7175), a titanium alloy (Ti6Al4V), and an high strength steel (34CrNiMo6). Push-Pull tests (R = -1) were carried out at different temperatures, from low temperatures, (-100ºC), to somehow high temperatures (+ 400ºC), in air. At each temperature the shape of the da/dN-K_{max} curve was assessed, as well as the initiation life, ($a - N_f$ curve). The relation initiation life/propagation life was also assessed, ($a - N/N_f$ curve). The effect of temperature in the referred subjects was discussed.

The existence of a ductile-brittle fatigue transition temperature, parallel to the monotonic ductile-brittle transition temperature, although these transition temperatures are not the same, was assessed. Even on materials without a monotonic ductile-brittle transition temperature, a ductile-brittle fatigue transition temperature was detected.

1. INTRODUCTION

Many components, particularly in aircraft industry, should be prepared to operate in a range of temperatures, which may vary from low temperatures (-100ºC) to temperatures well above ambient temperature, for example (+200ºC). It's widely accepted that fatigue life increases with decrease in temperature. It's also known that the percentage of total life spent on crack initiation also increases with decrease in temperature. On the other hand propagation life decreases with a lowering in temperature. Some components in the aircraft industry are designed based on a 'safe life' philosophy while some other components are designed based on a 'damage tolerant' design. For example, for large civilian and military aircraft, cracks are so commonly found during periodic inspections that safe operation and economic maintenance are both critically dependent on fracture mechanics analysis [1]. Thus, in order to make a decision on what design philosophy should be used, it is important to study both the initiation and the propagation behavior of the materials at different temperatures. Not only the material or the component are the main variables when is decided the philosophy to be used.

Many studies exist on the effect of high temperature on fatigue behavior but very few studies exist on low temperatures. Some of the most common alloys used in aircraft industry are: Ti6Al4V, Al 7175, and 34CrNiMo6 alloys. This paper is concerned with a comparison study on the influence of temperatures, very common on turbine engine and aircraft airframe applications, on fatigue behavior on the referred alloys.

2. MATERIALS AND METHODS

2.1 Material and specimens

Materials used in this investigation are: a Ti6Al4V alloy, an Al 7175 alloy, and an high strength steel, 34CrNiMo6 alloy. Mechanical properties are listed in table 1. The specimens used are round specimens (fig. 2) according to ASTM E 606-80 with a pre-crack.

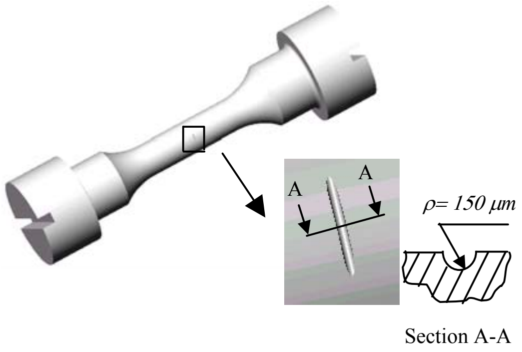

Fig. 1. Specimen and pre-crack geometry

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Table 1. Mechanical Properties

Mechanical Properties (20ºC)	σ_{ced} *(0,2%)* MPa	σ_r *(MPa)*	*E* (MPa)	ε_r *(%)*
Ti6Al4V	989	1055	$1,15*10^5$	16,1
Al 7175	461	535	$0,736*10^5$	13,8
34CrNiMo6	1101	1204	$2,35*10^5$	21,6

2.2 Methods

Fatigue tests were conducted at different levels of temperature (*-100ºC; 20ºC; +400ºC*) in laboratory air using a sinusoidal loading ($R = -1$) under loading control at a frequency of *8 Hz* on a servo-hydraulic testing machine. At each temperature the shape of *the da/dN-*K_{max} curve was assessed. The $a - N$ and $a - N/N_f$ curves were also studied. A Pulsed DCPD system with a high resolution [2] was used to measure the crack growth. High temperature tests were done with a heating furnace with three heating levels and a control of ± 1 ºC . Low temperature tests were done with a cooling camera, with liquid nitrogen, and a control of ± 1 ºC.

Charpy tests were made on a Charpy Wolpert-Probat equipment, and nitrogen was used to lower the specimens temperature and a thermocouple was used to control the temperature inside the specimens

3. RESULTS

Crack growth data is presented in figs. 4, 7 and 10 in accordance with ASTM 647, which states that $\Delta P = P_{max}$ *for* $R \leq 0$. In these figs it's shown the effect of temperature on propagation rate from –100 ºC to +400ºC, depending on each material.

In order to understand the effect of temperature on both crack initiation life and crack propagation life figs. 2, 3, 5, 6, 8, and 9 show $a - N$, and $a - N/Nf$ curves for the studied materials.

On fig. 11 are the monotonic ductile-brittle transition curves. In table 2 are shown the testing conditions.

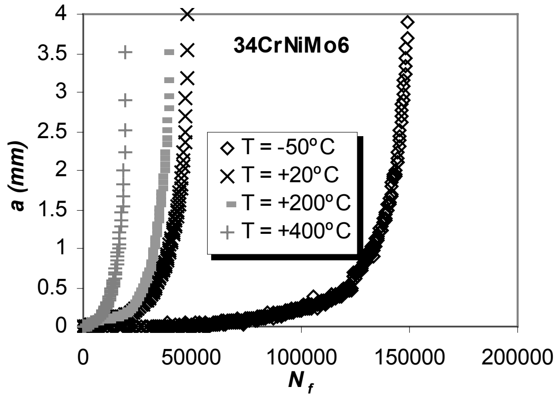

Fig. 2. $a - N_f$ curve. Material: 34CrNiMo6. *T= variable.* N_f – Average life until complete fracture.

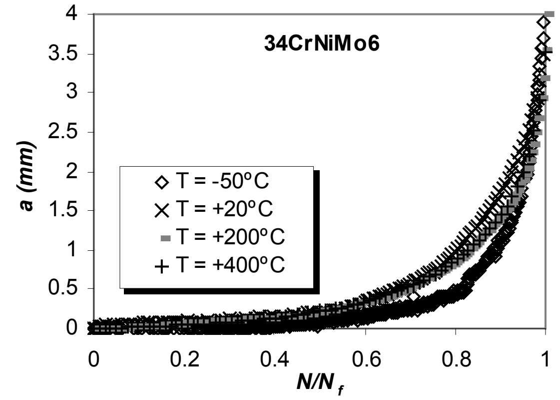

Fig. 3. $a - N/N_f$ curve. Material: 34CrNiMo6. *T= variable.* N/N_f – Relative life until complete fracture.

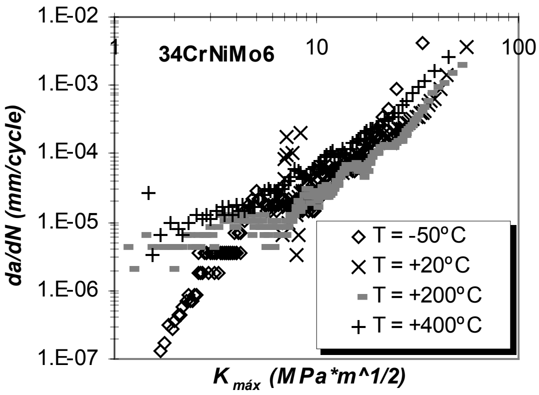

Fig. 4. $da/dN - K_{max}$ curve. Material: 34CrNiMo6. *T = variable.*

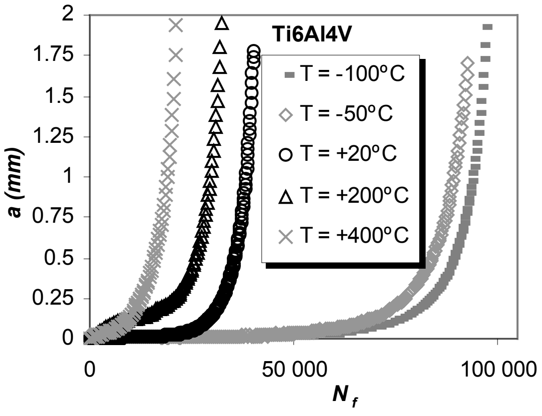

Fig. 5. $a - N_f$ curve. Material: Ti6Al4V. *T= variable.* N_f – Average life until complete fracture.

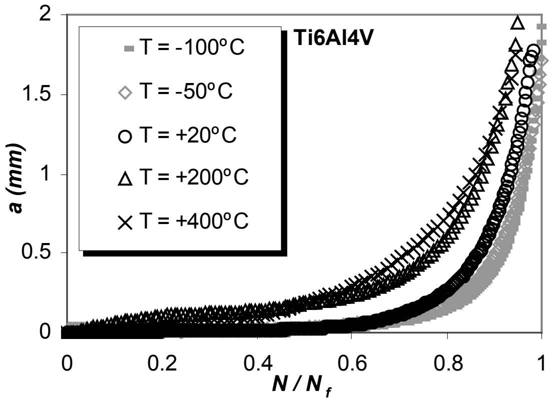

Fig. 6. $a - N/N_f$ curve. Material: Ti6Al4V. *T= variable.* N/N_f – Relative life until complete fracture.

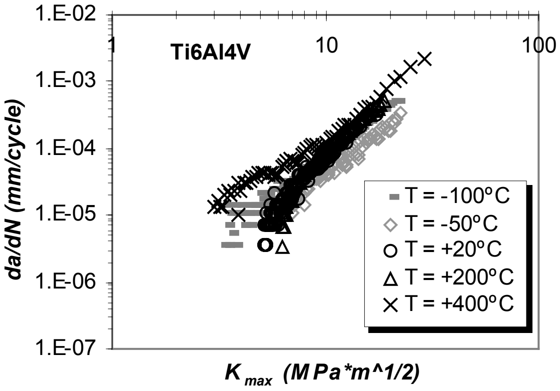

Fig. 7. $da/dN - K_{max}$ curve. Material: Ti6Al4V. *T = variable..*

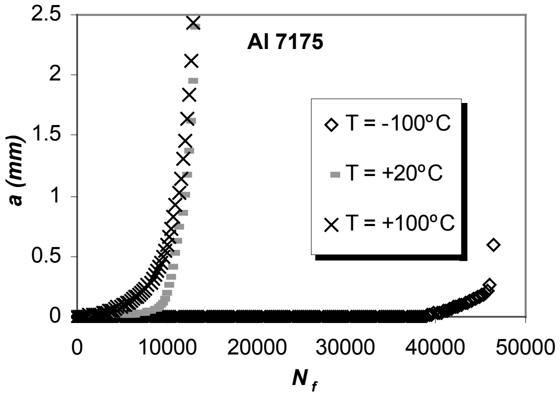

Fig. 8. $a - N_f$ curve. Material: Al 7175. *T= variable.* N_f – Average life until complete fracture.

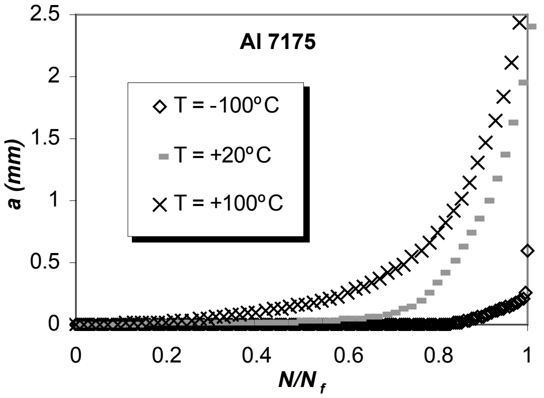

Fig. 9. $a - N/N_f$ curve. Material: Al 7175. *T= variable.* N/N_f – Relative life until complete fracture.

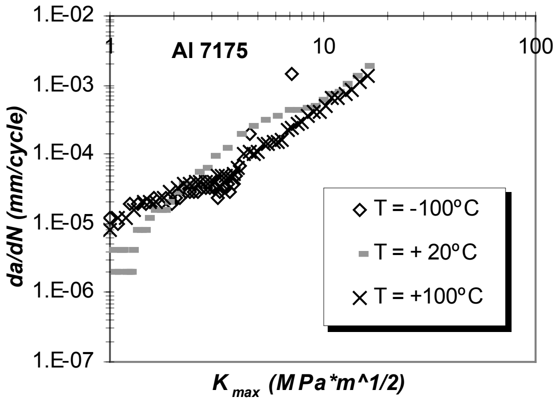

Fig. 10. $da/dN - K_{max}$ curve. Material: Al 7175. *T = variable.*

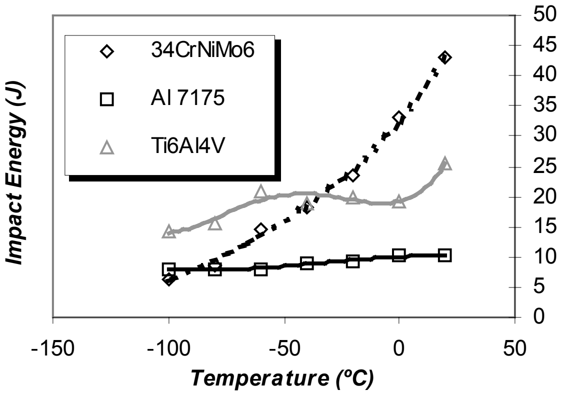

Fig. 11. Impact energy absorption curves (Charpy). Materials: 34CrNiMo6, Ti6Al4V, and Al 7175.

Table 2. Testing Conditions. R=-1; f=8 Hz. N_f – Average life until complete fracture.

Loading Conditions Δσ/2 [MPa]			
T [ºC]	*34CrNiMo6*	*Ti6Al4V*	*Al 7175*
- 100	-	442	256
- 50	530	442	-
+ 20	530	442	256
+ 100	-	-	256
+ 200	530	349	-
+ 400	530	349	-

The results can be summarised as follows:

- Fatigue lives increase substantially with the lowering of temperatures (figs. 2, 5, 8);
- The effect of temperature changing seems to be particularly relevant for low temperatures. For example, a changing of about 100ºC below room temperature seems to have more impact on fatigue life than a changing of 100ºC above room temperature (figs. 2, 5, 8);
- The percentage of life spent on crack initiation (accepting crack initiation as life till the crack reaches 0,5 mm) is higher for low temperatures, and decreases as the temperature raise (figs. 3, 6, 9). The opposite occurs for the percentage of life spent on crack propagation;
- Life spent on crack propagation can be much lower at low temperatures than life spent on crack propagation at room or high temperatures (figs. 2, 5, 8). This seems to be particularly true for the aluminium alloy (figs. 8, 9);
- As a general rule crack propagation rate decreases with the lowering of the temperature (figs. 4, 7, 10). However, below a certain temperature crack propagation rate increases substantially. The tendency to decrease crack propagation rate with the lowering in temperature reverses. This is true for all materials (figs. 4, 7, 10);
- The temperature in which there is a reversal on crack propagation rate is not the same for all materials (figs. 4, 7, 10);
- The monotonic ductile-brittle transition temperatures are shown on fig. 11. The aluminium alloy does not have a ductile-brittle transition; the titanium alloy has a transition temperature although not very substantial; and the steel shows a substantial transition between brittle behaviour, at low temperatures, and ductile behaviour, at room and high temperatures;

4. DISCUSSIONS

It's not a novelty that the overall fatigue behavior of the materials is better when the temperature is lower than normal (room temperature) and decreases when the temperature increases. Although it seems that the rate on increase of fatigue strength with the decrease in temperature is more relevant on unnotched specimens than on notched specimens [3], it is clear that there is a huge increase on fatigue strength when the temperature lowers below room temperature. Although a comparison on changing of monotonic properties and fatigue properties with temperature, and in particular with low temperatures, is not made on this paper, it seems that fatigue strength is more sensitive to low temperature than monotonic strength. And this is also true for notched specimens.

By figs. 2,5,8 its clearly shown that it seems to be much more relevant a decrease of 100ºC when we go below room temperature than when the temperature is raised above room temperature. It must be said that this reasoning is only for temperatures around room temperature (+20ºC ± 100ºC).

It seems, by the previous discussion, that an approach based on a 'safe life' philosophy, and also based on room temperature fatigue properties, may be used with safety when predicting lives for low temperatures. A lowering in temperature provides an additional safety factor.

However, most components, mainly in the aircraft industry, are designed based on a 'damage tolerant' approach. This means that it is not the total life that is taken into account but is the crack propagation behavior that must be assessed [3].

On figs. 3, 6, and 9 it is observed that as the temperature decreases from high to low temperatures the percent of life spent on crack propagation reduces. And, if it is considered that crack initiation life is life till the crack reaches 0,5 mm, it is observed that some materials do not seem to have almost propagation life at low temperatures. That is to say that propagation life can be drastically reduced or be even inexistent at low temperatures.

This can be attributed to a faster crack propagation rate and to a shorter final fatigue crack length. Both seem to be true.

In terms of final fatigue crack length it is expected a reduction with a decrease in temperature. As a fact the ductility usually reduces for all materials for a lowering in temperature (at the same time that ultimate tensile strength and yield strength increase). The impact energy, as measured by the Charpy impact test, also decreases at lower temperatures (fig. 11). Some materials show a more continuous energy curve (those who have a CFC – Cubic Face Centered crystalline structure)(this is the case of the aluminum alloy used in this study), and some other materials, usually steel alloys, show an accentuated transition region (these materials have mainly CBC – Cubic

Body Centered crystalline structures). The titanium alloy is in the middle of the previous alloys. As a fact this Ti6Al4V alloy has a phase (α phase) that is HC – Hexagonal Compact, and is not sensitive to lower temperatures, but the β phase is CCC and is very sensitive to low temperatures. Thus the behavior of this titanium alloy is in the middle of the tendency of each of its crystalline phases.

Thus, the lower fracture toughness and lower ductility explains why final fatigue crack length is shorter. And it should also be able to explain the way in which cracks propagate.

However it is interesting to observe the crack propagation behavior on figs. 4, 7, and 10. As expected the crack propagation rate increases with increasing temperature, above +20ºC. However decreasing temperature to –100 ºC the crack propagation rates become faster than for +20 ºC and in some cases rates are even faster than at +200ºC.

It is observed that at low crack growth rates (region I and lower part of region II of the sigmoidal curve of fatigue behavior) the lower temperatures seem to be beneficial. However at high crack growth rates the low temperature is detrimental for all materials. And it seems to be more detrimental for the aluminum and the steel alloys. This seems to be an unexpected result because the aluminum alloy, from those presented in this paper, is the less sensitive alloy to low temperatures (see fig. 11). However, in terms of fatigue crack propagation the aluminum alloys is one of the most sensitive, along with the steel alloy. Thus, it seems that an extrapolation from the ductile-brittle monotonic transition curve cannot be done to fatigue propagation behavior.

Gerberich and Moody [4] reviewed substantial fatigue crack growth behavior for a variety of materials. They indicated that many alternate fatigue crack growth processes exist in metals at low temperatures and they emphasized the importance of the microstructure on fatigue behavior at these temperatures. They also showed that region II fatigue crack growth rates could be substantially altered at different low temperatures. They showed some results on a steel alloy, from room temperature to –150ºC, where at some temperature in between they observed a reverse in the crack growth behavior. d*a/dN* decreased with the lowering in temperature till a certain point where it began to increase. They also observed that there has been a change in the mechanism becoming cyclic cleavage to be the dominant mechanism. Thus, they concluded that a ductile-brittle transition temperature exists for that steel. And what is interesting to observe is that the fatigue transition temperature was not the same of the impact Charpy transition temperature. Kawasaky [5] found that the fatigue transition temperature was substantially below the impact Charpy transition temperature. Stonesifer [6] found that the ductile-brittle fatigue transition mechanisms could be completely different than ductile-brittle monotonic transition mechanisms.

Thus, it seems that a fatigue transition temperature must exist, parallel with the monotonic ductile-fragile transition temperature although this transition temperatures are not the same. Some materials like titanium alloys and aluminum alloys do not have a monotonic transition temperature (fig.11). Nevertheless they seem to have a fatigue ductile-fragile transition temperature.

From fracture surface morphologies [7-8] it can be seen that roughness increases with temperature. This is particularly clear on temperatures above 0ºC. Thus, an eventual roughness crack closure mechanism wouldn't be able to explain this shift in crack growth behavior. Neither would the plastic induced crack closure mechanism be able to explain this shift because the loss of ductility does not have the same tendency.

From the above considerations it is clear that when components may have to stay under low temperatures, such as those of aircraft industry, where a component may be at –50ºC (for example during the flight) and at +50ºC (when in landing in a tropical country), a 'damage tolerant' approach may be inadequate. As a fact, for these three materials in this study, all of them are used in the aircraft industry, and all of them seem to be sensitive to low temperatures, but some of them, namely the Al 7175 and the 34CrNiMo6 alloys are not definitely adequate to be used in components where a 'damage tolerant' design is used.

5. CONCLUSIONS

The main conclusions of this study can be drawn as follows:

- Fatigue life of components is substantially affected by little (±50ºC or ±100ºC) changes in temperature, around room temperature. This is true for low temperatures;

- Fatigue propagation life may, for low temperatures, almost disappear. Fatigue life is, then, approximately the fatigue initiation life;

- There is a fatigue ductile-brittle transition temperature which is not the same of the monotonic ductile-brittle transition temperature;

- It seems that even materials without a monotonic ductile-brittle transition temperature may have a fatigue ductile-brittle transition temperature;

- Special attention must be paid when a 'damage tolerant' approach is used in components that may be used at low temperatures, common in some industries such as the aircraft industry.

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