Stress Relaxation in Powder Metallurgy Superalloy Disks

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Abstract

Modern powder metallurgy (PM) processed disk superalloys have improved mechanical properties and temperature capabilities over previous cast and wrought disk alloys, due to improved microstructural uniformity and higher refractory element contents. However, these PM improvements have been accompanied by increased sensitivities to notches and defects at disk surfaces. These surface sensitivities can be addressed by applying beneficial compressive residual stresses at disk surfaces. The compressive residual stresses are produced with surface enhancement processes such as shot peening which plastically deform the near-surface material, usually performed after final disk machining. Such compressive residual stresses act to preclude or delay surface cracking during service due to loading, defects, handling or foreign object damage, and environmental attack. An issue of general concern is the potential relaxation of beneficial compressive surface residual stresses as engine temperatures increase. The objective of this study was to assess the relaxation of stresses at increasing temperatures in several PM superalloy disks. The effects of temperature, time, and plasticity were examined.

Materials and Procedures

Five second stage turbine disks were obtained from an Army maintenance depot after serving full, comparable lives on T700 helicopter engines. Two disks were subjected to extensive residual stress measurements, with X-ray depth profiles taken at several key locations. These two disks were then sectioned to allow X-ray measurements at inaccessible locations, to provide bore sections for exposures, and to provide blanks for machining mechanical test specimens. The bore surface had the highest magnitude of compressive residual stresses, in comparison to web, air slot, and air hole locations. However, the bore surface was not accessible for X-ray measurement unless the disk was sectioned, which greatly disturbed the stress state. Therefore, a location just inboard of the cooling air slots on the forward side of the rim was selected for multiple measurements (Fig. 1).

The three remaining whole disks and extracted bore sections were exposed at 593, 650, and 704°C. Exposures of disks at 593 and 704°C were interrupted to allow X-ray measurements of residual stresses at 1 and 500 h. The disk exposed at 650°C was interrupted at 1, 24, and 500 h. At each interval, residual stress and cold work were measured on the surface at five locations, and a depth profile was taken at one location (Fig. 1). X-ray measurements were performed using a two-angle sine-squared-psi technique, in accordance with SAE J784a, employing the diffraction of manganese K-alpha radiation from the (311) planes. The diffraction K-alpha 1 peak angular positions at each of the psi tilts were determined according to procedures previously described [1]. The resulting strains were then used to determine macroscopic residual stresses [2]. Cold work was determined through measuring the half peak width of the (311) diffraction peak. Previous calibration tests provided the relationship between this half peak width and plastic strain in compression tested specimens.

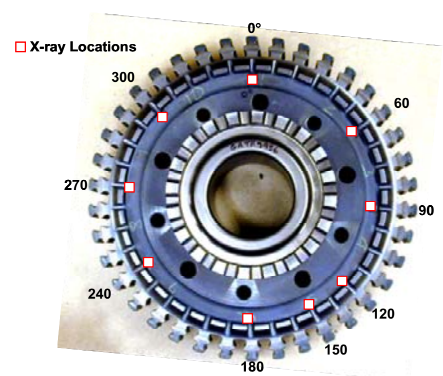

Fig. 1. Disk locations selected for measurements.

Results and Discussion

X-ray Measurements Exposures of 593 to 704°C produced significant relaxations in residual stresses and cold work in the disks. Depth profiles as measured on whole disks and on bore sections are shown at each temperature and exposure time in Fig. 2. Relaxation of residual stress and cold work clearly increased with increasing temperature and time. For disks at the extreme exposure condition of 704°C for 500h, maximum compressive residual stress was reduced by 70% and cold work was reduced by 50%.

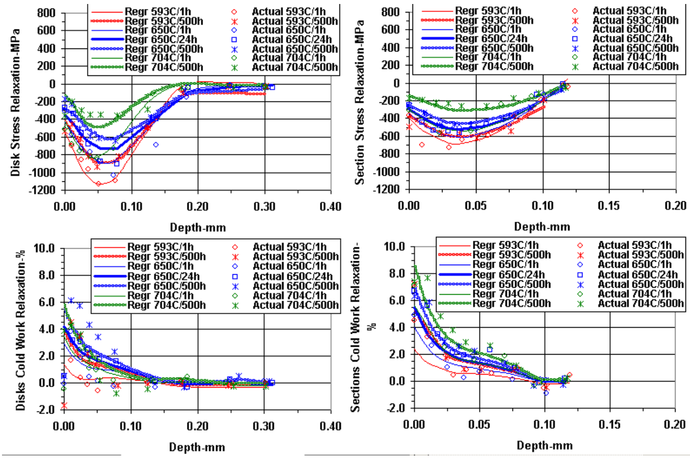

Fig. 2. Residual stress and cold work profiles before and after exposures of disks and disk sections.

Regressions The relaxations of residual stress and cold work were modeled using multiple linear regression, evaluating terms of exposure temperature (T), common logarithm of time (LT), initial compressive stress (IS), initial cold work (ICW), and their interaction terms. Forward stepwise selections of terms were performed, with a probability of significance exceeding 90% necessary for inclusion of a term. Stress relaxation (SR) was found to increase with greater exposure temperature, time, initial compressive stress, and initial cold work, as given in the resulting regression equation 1. Significant interaction terms indicated stress relaxation was accentuated for combinations of high temperature with long time. Stress relaxation was also accentuated for combinations of high initial compressive residual stress with high temperature, time, or initial cold work. The regression equation estimates are included in Fig. 2.

$$SR=422.1-0.606*T-338.2*LT+1.9401*IS-16.1858*ICW+0.4864*T*LT-0.0029*T*IS-0.1213*LT*IS-0.05165*IS*ICW; \quad R^2_{adj}=0.8566, \text{ rmsError}=77 \text{ MPa} \quad (1)$$

Cold work relaxation (CWR) was also found to increase with greater exposure temperature, time, initial compressive stress, and initial cold work, equation 2. Significant interaction terms indicated cold work relaxation was accentuated for combinations of high initial cold work with high temperature, time, or initial compressive stress.

$$CWR=-1.052+0.0012*T+0.0695*LT-0.0007*IS-0.7203*ICW+0.0017*T*ICW+0.0602*LT*ICW+0.0003*IS*ICW; \quad R^2_{adj}=0.6308, \text{ rmsError}=1.3\% \quad (2)$$

Specimen Tests Cylindrical specimens having a gage diameter of 4 mm and gage length of 21 mm were machined from an unexposed disk. They were tested at 593, 650, and 704°C in a servohydraulic test machine using a resistance heating furnace and axial extensometer. The tests were started with strain increased at a constant rate of 0.5%/min. in accordance with tensile testing procedures described in ASTM E21. The tests were then stopped at 1% strain and held at this constant strain, to measure stress relaxation rates. In subsequent tests, specimens were first tensile tested at room temperature to introduce plastic prestrains up to 13.7%. These prestrained specimens were then also given the tensile-stress relaxation tests. As shown in Fig. 3, stress relaxation again increased with temperature and stress, and also increased with cold work introduced by the plastic pre-strains in these specimen tests. Therefore the previous findings on disks and disk sections were an inherent material response, which could be screened with these simple specimen tests.

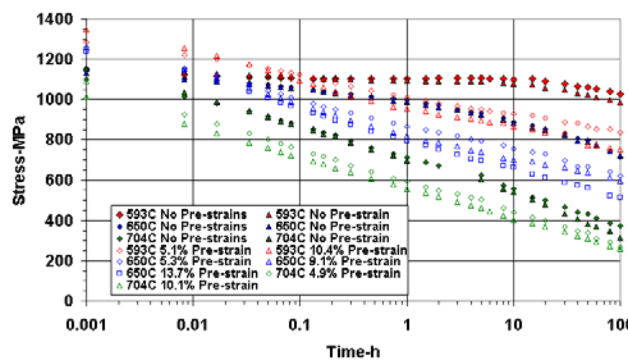

Fig. 3. Specimen tensile stress relaxation tests results.

Summary and Conclusions

Stress relaxation was evaluated in fully machined and fielded Rene′ 95 turbine disks and disk sections using exposures at temperatures of 593 to 704°C, and times of 1 to 500 h. Regression analyses indicated stress and cold work relaxation both increased with greater exposure temperature, time, initial compressive stress, and initial cold work. It can be concluded that the relaxation of beneficial compressive residual stresses can be reduced by optimizing initial cold work during surface enhancement processes, and then minimizing time at high temperatures. These residual stresses can be modeled and predicted during disk service exposures. This would allow full quantification of their benefits to fatigue life during service, after calibration of the effects of varied residual stresses on fatigue crack initiation and growth.

References

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