

Relaxation of shot-peened residual stresses under creep loading

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Creep tests on shot-peened nickel-base superalloy specimens, subject to applied stresses near and above monotonic yield, have been performed to characterize residual stress relaxation under sustained loading at 650 °C in IN100. Retained residual stress–depth profiles, measured on crept samples, show that yielding during initial loading produces the largest change in the residual stress profile. Furthermore, it is shown that applied stresses below yield exhibit similar retained residual stress profiles in the axial and transverse orientations.

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Shot-peening is a standard practice employed by numerous industries to impart compressive residual surface stresses into components to suppress crack initiation and crack growth. Several studies have characterized the beneficial effects of compressive residual surface stresses on fatigue life in turbine engine alloys [1–6].

Understanding the relaxation of residual stresses is necessary to improve the ability to predict the fatigue life of shot-peened components. Currently, designers do not account for the beneficial effect of shot-peening, which sometimes results in grossly conservative design practices. For applications that utilize aluminum and titanium alloys, subjected to moderate temperatures and stresses, residual stresses are assumed to be stable with repeated cyclic stress-controlled loading. In contrast, nickel-base superalloys are typically selected for applications where temperatures may reach 80% of the melting temperature and stresses approach or exceed the monotonic yield strength. For elevated temperature and high stress conditions, inelastic strain will alter the original (as-peened) residual stress–depth profile. Thermal relaxation studies on shot-peened titanium alloys [7] and nickel alloys [6,8–10] have demonstrated that relaxation of residual stresses may occur at relatively

low temperatures and over short durations. Further, changes in the microstructure and mechanical behavior from shot-peening, long-term elevated temperature exposure and deformation history may accelerate the relaxation rate of residual stresses. Understanding the relaxation of shot-peen-induced residual stresses under elevated temperature and yield stress conditions is important in improving the ability to predict fatigue life accurately.

For many standardized mechanical tests, such as tensile, creep and fatigue, specimen geometry is specified in the testing standard to avoid the pitfalls of specimen design. The shot-peening Almen strip provides only a qualitative measure of shot-peening intensity. No standard test geometry exists for characterizing residual stress–depth profiles or relaxation behavior of surface treatment processes. For this study, the design of the specimen geometry is based on the mechanics of the shot-peening process, the mechanical test matrix, the X-ray diffraction (XRD) measurement procedure and the planned modeling of relaxation behavior. XRD measurements are interpreted based on the diffraction of radiation reflected from the surface and to a depth of approximately 0.010 mm for this material. Since the XRD technique measures an average throughout a volume, it is important to have a uniform stress field in the plane of the material. Stress corrections for volume averaging and electropolishing for subsequent depth measurements [11] are valid when the stress is equally

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biaxial and only varies as a function of the depth. XRD cannot capture nonlinear stress gradients existing in the plane of the stress field. Therefore, careful review of XRD measurements is necessary in stress gradient regions such as notches, fillets and holes. A flat dogbone specimen with uniform gage section dimensions of width = 10 mm and thickness = 2 mm was used in this study. Additional details of the specimen design can be found in a previous study [14].

The residual stress measurements were collected at the surface and at nominal depths of 0.012, 0.025, 0.050, 0.075, 0.125, 0.175, 0.250 and 0.350 mm. XRD measurements were made in both the axial (loading) and transverse directions of the specimen, at the center of the gage section. The transverse measurements provide a nearly independent measure of thermal residual stress relaxation. The constant volume assumption of inelastic flow for plastic strain increments ($\Delta\epsilon_{11}^p + \Delta\epsilon_{22}^p + \Delta\epsilon_{33}^p = 0$) and creep strain increments ($\Delta\epsilon_{11}^c + \Delta\epsilon_{22}^c + \Delta\epsilon_{33}^c = 0$) implies that the transverse relaxation of strain increments ($\Delta\epsilon_{22}^p, \Delta\epsilon_{33}^p, \Delta\epsilon_{22}^c, \Delta\epsilon_{33}^c$) are dependent on the applied plastic strain ($\Delta\epsilon_{11}^p$) and creep strain ($\Delta\epsilon_{11}^c$) increments in the applied loading direction. Therefore, the retained transverse residual stress is not strictly a function of thermal exposure alone, but also the inelastic axial loading history.

Based on residual stress–depth profiles from a similar superalloy, IN718 [7], and typical shot-peening specifications for turbine engine components [1,3], a shot-peening Almen intensity of 6A was selected for this study. In a previous study [10], baseline residual stress–depth profiles were measured on six as-peened specimens. The six residual stress–depth profiles, shown in Figure 1, were measured from four different plates (A2, B2, C1, C2), all shot-peened at the same time. The surface residual stresses, compensatory tensile residual stresses and overall response for all six samples are similar. The peak compressive residual stress always occurs within 0.050 mm from the surface, as shown in Figure 1. Only one specimen, plate C2-1, exhibits an obviously different residual stress profile from the other five. The shot-peening coverage is assumed to be incomplete, for this particular sample.

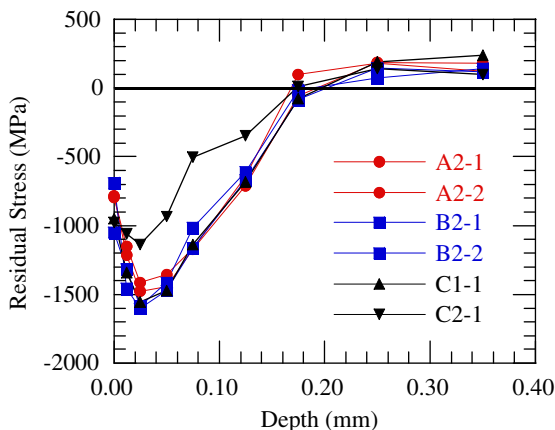


Figure 1. Residual stress–depth profiles of as processed (baseline) IN100.

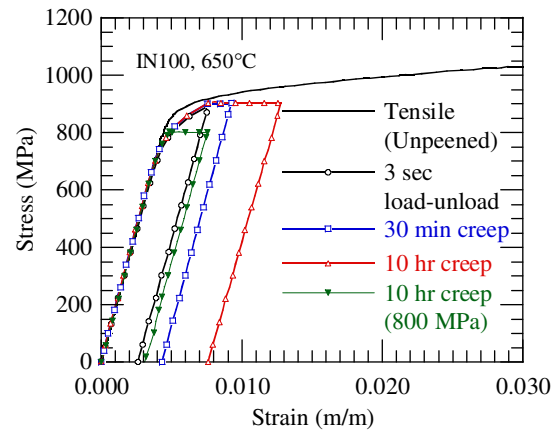


Figure 2. Stress–strain response of shot-peened IN100 specimens tested in this study.

Shown in Figure 2 is the tensile stress–strain curve of the virgin (unpeened) IN100 at 650 °C. As shown in this figure, plastic yielding begins at approximately 800 MPa in the virgin material. The applied stress levels chosen for the creep tests on peened specimens were 800 and 900 MPa. At 800 MPa the stress–strain curve is elastic, whereas at 900 MPa, a 0.2% plastic strain develops during loading. These stress levels provide a comparison for observing the change in the residual stress profiles under elastic and inelastic material responses, and for several sustained loading times. The remaining curves show the stress–strain responses of several shot-peened specimens under various loading histories. For example, the 3 s load–unload cycle to 900 MPa results in an total plastic strain of 0.0026 m m^{-1} (0.26%) that occurs during loading. For sustained loading, an additional time-dependent strain (creep) adds to the initial plastic strain. For example, the total plastic strain for the 30 min and 10 h creep tests are 0.0044 (0.44%) and 0.0080 m m^{-1} (0.80%), respectively. In contrast, the 10 h creep test at 800 MPa exhibits plastic strain similar to the 900 MPa 3 s load–unload cycle. Clearly, the applied stress level, the presence of plastic strain during loading and the duration of the sustained stress have an affect on the total plastic strain after unloading. The remainder of this paper discusses the effects of these loading parameters on the retained residual stress profile after unloading.

The retained residual stress–depth profiles for a shot-peened specimen subject to a single 3 s mechanical load–unload cycle are shown in Figure 3, along with the nominal as-peened (baseline) profile, from Figure 1, for comparison. The experimental procedure includes a 10 min elevated temperature soak at zero applied stress to ensure uniform temperature throughout the specimen gage section prior to mechanical loading. The maximum applied stress of 900 MPa, applied in the axial direction, results in yielding of the tensile residual stress in the core of the specimen during loading. The resulting effect is a decrease in the retained compressive and tensile residual stresses in both the axial and transverse orientations after unloading. The changes in the residual stress profiles are a result of the 10 min thermal exposure followed by yielding during mechanical loading. The peak compressive residual stresses are

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