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Residual stress redistribution in shot peened samples subject to mechanical loading

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ABSTRACT

Shot peening is a well-established surface treatment process that imparts large compressive residual stresses onto the surface and at shallow depths to retard initiation and growth of fatigue cracks. The plastic deformation developed during the surface treatment sets up a constraint that retains compressive stresses on the surface balanced by tensile residual stresses in the interior. However, component service histories that produce subsequent plastic deformation may redistribute these residual stresses. In most engineering components, this additional plastic deformation is localized to stress concentration sites such as holes, notches, and fillets. In the case of gross plastic deformation where the entire cross section experiences material yielding the residual stress profile may redistribute, resulting in tensile stresses on the outside surface balanced by compression in the interior. This paper describes a series of experiments combined with models to explain the redistribution in residual stress depth profiles subject to applied stresses producing gross plastic strains in shot peened laboratory specimens. The initial room temperature residual stress and plastic strain profiles provide initial conditions for predictions. Model predictions correlate well with experimental results on shot peened dogbone specimens subject to single cycle and fatigue loading conditions at elevated temperature. Experiments on shot peened notched specimens do not exhibit the same stress redistribution even for larger applied stresses.

1. Introduction

In comparing and contrasting of structural materials, particularly metal alloys, we often cite the tensile, fatigue, or creep properties. However, for today's modern structural applications subject to high temperature and stress loading conditions mechanical properties are no longer static, but are a function of temperature, strain rate, environment, and more importantly prior loading history. Characterizing the mechanical behavior of advanced materials requires a complete knowledge of the material processing history for that particular alloy. This is especially true in evaluating the effects of surface treatment processes on mechanical behavior. Machining processes and surface treatments such as shot peening (SP), low plasticity burnishing (LPB) and laser shock peening (LSP) all impart plastic deformation into the material that results in residual stresses.

Surface treatment processes produce three important changes to the near surface state of the material. First, the surface treatment produces extensive plastic deformation resulting in an unstable dislocation structure at the surface. This localized damage has the potential to accelerate hydrogen diffusion, initiate cracks, and promote early failure. Fortunately, the second change is an increase in the local yield strength caused by material hardening, which makes the material more resistant to further plastic deformation from additional loading. The third and most important change in the material is the resulting biaxial compressive surface residual stress produced from the localized plastic deformation with smaller compensatory tensile stresses set up in the surrounding material. In most instances, residual stress is often cited in the literature as the single cause affecting change in mechanical behavior when in most instances all three changes are contributing factors.

Most residual stress models in the literature only account for the initial state of residual stress in the structure. However, surface treatment produces a highly deformed and stressed dislocation structure that is easily perturbed by thermal exposure or mechanical loading. Thus, the plastic deformation and change in yield surface must also be incorporated into these models so that residual stress relaxation of advanced surface treatment processes, such as LSP and LPB, can be included in a deformation mechanism based approach.

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2. Shot peening and residual stresses

The automotive, aerospace, and many other industries confidently use surface treatment processes such as shot peening to impart compressive residual surface stresses to delay crack initiation and retard crack growth rate. Numerous studies have characterized the beneficial effects of compressive residual surface stresses on fatigue life in aluminum-, titanium-, steel-, and nickel-base alloys [1–11]. McClung [1] provides a thorough survey of residual stress literature and highlights many of the important issues related to fatigue response. For many applications where components are subject to moderate temperatures and elastic stresses, residual stresses are stable or change predictably with repeated cyclic loading [7–11]. However, nickel-base superalloys used in gas turbine engine applications typically experience temperatures approaching 80% of their melting temperature, and stresses approach or exceed the monotonic yield strength. At elevated temperatures and high stress loading conditions, inelastic deformation may significantly alter the original residual stress depth profile.

Holzapfel et al. [8] describe residual stress relaxation as three different stages: (1) relaxation due to specimen heating, (2) relaxation during the first cycle, and (3) relaxation with the logarithm of applied cycles. A similar approach by Cao et al. [7] describes thermomechanical relaxation as a two-stage process, in which the first stage is a shakedown of the initial residual stresses described by a monotonic stress strain law, and a second stage that is slower and is described by a cyclic softening related to the logarithm of applied cycles. Another approach [12] performs shakedown analysis using finite elements with a cyclic plasticity model that incorporates kinematic hardening, followed by a scheme to advance the state variables under constant amplitude loading.

Prevéy [4,13] argues that the rate of residual stress relaxation and the amount of relaxation are directly correlated to the level of cold work in surface-treated Ti–6Al–4V and IN718. Furthermore, Buchanan et al. [14] reported that LSP surface treatment retains a higher percentage of the initial residual stress profile over that of SP when subject to thermal exposure. The higher retention of residual stress in LSP samples was attributed to lower level of cold work.

The literature is rich with investigations into relaxation of mean stresses [15–17] and residual stresses [7–11,18] subject to cyclic plastic loading. In contrast, only a limited number of studies, Vöhringer [19] in steel, Kirk [20] in copper and nickel, and Prevéy et al. [21] in IN718 have investigated residual relaxation and stress reversal subject to large monotonic plastic strains. A major issue not discussed in the literature is the hazard of extrapolating residual stress relaxation behavior on small-scale surface treated laboratory specimens to the behavior of large-scale engineering components. In both the laboratory specimens and engineering components, residual stress profiles have to satisfy load equilibrium. Therefore, the volume of material or size of the component subjected to surface treatment has an impact on the shape of the residual stress depth profile. Fig. 1 demonstrates how residual stress depth profiles must satisfy load equilibrium for different thicknesses or volumes. The left portion of the figure shows four different IN100 plates with thicknesses ranging from 2 to 20 mm. Each plate was shot peened on both sides using identical peening parameters. All IN100 specimens were 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. PEENSCAN® was applied prior to shot peening to verify complete coverage and uniformity over the entire surface of the specimen. The plots on the right are the residual stress depth profiles for the different thickness plates measured using x-ray diffraction and electropolishing for material removal. The x-ray diffraction measurements were made by an outside laboratory following the SAEJ784a [22] standard. The residual stress measurements were made 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. The x-ray diffraction measurements are interpreted on the diffraction of radiation reflected from the surface and to a depth of approximately 0.010 mm for this material. Therefore, subsequent x-ray measurements made after material removal via electropolishing are used to correct for depth averaging. The stress corrections for material removal were completed following the Moore and Evans [23] elasticity solution for flat plates. In summary, after each depth measurement the raw stress measurement from x-ray diffraction was corrected for both depth averaging and material removal. All four plates have similar near surface (0–0.03 mm) depth profiles where shot peening stresses and cold work are the highest. Beyond this depth, the magnitude of compressive residual stress decreases for all curves with the 2 mm thick plate profile deviating from the other depth profiles. The transition from compressive to tensile residual stress exhibits a trend with plate thickness with the 2 mm thick plate transitioning at a much shallower depth. As a result, growth of small cracks in shot peened laboratory specimens could be faster than shot peened components with a greater thickness because of the difference in their residual stress profiles. The final observation is the difference in the compensatory tensile residual stress in the interior of the plates. As the plate thickness decreases, the interior tensile residual stress has to increase to satisfy load equilibrium. In particular, the 20 mm thick plate has approximately 20 MPa

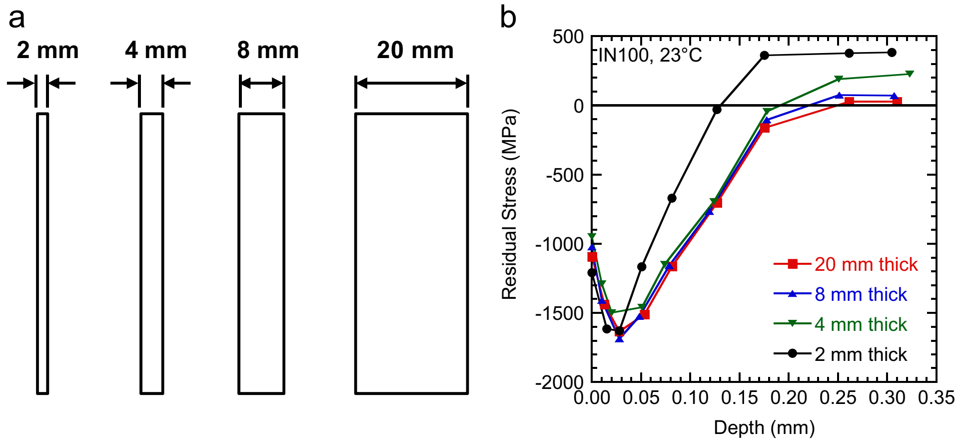

Fig. 1. Effect of part thickness on induced residual stress depth profile from shot peening in IN100: (a) shot peened sample thicknesses range from 2 to 20 mm and (b) XRD measured residual stress depth profiles in samples.