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# STABILITY OF SHOT PEEN RESIDUAL STRESSES IN IN100 SUBJECTED TO CREEP AND FATIGUE LOADING (PREPRINT)


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**14. ABSTRACT**
Shot peening is commonly used to retard initiation and growth of fatigue cracks in fracture critical components. During service, the shot-peened residual stresses may change due to thermal-mechanical loading. This paper describes an approach for characterizing and modeling residual stress relaxation in supersolvus IN100 at 650 °C. The model incorporates the dominant creep deformation mechanism, coupling between the creep and plasticity models, and effects of prior plastic strain. Significant shot peen residual stresses are retained even after 300 hours of thermal exposure to 650 °C. Fatigue loading resulted in relaxation only in the initial load-unload cycle for the entire stress distribution. Under uniform applied stresses, residual stress reversal occurred for stresses greater than 1000 MPa. In geometries with steep gradients, such as notches, significant compressive residual stresses are retained near the surface even when the local stresses exceed the yield stress.

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# Stability of Shot Peen Residual Stresses in IN100 Subjected to Creep and Fatigue Loading

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**Abstract**

Shot peening is commonly used to retard initiation and growth of fatigue cracks in fracture critical components. During service, the shot-peened residual stresses may change due to thermal-mechanical loading. This paper describes an approach for characterizing and modeling residual stress relaxation in supersolvus IN100 at 650°C. The model incorporates the dominant creep deformation mechanism, coupling between the creep and plasticity models, and effects of prior plastic strain. Significant shot peen residual stresses are retained even after 300 hours of thermal exposure to 650°C. Fatigue loading resulted in relaxation only in the initial load-unload cycle for the entire stress distribution. Under uniform applied stresses, residual stress reversal occurred for stresses greater than 1000 MPa. In geometries with steep gradients, such as notches, significant compressive residual stresses are retained near the surface even when the local stresses exceed the yield stress.

*Keywords:* Creep; Fatigue; IN100; Nickel alloy; Residual stress; Shot peen;

## 1. Introduction

The US Air Force uses Engine Structural Integrity Program, ENSIP [1] for managing the life of safety-critical components. This damage-tolerance based approach utilizes systematic inspections of critical life-limiting locations in components. The inspection intervals are determined as 50% of the predicted crack growth life from an assumed initial crack size. Prior to insertion in service, most critical locations, such as holes, stress concentration sites, etc., are subjected to surface enhancement procedures such as shot-peening [2-4]. Shotpeening introduces significant near-surface (within 0.15-0.20 mm) compressive residual stresses. The benefits of these compressive residual stresses in improving fatigue life, retardation of crack growth and resistance to foreign object damage have been extensively demonstrated [5-7]. However, current life management practices do not explicitly account for the beneficial effects of residual stresses on crack initiation and propagation [5]. Hence, incorporating residual stresses into crack growth life prediction is a key life extension technology. Many authors have shown that surface treatment, e.g. shot-peen, induced residual stresses relax following thermal exposure, and static and cyclic

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mechanical loading [5-19]. Hence, prior to incorporation into life prediction, detailed quantification of the residual stress relaxation is required. This paper provides an assessment of the stability of the shot-peen residual stresses in a Ni-base superalloy under thermal exposure, creep, and fatigue loading at 650°C.

## 2. Material and Experimental Procedure

The material investigated in this study is a supersolvus IN100. IN100 is a powder metal nickel-base superalloy. The average grain size of this material is approximately 0.025 mm. Additional details of this material can be found in Refs. [20,21]. The true stress-strain behavior of the supersolvus IN100 at 23 and 650°C is shown in Fig. 1. The modulus (E), yield stress and ultimate strength at 23 and 650°C are 214 and 180 GPa, 938 and 912 MPa, and 1975 and 1555 MPa, respectively.

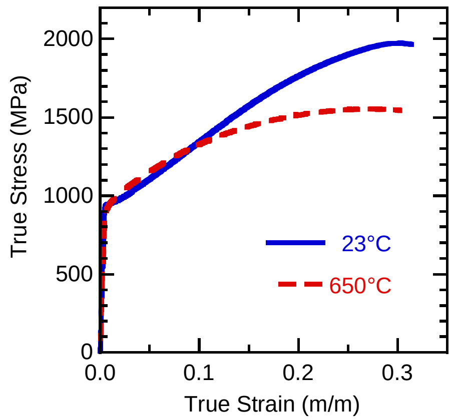


Fig. 1. Tensile stress-strain behavior of baseline (unpeened) supersolvus IN100.

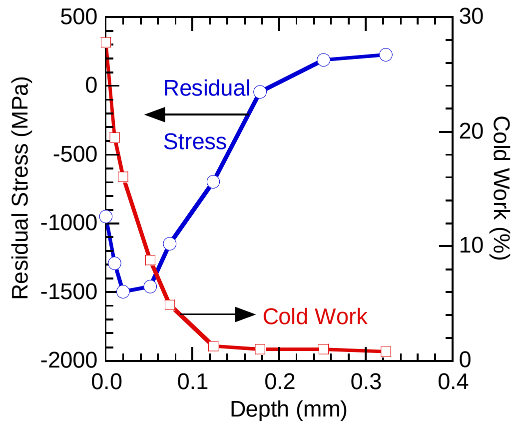


Fig. 2. Typical residual stress profile in IN100 subjected to 6A shot peening.

For thermal exposure studies, 16 x 13 x 4 mm specimens were used. These specimens were machined from 49 x 40 x 4 mm plates that were shot peened. Additional specimen design details can be found in Ref. [12]. For tensile and creep studies, a flat dogbone specimen with uniform gage section dimensions of width = 10 mm and thickness = 2 mm was used, as discussed in Ref. [13]. Double edge notched specimens with notch radius = 5 mm were used to simulate a net-section stress concentration factor, $k_t$ = 1.63. These specimens had thickness of 2 mm [22] similar to the uniform gage section dogbone specimens. The fatigue specimens [23] had cylindrical gage with button-head ends. The gage length was 15.2 mm and the diameter was 5 mm. The fatigue specimens were tested with low stress ground (LSG) and shot peen surface finishes. All the fatigue tests and the corresponding load-unload cyclic tests were run at 0.33 Hz with a minimum to maximum load ratio, R = 0.05. The elevated temperature chosen for this study was 650°C.

The IN100 superalloy was shot peened to an Almen intensity of 6A−0+2 using a MI-170-R (SAE 170 max. cast steel shot, regular) shot with 125 % coverage. All sides of the specimens were shot peened simultaneously to reduce out-of-plane deformation often associated with shot peening a single side. Additional peening details can be found in Refs. [12,13,21]. The residual stress and cold work measurements were made using X-ray diffraction technique at the surface and at nominal depths of 0.012, 0.025, 0.05, 0.075, 0.125, 0.175, 0.25, and 0.35 mm. A typical baseline shot peen residual stress distribution is shown in Fig. 2. Sub-surface peak compressive stresses of about -1500 MPa were observed. The compressive stresses were active up to a depth of about 0.2 mm. As shown in Fig. 2, cold work measurements were also made in all the specimens during this study.

## 3. Coupled Creep Plasticity Model

The effect of sustained and fatigue load on the relaxation and redistribution of shot peen residual stresses were analyzed using a coupled creep plasticity model [21,24]. The constitutive model developed in this study is based on a rate-independent plasticity model and a strain hardening creep model that is coupled to the plasticity model through the plastic strain rate and yield surface size. The total strain rate, $\dot{\varepsilon}_{ij}$ was decomposed into elastic, plastic, and creep components as shown in Eqn. (1).

$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}_{ij}^{e} + \dot{\varepsilon}_{ij}^{p} + \dot{\varepsilon}_{ij}^{c} \tag{1}$$

Decomposing inelastic behavior into plastic and creep components enabled incorporation of creep and plasticity deformation mechanisms. The plasticity and creep mechanisms are coupled through a back-stress tensor and dislocation mobility model, which allowed the creep strain rate to be dependent on plastic strain rate, plastic strain, and the yield surface. Thus the coupled creep-plasticity model captured the effects of prior plastic strain, plastic strain during loading, and applied stress level. Details of the model development and extensive validation under tensile, creep and cyclic loading can be found in Refs. [21,24]. This model was implemented into an ABAQUS material user subroutine for analyzing unnotched and notched specimens under tensile, creep, and cyclic loading. Some key predictions using this model are shown in the next section.

## 4. Results and Discussion

### *4.1. Thermal Exposure and Sustained Loading*

The effects of exposure duration on shot peen residual stresses are shown in Fig. 3 at temperature of 650°C for up to 300 hours. These results were collected on five specimens, all taken from a single shot peened plate. A compressive surface residual stress of 250–400 MPa remained at the surface for all exposures. Stress relaxation was greatest at the free surface. The stress relaxation was less for the peak compressive stress. There was also a shift of the peak compressive stress from 0.025 to approximately 0.075 mm. Majority of the residual stress relaxation occurs within the first 30 minutes of exposure. However, even after 300 hours of exposure to 650°C residual stress retention is approximately 65 %.

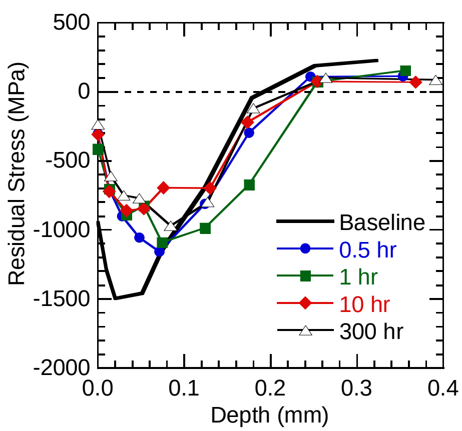


Fig. 3. Effect of exposure time at 650°C on shot peen residual stress distribution in IN100.

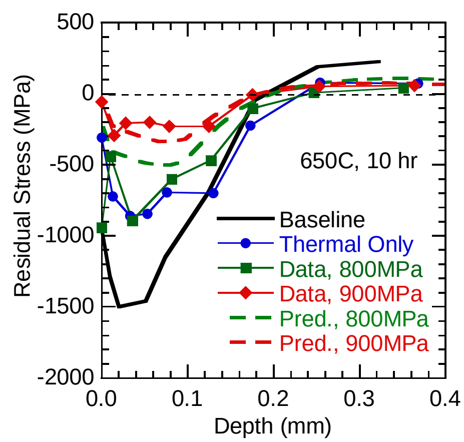


Fig. 4. Retained residual stress–depth profile after 10 hours of sustained stress levels of 800 and 900 MPa.

The relaxation of shot peen residual stresses under sustained (creep) loading is shown in Fig. 4. Data and predictions for two stress levels are shown, 800 and 900 MPa. As shown in Fig. 1, 800 MPa is in the elastic range and 900 MPa is very close to the yield stress. At 800 MPa, the relaxation of the residual stress distribution is almost similar to or slightly higher than for thermal exposure only. Approximately 60% of the sub-surface peak residual stress was retained after 10 hours under sustained loading of 800 MPa. However, at 900 MPa, significant relaxation was observed. After 10 hours under 900 MPa, the sub-surface peak residual stresses were reduced to about 20% of the baseline stresses. As shown in Fig. 4, the predictions capture the observed trend satisfactorily, although at 800 MPa the predicted relaxation is twice the observed behavior.

To better illustrate the effect of stress level and exposure duration, the data from Figures 3 and 4 are plotted in Fig. 5 as average sub-surface residual stresses up to depth of ~0.075 mm versus time at temperature. As discussed earlier, the majority of the relaxation occurs within the first 30 minutes of exposure to temperature and immediately upon applying mechanical load. The difference between below-yield (800 MPa) and almost-yield (900 MPa) stress under sustained loading is clearly evident in this figure. The difference in relaxation is associated with the difference in total plastic strain experienced by the material. At 800 and 900 MPa, after 10 hours of sustained loading, the total plastic strain is 0.3% and 0.88%, respectively [13].

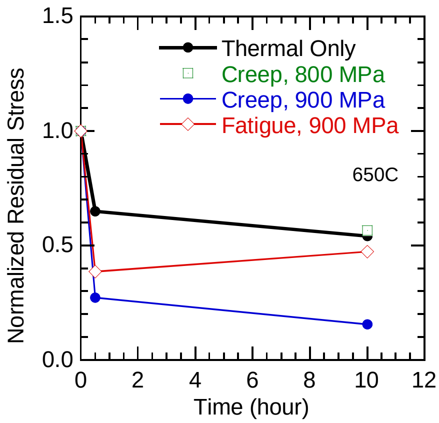


Fig. 5. Effect of applied stress and exposure time at 650°C on average near-surface (average up to 0.075-0.080 mm depth) residual stress. Normalizing stress = -1269 MPa.

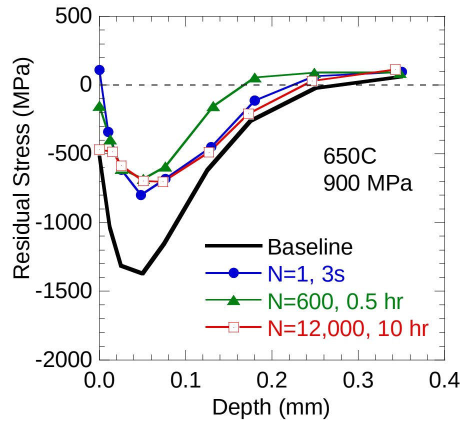


Fig. 6. Effect of cycles on residual stress profile under uniform stress of 900 MPa at 650°C.

## 4.2. *Cyclic Loading Under Uniform and Gradient Applied Stresses*

The effects of cyclic loading on the relaxation of shot peen residual stresses are shown in Fig. 6. Data corresponding to the first load-unload cycle, 600 cycles and 12,000 cycles are shown. These cycles correspond to exposure duration of 3 seconds, 30 minutes and 10 hours, respectively. As seen clearly in the figure, all the relaxation occurs in the first cycle, similar to the analytical results of Zhuang and Halford [25]. This trend is also shown in Fig. 5, where the average sub-surface residual stress is plotted as function of total time at temperature. In fact, the trend is almost similar to that under sustained loading of 800 MPa showing significant retention of residual stresses. Buchanan and John [13] showed that under fatigue loading at 900 MPa, the total plastic strain was 0.26% after 10 hours, similar to the 0.3% total strain observed under sustained loading of 800 MPa. Hence, it appears that the extent of relaxation of residual stresses is closely related to the accumulated total strain.

During service, Ni-base superalloys typically experience stress levels higher than yield stress. In fact, the low cycle fatigue regime (10,000 to 1,000,000 cycles) corresponds to stress levels higher than yield stress in IN100 at 650°C [23]. Hence, we studied the effect of above-yield stresses on relaxation and redistribution of shot peen yield stresses under cyclic loading conditions. The S-N (maximum stress vs. cycles to failure) behavior at 1000 and 1100 MPa for LSG and shot-peened specimens is shown in Fig. 7. Surprisingly, at these stress levels, the shot-peened specimens exhibited minimum fatigue life either similar or lower than that of LSG specimens. At 1000 MPa, the minimum fatigue lives were similar. However, at 1100 MPa, the minimum life of shot peened IN100 was significantly lower than that of LSG IN100. This trend is in sharp contrast to majority of the results seen in the open literature, for example Ref. [7], where shot peening has been shown to increase the total fatigue life. Hence, some of the failed specimens were used to measure the retained shot peen residual stress distribution. These results are shown in Fig. 8. The specimen tested at 900 MPa still retained significant near-surface compressive residual stresses consistent with the results shown in Fig 6. At 1000 MPa, the residual stresses were almost eliminated. And at 1100 MPa, we see a significant and complete stress reversal, resulting in near-surface tensile stress of almost 400 MPa and compressive stresses in interior region. Similar reversal of residual stresses were also reported by Eigenmann et al. [26] in steel, Kirk [27] in copper and nickel and Prevéy et al. [28] in IN718. The measured residual stress profile at 1100 MPa (Fig. 8) is consistent with the observed significant decrease in minimum fatigue life for peened specimens compared to baseline LSG specimens (Fig. 7).

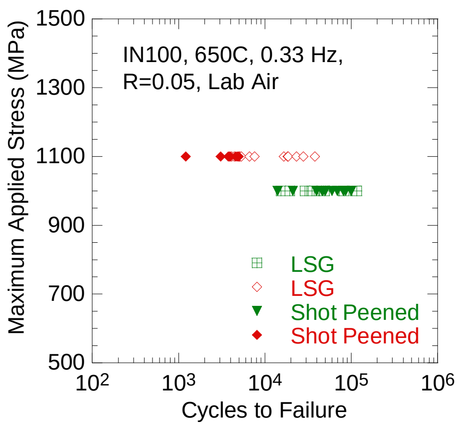


Fig. 7. Effect of shot peening on fatigue behavior of IN100 at 650°C under uniform applied stress ($k_t$=1.0).

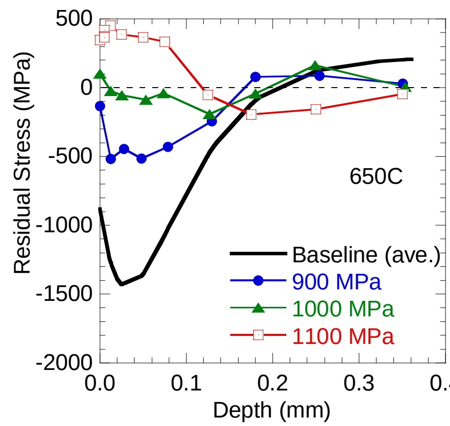


Fig. 8. Measured effect of uniform applied stress ($k_t$=1.0) on shot peen residual stress in IN100 at 650°C.

The coupled creep-plasticity model was used to predict the effect of applied stresses on the relaxation and redistribution of shot peen residual stresses in a cylindrical specimen similar to that used in fatigue tests shown in Figs. 7 and 8.

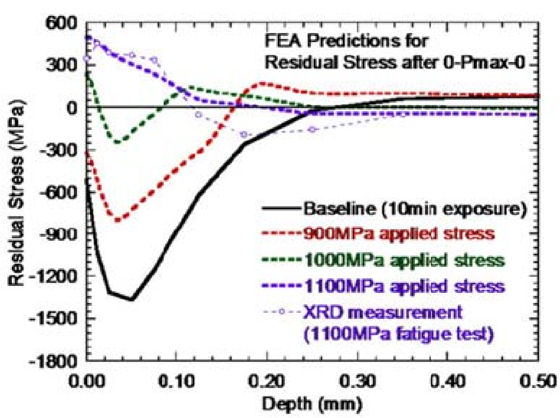


Fig. 9. Predicted effect of uniform applied stress ($k_t$=1.0) on shot peen residual stress in IN100 at 650°C.

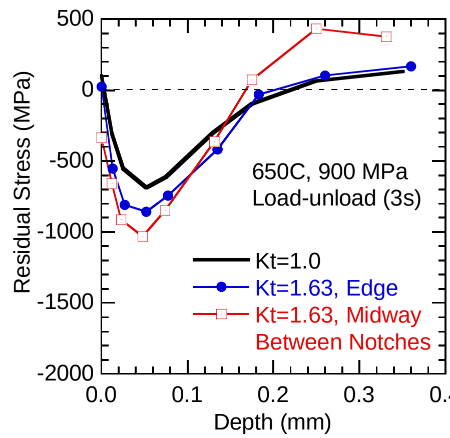


Fig. 10. Redistribution of residual stresses in the presence of stress gradients ($k_t$=1.63). Geom.: double edge notch.

Based on the observation that majority of the redistribution occurs during the first cycle, we conducted the finite element analysis for one load-unload cycle up to maximum stress levels of 900, 1000 and 1100 MPa. These results are shown in Fig. 9. Comparison of Figs 8 and 9 shows that the predictions using the model agree well the observed residual stress relaxation and stress reversal. The stress reversal effects reported in Figs. 7-9 correspond to uniform applied stresses. The sub-surface tensile residual stresses induced by shot peening are approximately 200 MPa, as shown by the baseline data in Fig. 8. When the applied stress exceeds 712 MPa, the interior material is subjected to stresses greater than yield stress, thus initiating redistribution of the residual stresses. As the interior stresses continue to increase, significant plastic straining occurs which upon unloading (removal of external applied stress) induces compressive stresses in this region. Hence, due to load equilibrium, the surface and near-surface stresses become tensile. The applied stress level at which such residual stress reversal will occur, depends on many conditions, including the geometry, overall 3-dimensional loading, thickness of component etc.

In the case of a geometry with a steep stress gradient, such as a hole, the stresses will be maximum near the surface. Hence, it is very likely that the interior material will not yield first and residual stress reversal may not occur at these locations. Figure 10 shows the results for a double edge notch specimen subjected to a load-unload cycle with maximum net-section stress of 900 MPa. This specimen had a net-section stress gradient, $k_t$ = 1.63. The applied net-section stress was 900 MPa, which corresponds to elastic stress of 1463 MPa at the edge of the notches and 723 MPa midway between the notches. As shown in Fig. 10, these localized high applied stresses at the notch edge did not result in residual stress reversal. The residual stress distributions measured at the edge of the notch and midway between the notches show significant compression similar to that of the unnotched specimen ($k_t$=1.0).

## 5. Summary

The stability of shot peen residual stresses in a Nickel-base superalloy, IN100 was studied under thermal exposure, tensile, creep and cyclic loading. The results included extensive depth measurements of the residual stress profile in post-test specimens. The results show that at 650°C, significant shot peen residual stresses are retained even after 300 hours of exposure. At these high temperatures, the residual stresses could be relaxed substantially under sustained (creep) stresses greater than the yield stress. In contrast, the residual stress relaxation was similar to that under temperature only for sustained stresses (creep) stresses lower than the yield stress. Fatigue loading resulted in relaxation only in the initial load-unload cycle for the entire stress distribution. Under uniform applied stresses, residual stress reversal occurred for stresses greater than 1000 MPa. In geometries with steep gradients, such as notches, significant compressive residual stresses are retained near the surface even when the local stresses exceed the yield stress.

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