The Influence of Surface Residual Stress on Fatigue Limit of Titanium

E. C. REED
Senior Materials Testing Engineer, Pratt and Whitney Aircraft Division, United Aircraft Corporation, East Hartford, Conn.

J. A. VIENS
Methods Development Group Engineer, Pratt and Whitney Aircraft Division, United Aircraft Corporation, East Hartford, Conn.

Investigation of the effect of surface residual stress on the endurance limit of 6Al-4V titanium alloy shows that this effect is equal within experimental error to the residual stress divided by a constant. Results can be expressed by a simple equation. A value for the constant has been derived.

The effect of surface residual stress on the fatigue strength of titanium has been of interest for some time because of increased use of titanium by industry and has led to a project to investigate this relationship. This paper presents correlation of fatigue and surface residual-stress results for 6Al-4V titanium alloy with stresses introduced into the surface by various grinding procedures and by wet blasting with 0.001-in-diam glass beads.

EXPERIMENTAL PROCEDURE

Test Piece Preparation
Test pieces consisting of modified Krouse plate fatigue specimens with integrally attached residual-stress test specimens were machined from 6Al-4V titanium alloy sheet in the annealed condition, Fig. 1. All tests were made on one lot of titanium alloy with the fol-
Fig. 1 Modified Krouse fatigue specimen and residual stress specimen.

Following percentage composition: 0.064 C, 0.30 Fe, 5.90 Al, 0.019 N₂, 3.90 V, 0.004 H₂ and remainder titanium. Hardness of alloy was RC 30-32.

Both surfaces of specimens were finished by grinding, followed by annealing in vacuum at 1250°F for 36 hr. Test grinding was done on a reciprocating table surface grinder with a variable-speed grinding-wheel spindle and a specially designed vacuum chuck to insure uniform clamping pressure on specimens.

After test-piece preparation, residual-stress and fatigue specimens were separated. An optical interferometer was used to determine residual stresses and Krouse plate fatigue machines were employed to determine endurance limits.

Residual-Stress Tests

After separation from the fatigue-test specimen, one 2.60 x 2.60-in. face of each residual-stress specimen was surface ground or wet glass-bead-blasted according to each test procedure. The opposite face of each specimen was polished by standard metallographic techniques to specular reflectance sufficient to produce an interference pattern when placed in contact with an optical flat and illuminated with mercury light. After surface preparation, each specimen was placed in the optical interferometer to obtain interference patterns caused by curvature of the polished face, resulting from removal of each increment of ground or blasted test surface. Material was removed by etching with an aqueous solution of 30 per cent HNO₃ (sp gr 1.41) and 3 per cent HF (sp gr 1.24) by volume. Etching was done at room temperature with the entire specimen masked off except the test surface. Increments removed were measured by determining weight loss from etching.

Biaxial residual stresses were calculated from changes in specimen longitudinal and transverse curvatures as layers of test surface were removed. For the ground specimens, longitudinal direction with the grind, and transverse direction was across the grind. The stress-calculation method has been used by Mattson(1), Leaf(2), and Letner(3), as well as by Reed(4).

Fatigue-Strength Tests

Modified Krouse plate fatigue specimens for each investigation were divided into groups of approximately 10 specimens each. One group was used for par bars and the other groups were surface ground or wet glass-bead-blasted on both faces according to each test procedure. The edges of test specimens were broken and shot-peened with No. 110 cast-steel shot to prevent specimen breakage at the edges. Endurance limits, where 10⁷ cycles was considered a run-out, were determined by the staircase method. Each specimen was run at a previously determined load increment, above or below the load of the preceding specimen, depending on whether that specimen ran out or failed. If the specimen ran out, the load was increased, and if it failed, the load was decreased. From these failures and run-outs, an average value was obtained which is reported as mean endurance strength.

RESULTS AND DISCUSSION

To evaluate the effect of surface biaxial residual grinding stresses on fatigue strength

$F_b = \frac{f_b}{f_p} \cdot S$

WHERE

$F_b = $ ENDURANCE LIMIT (PSI) OF STRESSED SPECIMEN
$f_b = $ ENDURANCE LIMIT (PSI) OF PAR BAR SPECIMEN
$S = $ SURFACE RESIDUAL STRESS (PSI)

Fig. 2 Surface residual stress-endurance limit relationship for 6 Al-4 V titanium alloy.
of 6 Al - 4 V titanium alloy, stresses were introduced by "low-speed," "normal-speed," and "near-normal speed" methods. The low-speed method employed a table speed of 30 fpm, a monocrystalline (1 crystal/grain) aluminum-oxide wheel, aqueous potassium-nitrite grinding fluid and wheel speed of 1800 sfpm. The normal-speed method employed a table speed of 30 fpm, a black-silicon-carbide wheel, sulphur-chlorinated, fatty-type oil grinding fluid, and a wheel speed of 5500 sfpm. The near-normal-speed method was similar to the normal-speed method except for wheel speed which was 4000 sfpm.

Maximum biaxial surface-grinding stresses ranged from 62,000 psi tension (normal-speed method - 0.001 in. per pass downfeed and 0.050 in. per pass crossfeed) to 25,000 psi compression (low-speed method - 0.001 in. per pass downfeed and 0.050 in. per pass crossfeed).

To evaluate the effect of a high compressive residual surface stress on endurance limit, 6 Al - 4 V titanium alloy was wet-blasted with 0.001-in-diam glass beads at 90 psi pressure, resulting in a surface stress of 108,000 psi compression. Endurance limits under completely reversed stress varied between 36,800 psi and 53,900 psi. Surface compressive stress increased endurance limit and tensile stress reduced endurance limit, Table 1. Residual stresses plotted versus fatigue results, Fig. 2, indicated that these properties are related by the following empirical formula:

$$F_s = F_p - (S/10)$$

where $F_s$ = endurance limit (psi) or stressed specimen at $10^7$ cycles

$$F_p = \text{endurance limit (psi) of par bar at } 10^7 \text{ cycles}$$

$$S = \text{surface residual stress, psi}$$

The endurance limits may appear low when compared with values obtained with round rotating-beam specimens, which give par-bar values of approximately 70,000 psi. However the present results are believed associated with the size and shape of the fatigue specimen. Tarasow, Hyler, and Letner found similar results in tests conducted on hardened steel specimens (5). In these tests an effort was made to minimize all variables except surface stress and endurance limit. All surface finishes were kept in the same magnitude - less than 20 microin. - rms. Depth of residual stresses were also similar.
less than 0.004 in. Fig. 3 shows typical stress distributions.

A previous paper by Clorite and Reed (6) presented effects of various grinding conditions on uniaxial residual stresses in titanium test bars. The uniaxial stress values correlate within experimental error with the biaxial stress values of the present paper with the exception of the low-speed test, Fig. 4. However the discrepancy in the low-speed values can be explained by an examination of Fig. 5 taken from a supplementary test made by Reed. For a 1-10 concentration of KNO2-H2O, as used in this investigation, residual stresses can vary over a large range and still be near the stress-grinding fluid-concentration curve. Fig. 5 also shows the close relationship between grinding ratios and residual stresses. Some grinding departments are reluctant to use a 1-10 concentration of KNO2-H2O grinding fluid, as used in these tests, as this concentration may leave some salt deposit on grinding machinery and may tend to irritate operators’ hands. Therefore for some applications less concentrated grinding fluid should be used. Of interest to grinders, Viens has shown that while a 1-10 concentration of KNO2-H2O produces less wheel wear than a 1-20 concentration, stock removal is approximately the same.

Conclusions

Based upon the tests conducted, it is concluded that endurance limit of residually stressed titanium differs from that of unstressed titanium by 1/10 of the value of the corresponding residual stress. Compressive stress causes increase, and tensile stress causes decrease from par bar value.

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References