INFLUENCE OF CORROSIVE ENVIRONMENT ON FATIGUE CRACK INITIATION IN ALLOYS FOR STEAM TURBINE BLADES

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ABSTRACT

The titanium alloy TA6V is under consideration to replace 12 % chromium steels in some cases for the manufacture of blades for low pressure steam turbines. Tests were therefore conducted to compare the notch crack initiation strength (in three different media) and the crack growth threshold in air, of a 12 % chromium steel and a TA6V alloy forged in the "$\alpha + \beta$" two-phase region and in the β phase. From the results of these tests, it may be considered that the behaviour of TA6V is independent of the medium investigated. However, the steel's crack initiation strength deteriorates in the most corrosive of the three media investigated (1 g/ℓ NaCl, pH 9, Θ = 80 °C) due to the appearance of corrosion pits. In this medium, TA6V "β" seems to show the best high-cycle fatigue behaviour among the three materials tested.

KEYWORDS

Crack initiation, ΔK threshold, stress corrosion, titanium alloys, 12 % Cr steel, steam turbine blades.

INTRODUCTION

The fatigue strength and erosion and corrosion resistance properties of the titanium alloy TA6V, together with its low density, point to the possibility of its use to manufacture LP steam turbine blades, instead of the 12 % chromium steels used at present. Depending on the heat treatment selected, the microstructure of TA6V may be equiaxial or acicular.

In the case of gas turbines, for which this alloy is already used, the microstructures of the Widmanstatten type are prohibited due to their mediocre fatigue behaviour (Duncan, 1981). However, according to a bibliographic study made by Wood (1977) on titanium and its alloys, it appears that this poor behaviour of acicular microstructures occurs more in low-cycle fatigue than in high-cycle fatigue. Moreover, certain investigations (Eylon, 1976) seem to indicate that the fatigue behaviour of notched test specimens of TA6V with an acicular structure is better than the behaviour observed for an equiaxial microstructure.

As in the case of blades for steam turbines, the high-cycle fatigue strength is the primary criterion, and, since the cracks tend to initiate from notches, we decided to compare the notch crack initiation strength of a 12 % chromium steel with that of a TA6V alloy forged either in the "α + β" two-phase region (equiaxial structure), or in the β phase (Widmanstatten type structure). This study was conducted with R = 0.5 and in three different media, including two aqueous media, to simulate the blade operating conditions. Crack growth threshold tests were also performed to characterize the effect of any machining defects on the fatigue behaviour of these materials.

MATERIALS INVESTIGATED

The materials investigated were a 12 % chromium steel type Z19 CD12-1 (according to AFNOR Standard) and a TA6V alloy forged in the " α + β " two-phase region and in the β phase. Test specimens were taken from different blades whose compositions are given in Tables 1 and 2.

The steel blades underwent the following heat treatment :

- austenitization at 1045 to 1050 °C/air quench,
- tempering at 640 to 660 °C/2 to 4 hours/air cooling.

After forging, the TA6V blades were kept for 1 to 2 hours at 700 °C and cooled in air.

The mechanical properties resulting from these treatments are summarized in Table 3, and the microstructures obtained are shown in Fig. 1.

EXPERIMENTAL

Testing Equipment

The tests were performed on an Instron 1273 servo-hydraulic fatigue machine, capacity 100 kN, equipped with :

- a thermostatically controlled corrosion cell used to operate in aqueous medium up to 80 °C,
- a DF 20 type crack initiation detector sold by Instruments SA, its operation based on an a.c. (50 Hz) potential drop method,
- a binocular microscope with 50X magnification, mounted on a micrometric table, used to measure the crack length to within 0.01 mm.

Test Specimens

Crack initiation was investigated with notched bend test specimens (Fig. 2) called KF 10A. The notch profile was selected to obtain a K_{Tn} of about 2, similar to those routinely encountered in the blades. The stress concentration factor K_{Tn} of the notch selected was calculated from Peterson (1974) and was equal to 2.02. The notch was machined by electro-erosion and its surface polished mechanically (finishing with 200 Å alumina) to eliminate any pre-existing incipient cracks.

Compact CT 25 chevron test specimens were employed for crack growth threshold tests.

TABLE 1. Z19 CD12-1 Composition (wt %)

	C	S	P	Si	Mn	Cr	Ni	Mo	V
Smith Clayton	0,17	0,04	0,012	0,29	0,45	12,1	0,76	0,94	0,03
Thyssen	0,18	0,06	0,025	0,29	0,52	12,3	0,59	0,81	0,02

TABLE 2. TA6V composition (wt %)

Fe	C	O	N	H	Al	V
0,08	0,008	0,16	0,008	0,0024	6,1	3,8
0,13	0,014	0,19	0,019	0,0033	6,3	4,1

TABLE 3. Mechanical Properties

Material	0,2 % Proof Strength (MPa)	σ_{ult} (MPa)	Elongation to Fracture (%)	Reduction of area (%)
Z19 CD12-1				
Smith Clayton	745	925	17	53
Thyssen	655	848	17,6	51
"α + β " forged	854	925	12	36
TA6V	932	980	18	42
" β " forged	810	903	10	15
TA6V	855	950	10	23

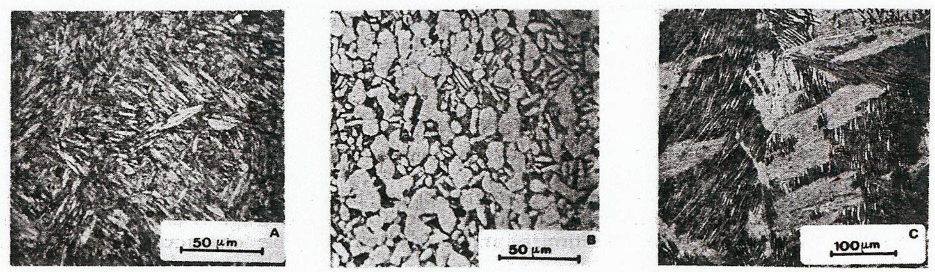


Fig. 1. Micrographs of the alloys studied
A) Z19 CD12-1
B) "α + β" forged TA6V
C) " β " forged TA6V

Media Investigated

Tests were conducted in the following media :

- medium 1 : air at ambient temperature,
- medium 2 : aerated water + NH_4^+ OH^- (pH ≃ 9) at 80 °C,
- medium 3 : medium 2 + NaCl (1 g/ℓ).

CRACK INITIATION TESTS

Test Procedure

The KF 10A test specimens were bend stressed at four points in the following conditions :

- inner span 28 mm, outer span 84 mm,
- sine force signal with frequency between 10 and 100 Hz,
- ratio R = 0.5,
- media investigated : 1, 2 and 3.

Crack initiation was identified using a DF 20 detector, of which the detection limit corresponds to a crack area of about 0.5 mm².

Results

The results are presented in the $\Delta S = f(\log Na)$ diagrams where :

- Na is the number of cycles to initiation,
- $\Delta S = S_{max} - S_{min}$ is equal to $K_{Tn} \Delta\sigma_n$ and was taken as the initiation parameter.

The results concerning Z19 CD12-1 steel are presented in Fig. 3. The crack initiation strength of this steel appears to decline as the medium becomes more corrosive. The degradation observed between medium 2 (ΔS_D = 675 MPa) and medium 3 (ΔS_D = 500 MPa) was attributed to the formation of corrosion pits in the latter medium (Fig. 4) where the crack initiated.

However, in our opinion, the difference observed between medium 1 and medium 2 is chiefly related to the difference in mechanical strength of the two blades used. In fact, tests performed in air with specimens taken from the Thyssen blade (Coulon, 1983) showed that, between R = 0.1 and R = 0.7, the initiation endurance limit could be taken as 650 MPa.

To conclude, the crack initiation strength of Z19 CD12-1 deteriorates in medium 3 (presence of NaCl) due to the appearance of corrosion pits.

For TA6V, it may be considered that the crack behaviour is independent of the medium considered, whether its structure is of the equiaxial (Fig. 5) or Widmanstatten (Fig. 6) type. The endurance limits at 10^7 cycles can be characterized by the following values of ΔS_D :

- TA6V "α + β" ΔS_D ≃ 350 MPa,
- TA6V "β" ΔS_D ≃ 500 MPa.

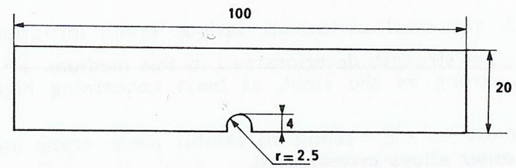


Fig. 2. KF 10 A specimen

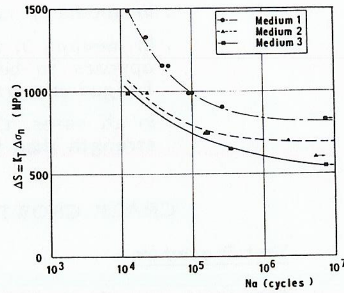
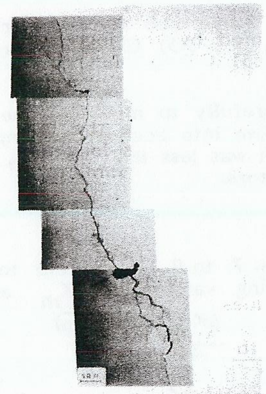


Fig. 3. Number of cycles at crack initiation (Na) versus Δ S for Z19 CD12-1 steel



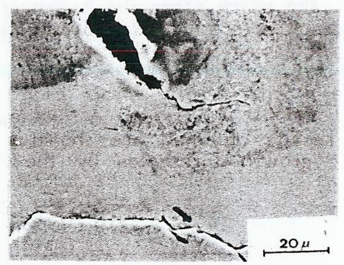


Fig. 4. Z19 CD12-1 steel in medium 3. Corrosion pits observed at the notch root.

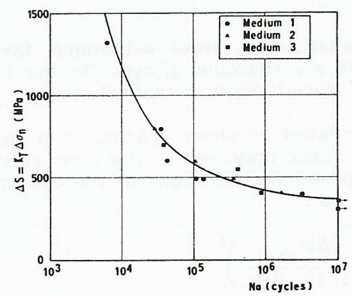


Fig. 5. Number of cycles at crack initiation (Na) versus ΔS for "α + β" forged TA6V

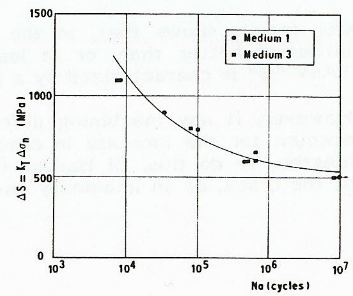


Fig. 6. Number of cycles at crack initiation (Na) versus ΔS for "β " forged TA6V

Hence it appears that :

- in media 1 and 2, the steel withstands fatigue crack initiation best,
- in medium 3, the steel strength deteriorates : in this medium, TA6V "β" appears to be as strong as the steel, at least concerning high-cycle fatigue strength,
- in all cases, the TA6V "α + β" seems to exhibit lower crack initiation strength than the other alloys investigated.

CRACK GROWTH THRESHOLDS

Test Procedure

The crack growth threshold tests were performed by the increasing ΔK method applied to tensile stressed (F = 60 Hz, R = 0.5) CT 25 chevron test specimens in air (medium 1).

The pre-crack stage was reproduced carefully to minimize the influence of load reductions, and no measurement was taken into account as long as the growth of the crack after the "exit" of the chevron was less than 2.5 mm, to avoid distorting the calculation of the stress intensity factors.

Results

The results obtained are shown in Figs. 7 to 9. They help to characterize the crack growth thresholds by the following values of ΔK_{th} at 10^{-7} mm/cycle :

alloy	ΔK_{th} (MPa$\sqrt{m}$)
Z19 CD12-1	4
TA6V "α + β"	3.5
TA6V "β"	5.9

This shows that the steel exhibited slightly better behaviour than TA6V "α + β" concerning the crack growth threshold in air, but did not behave as well as TA6V "β".

DISCUSSION

Our results shows that, in the media investigated, steel withstands fatigue crack initiation better than, or at least as well as, titanium alloys. On the other hand, TA6V "β" is characterized by a higher ΔK threshold than that of steel.

However, if any machining defects are treated as short cracks, it is necessary to account for the increase in crack growth rates observed in the case of short crack lengths. To do this, El Haddad (1979) proposed the addition, to the effective length of the crack, of an imaginary length equal to :

$$\ell_0 = \frac{1}{\pi}\left(\frac{\Delta K_{th}}{1.12\ \Delta\sigma_D}\right)^2$$

where $\Delta\sigma_D$ represents the endurance limit on smooth test specimens.

Furthermore, Topper (1982) showed that the endurance limit of a specimen with a blunt notch could be considered as equal to $\Delta\sigma_D/K_T$. In other words, $\Delta\sigma_D$ is equal to ΔS_D.

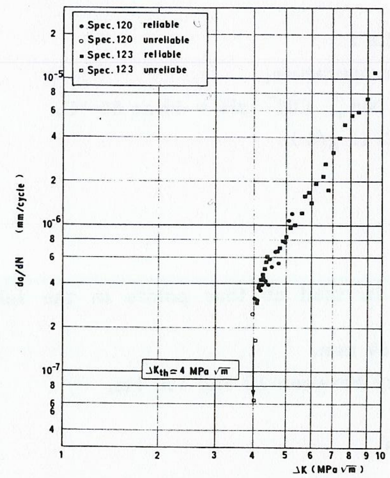


Fig. 7. Crack growth rate (da/dN) versus ΔK for Z19 CD12-1 steel

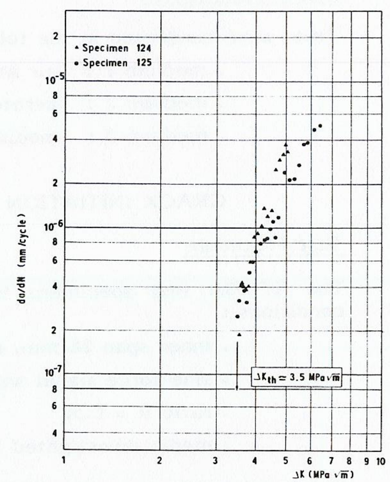


Fig. 8. Crack growth rate (da/dN) versus ΔK for "α + β" forged TA6V

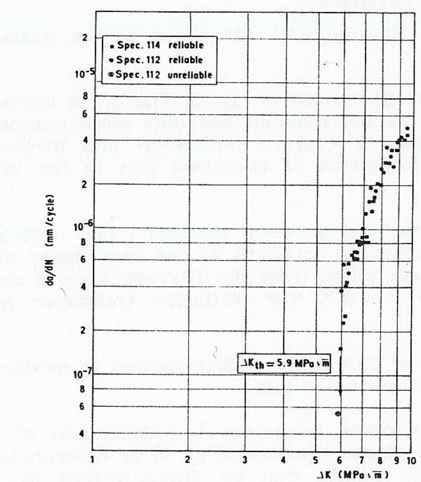


Fig. 9. Crack growth rate (da/dN) versus ΔK for "β" forged TA6V

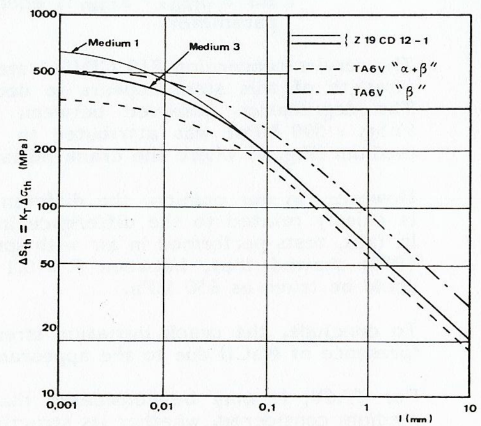


Fig. 10. Effect of crack length (ℓ) on threshold stress range (ΔS_{th}) for the alloys studied

Finally, a conservative estimate of the threshold stress range to ensure that a crack (small in comparison with the dimensions of the part considered) initiating from a blunt notch does not propagate, is given by :

$$\Delta S_{th} = K_T \, \Delta\sigma_{th} = \frac{\Delta K_{th}}{1.12\sqrt{\pi(\ell + \ell_0)}}$$

For the materials and media considered, Figure 10 shows ΔS_{th} as a function of length ℓ of a small crack in comparison with the dimensions of the part considered. For media 2 and 3, we assumed that the ΔK threshold was identical to the value measured in air. This is a reasonable assumption in our opinion because :

- it is confirmed in other 12 % chromium steels (Coulon, 1979),
- the initiation behaviour of TA6V is identical in the three media considered.

The examination of this figure shows that, in the presence of notch cracks longer than 10 μm (corresponding to a small machining defect), "β" forged TA6V displays the best behaviour in the media considered.

CONCLUSIONS

With respect to fatigue crack initiation, Z19 CD12-1 steel seems to be at least as good as TA6V in the media considered. However, corrosion pits appeared in the steel in medium 3, causing the crack initiation strength to deteriorate. On the other hand, TA6V appears to be unaffected by the media investigated, and seems to be competitive in absolute value in medium 3.

Furthermore, it is important to point out the potential value of forging in phase "β" for TA6V in relation to crack initiation and the crack growth threshold (which seems to be more favourable than for "α + β" forged TA6V).

Finally, it may be considered that, in the presence of machining defects, "β" forged TA6V behaves better than 12 % chromium steel in the three media investigated.

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