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EFFECTS OF TENSILE STRENGHT ON FATIGUE BEHAVIOR AND NOTCH SENSITIVITY OF TI-6AL-4V

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Abstract: *In this research, rotating bending fatigue test at minimum to maximum stress ratio of R=-1 was used for investigating the fatigue behavior of Ti-6Al-4V alloy. Both smooth and notched specimens, with elastic concentration factor,* k_t*, of approximately 3.6 and 4.1 were used for this purpose.*
In addition, the effect of variation in ultimate tensile strength, UTS, on the fatigue behavior of this alloy was studied. S-N curves were drawn and the value of notch sensitivity was obtained for each case.
The results showed that the presence of notch in Ti-6Al-4V alloy has a different amount of sensitivity when the notched specimens were subjected to high cycle fatigue (HCF) and low cycle fatigue (LCF) tests. However, the notch sensitivity of this alloy was shown generally to be much lower than steel alloys with similar UTS values.Thus, considering the high compatibility of this alloy with the body environment and its low sensitivity to notch, one can strongly recommend this alloy for use in biomedical application.

KeyWords: *Ti-6Al-4V alloy, Fatigue, Stress concentration factor, Fatigue notch factor, Notch Sensitivity, Effect of UTS on fatigue.*

1. INTRODUCTION

1.1. High Cycle Fatigue of Ti-6Al-4V

Titanium continues to be widely used for aircraft engine, air frame components, implant and biomedical applications. Titanium alloys have a high Strength-to-weight ratio with a density approximately 60% that of Steel [1]. Their excellent corrosion resistance in many environments is due to the formation of a stable oxdie surface layer [2]. The most commonly used titanium alloy is Ti-6Al-4V, an alpha- beta alloy which at room temperature is around 90% alpha phase by volume. Therefor, the alpha phase tends to control the mechanical properties of this alloy when used at low temperature. In addition to the alpha grain size, the fatigue life of Ti-6Al-4V components is influenced by the amount of age hardening, oxygen content, and grain morphology [3].
High cycle fatigue tests performed on Ti-6Al-4V alloy showed that by decreasing alpha grain size, fatigue properties of both smooth and notched (k_t=1.8) specimens, can be improved [4].
The fatigue limit (σ_e) of the alloy under investigation, subsatncially improved by increasing the UTS values. The UTS values, for the specimens with the same compositions can be increased by reducing their grain size. In a different research performed by Lucase and Konieczny [5] on the effect of UTS on fatigue behavior of steel alloys, was shown that the fatigue limit can be changed by variying UTS of these alloys. So, their observation, is similar to that observed in this research.

1.2. Fatigue Notch Factor and Notch Sensitivity

An elastic structural member containing a notch has an elastic stress concentration factor, k_t, associated with it. This depends not only upon the geometry of the notch but also the mode of loading [4]. Stress concentration factor defined as the ratio of maximum local stress, σ_{max}, to a nominal stress, σ_{nom} (figure 1-1) [6]:

$$k_t = \frac{\sigma_{max}}{\sigma_{nom}} \qquad (1\text{-}1)$$

The fatigue notch factor, k_f, is alternately used instead of k_t for a notched component, and is defined as [7]:

$$K_f = \frac{\text{Unnotched fatigue limit}}{\text{Notched fatigue limit}} \qquad (1\text{-}2)$$

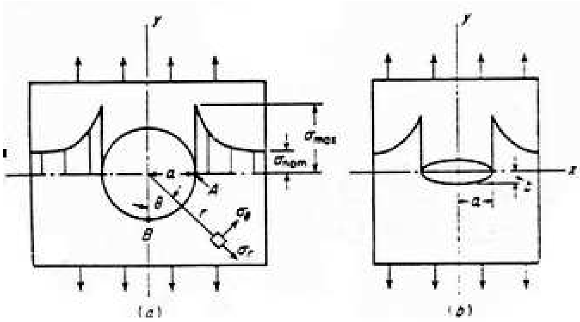

Fig. 1-1. Schematic of stress distribution around a crack perpendicular to applied stress [6].

When $k_f = 1$, there is no degradation in the component due to the notch, and when $k_f = k_t$, the notch produces the full theoretical reduction in the fatigue limit. A size effect argument is often used to help explaining the observed variation in fatigue limit. A large notch in a specimen is accompanied by a reduced stress gradient, in comparison to a sharper sterss gradient which is created by a smaller notch of similar theoretical elastic stress concentration factor. The more gradual stress gradient together with the same k_t means that a larger volume of material is subjected to the elevated stresses, and consequently the reduction in fatigue strength is greater than that due to the smaller notch [7].

The fatigue notch factor is dependent not only upon the component geometry, but also on the material properties and the mode of loading. The degree of difference between these two quantities is of practical interest to engineers, and is frequntly expressed using the notch sensitivity, q, given by [8]:

$$q = \frac{k_f - 1}{k_t - 1} \qquad (1\text{-}3)$$

Where, in general, $0 \le q \le 1$. When the theoritical stress concentration factor equals the fatigue notch factor, q =1. If the notch has no adverse effect on the fatigue limit, q = 0 [7].

2. EXPERIMENTAL PROCEDURES

All specimens were prepared from Ti-6Al-4V round bars having different grain sizes and hence different UTS values. Worth mentionnting that diameters of the original bars where different (i.e. 8, 11, 14, 18, 20 & 25 mm), so that the lower the bar diameter the lower was the grain size.

Tensile tests were carried out at room temperature using an Instron-type testing machine. For each bar, five smooth tensile samples were prepared according to ASTM E8 standard.

The fatigue limit, for both smooth and notched specimens, was determined by rotating bending fatigue testing according to ASTM E466 at R= -1. Two sets of notched specimens were tested, one set with stress concentration factor, k_t=3.6, and the other set with k_t=4.1. Then S-N curves were drawn for each bar on the base of at least eighth fatigue tests.

3. RESULTS AND DISCUSSION

The mean results of all mechanical tests have been summarized in table 3-1. S-N curves of each bar were drawn for smooth and notched specimens [9], and then the fatigue strength of each bar was calculated from the S-N curves and the results were presented in Table 3-1.

Fatigue ratio (σ_e/σ_u) versus ultimate tensile strength curves are shown in figure 3-1. Fatigue ratio is approximately 0.4 for all smooth specimens, 0.35 for notched (k_t=3.6) and 0.32 for notched (k_t = 4.1) specimens. One can see from the results presented in Table 3-1 and Fig. 3-1, that the fatigue strengthes of various specimens tested at room temperature increased with increasing of tensile strength.

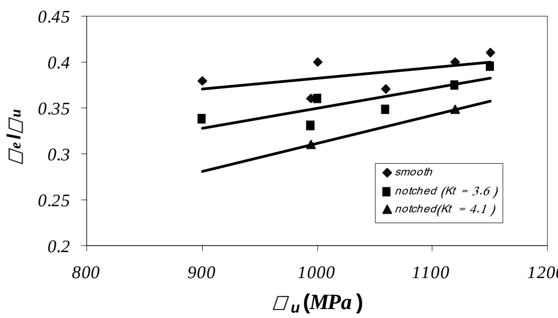

Fig. 3-1. Fatigue ratio vs tensile strength for Ti-6Al-4V alloy.

In a similar research performed on Austenitic steels by Lucas and Konieczny [5], was shown that an increase in UTS caused the fatigue limits of the steel alloys were increased too. Therefor, the relation between the fatigue strength and UTS of the present research and Lucas and Konieczny studies is consistent. So that it seems, the factors cause an increase in UTS will also

Table 3-1. Average tensile and fatigue strength results and their standard deviations.

Diameter of original bars having different grain sizes (mm)	25	14	18	20	11	8
Tensile strength (MPa)	900±5	995±5	1000±5	1061±6	1120±5	1150±7
Fatigue strength (MPa) (smooth)	345±10	360±8	400±9	400±5	445±8	475±7
Fatigue strength (MPa) (Notched) (k_t=3.6)	305±9	330±8	360±7	370±6	420±5	455±7
Fatigue strength (MPa) (Notched) (k_t =4.1)	---	310±6	---	---	390±4	---

increase the fatigue strength, at least for Austenitic steels and Ti-alloys.

Due to limited number of slip system in HCP Ti-alloys, i.e. (1000) <1120>, the chance of slip and moving mobile dislocations in favorite planes has been substancially reduced, so that probability of formation of intrusions and extrusions which are the prime cause of crack nucleation has been decreased. So, this means the fatigue crack nucleation process which apparently determines the maximum fatigue life for ductile materials is delaied [9].

Using the fatigue limits in both HCF and LCF, reduction percents of fatigue strengthes were obtained. Fatigue reduction percent is defined as:

$$\text{Fatigue reduction percent} = \frac{\sigma_e(\text{Smooth}) - \sigma_e(\text{notched})}{\sigma_e(\text{Smooth})} \times 100 \quad (3\text{-}1)$$

Fig. 3-2 shows fatigue reduction percent for LCF and HCF for various tensile strengthes but for constant stress concentration factor, k_t=3.6. According to this figure and equation (3-1), this percentage decreases with increaseing tensile strength.

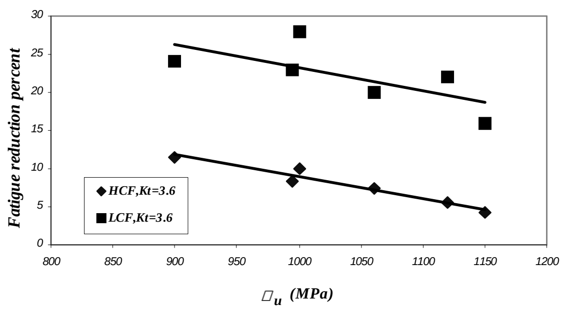

Fig. 3-2. Fatigue reduction percent vs. tensile strength for Ti-6Al-4V.

Fatigue notch factors for HCF, i.e. k_f , and for LCF, i.e. k'_f , were calculated from formula no. 1-2 and then were drawn versus tensile strength in Fig. 3-3.

This figure showes that the presence of notch, doesn't affect notticeably the changes in fatigue notch factor, which is a measure of sensitivity of a material to the presence of a notch. That is to say, since the slopes of k_f and k'_f lines in Fig. 3-3 did not change and two lines which represent fatigue notch factors for HCF and LCF are neerly parallel, then it seems the presence of notch has not affected the fatigue behavior of the alloy subjected to various fatigue conditions and this material has a very low sensitivity to notch. Therefor, one may say that the small rate of fatigue notch factor reduction due to increase of UTS is a good indication of non-sensitivity of this material to notch. This means that this alloy is an ideal alloy for complex shape specimens which can be used as body components.

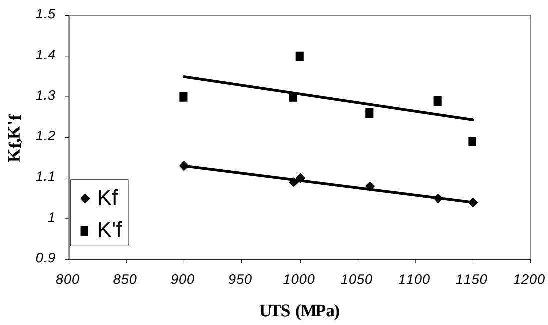

Fig. 3-3. k_f and k'_f vs tensile strength for Ti-6Al-4V.

As it was mention above, the mechanism of crack nucleation in deformable materials is said [6] to be usually the formation of intrusion and extrusion in HCF process. Howerver, in LCF process this is not the case. Crack nucleates in this process by bulk plastic deformations [9]. So, due to the presence of this huge plastic area, the palstic deformation due to notch is not practically effective. Therefor, sensitivity of the material subjected to LCF is nearly independent of the presence of notch. On the other hand, the rate of changes of k_f with UTS for HCF is similar to that of LCF (Fig. 3-3). This indicates that the fatigue crack growth of this alloy under the conditions of HCF is similar to that of LCF, hence it is non-sensitive to notch under HCF conditions. Thus, this alloy can be used under HCF conditions with acceptable amount of safety even if the surface conditions of the component surface is not to be smooth.

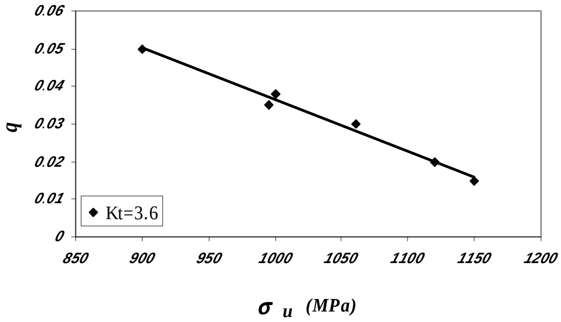

Fig. 3-4. Notch sensitivity vs tensile strength for Ti-6Al-4V.

Relation between notch sensitivity (q) and ultimate tensile strength of Ti-6Al-4V alloys was investigated in constant k_t and the results are presented in Table 3-2 and Fig. 3-4. The results show that notch sensitivity reduces with increasing UTS.

Table 3-2. Notch Sensitivity of Specimens.

Tensile strength (MPa)		900	995	1000	1061	1120	1150
q	$k_t = 3.6$	0.05	0.035	0.038	0.03	0.02	0.015
	$k_t = 4.1$	----	0.05	----	----	0.045	----

This might be, related to crack initiation mechanism. Slip happens more difficult in stronger materials. Therefor, under HCF conditions the chance of formation of intrusion and extrusion in a high strength material is reduced substancially. Thus, crack nucleation in this type of materical experience a delay which results to higher fatigue life of the component.By increasing the strength of material, k_f values decrease for a constant k_t value (Fig. 3-3). Therefore by decreaseing k_f values one expect the values of q decrease according to formula 1-3. That is to say under conditions of HCF, this alloy is less notch sensitive, when it has higher strength.

4. CONCLUSIONS

1. Fatigue strength of Ti-6Al-4V alloy increase with increasing of tensile strength.
2. Notch sensitivity of Ti-6Al-4V alloy reduces with increasing tensile strength for a constant concentraction factor (k_t).
3. Presence of notch in Ti-6Al-4V alloy, doesn't affect the fatigue crack growth behavior, under the condition of HCF and LCF. Therefor this alloy with high strength is the most suitable for parts that use in HCF conditions.

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