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On the eigenstrain application of shot-peened residual stresses within a crystal plasticity framework: Application to Ni-base superalloy specimens

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ABSTRACT

Shot-peening-induced compressive residual stresses are often introduced in Ni-base superalloy components to help prevent or retard surface fatigue crack initiation and early growth at near surface inclusions. In certain cases these compressive residual stresses can shift the fatigue crack initiation site from surface to sub-surface locations. However, the ability to computationally predict the improvement in fatigue life response and scatter due to induced compressive residual stresses are lightly treated in the literature. To address this issue, a method to incorporate shot-peened residual stresses within a 3D polycrystalline microstructure is introduced in this work. These residual stresses are induced by a distribution of fictitious or quasi-thermal expansion eigenstrain as a function of depth from the specimen surface. Two different material models are used, a J_2 plasticity and a crystal plasticity model. First, the J_2 plasticity model with combined isotropic and kinematic hardening is used to determine the distribution of quasi-thermal expansion eigenstrain as a function of depth from the surface necessary to induce the target residual stress profile within the microstructure. This distribution of quasi-thermal expansion eigenstrain is then used within a crystal plasticity framework to model the effect of microstructure heterogeneity on the variability in residual stresses among multiple instantiations. This model is verified with experimental X-ray diffraction (XRD) data for scatter in residual stresses for both the initial microstructure and after a single load/unload cycle.

1. Introduction

1.1. Motivation for modeling residual stresses

The beneficial effects of compressive surface residual stresses on high cycle fatigue (HCF) response have been well documented in the literature [1–4]. For Ni-base superalloys, a shift from surface-dominated to subsurface-dominated fatigue crack initiation sites exists for the transition from low cycle fatigue (LCF) to HCF regimes [5–9]. A similar surface to subsurface transition has been reported for titanium alloys [10,11] and high strength steels [12,13]. In the transition fatigue regime (cycles to failure, $N_f \sim 1 \times 10^4 - 5 \times 10^5$ cycles), subsurface-initiated fatigue cracks tend to require more cycles to failure as compared to surface-initiated fatigue cracks [5]. Accordingly, surface compressive residual stresses are often introduced in Ni-base superalloy components to help prolong/retard fatigue crack initiation [14] and early growth at near-surface inclusions and potentially shift fatigue crack initiation sites from surface to subsurface locations [1,2] to increase fatigue life. However, compressive residual stresses are usually only useful in the transition fatigue and HCF ($N_f > 5 \times 10^5$ cycles) regimes since residual stress relaxation at higher applied stress/strain values can eliminate the effectiveness of compressive residual stresses on fatigue life [14–17].

Compressive surface residual stresses can be applied via multiple techniques (shot/gravity peening, low plasticity burnishing, laser shock peening, etc. [18]). Shot peening is the most commonly used technique in industry to induce compressive residual stresses at the surface, and is the focus of this residual stress study. During the shot peening process multiple high-velocity shot beads impact the surface forming multiple indentations and inhomogeneous compressive elastic/plastic deformation of the near surface layer. As such, the resulting residual stress profile is dictated by (1) the

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interaction between multiple indentations, (2) localized constrained compression, (3) strain rate sensitivity and elastic/plastic response of the material, and (4) local microstructure. In modeling, these discrete impingement events can either be modeled explicitly or idealized as a collective elastic/plastic constrained compressive loading/unloading event as schematically shown in Fig. 1. The idealization of the multiple impingement shot peening process as a single deformation event is adopted in this paper.

While the influence of residual stress on fatigue life has been reported extensively in the literature, the ability to computationally predict the improvement in fatigue resistance and change of scatter due to induced compressive residual stresses are lacking in the literature. A significant effort in modeling inclusion and residual stress effects in shot-peened martensitic gear steels was undertaken by Prasannavenkatesan et al. [19–22]. They considered separate 3D finite element method (FEM) models at discrete depths subjected to the required amount of compressive load/unload strain to induce the required residual stress profile at each particular depth. The simulated inclusion sizes ($<10\,\mu m$) were small compared to the overall 3D FEM model dimensions, so the gradient in applied stress and residual stress over the inclusion was considered to be negligible in their analysis. Alternatively, inclusion sizes in powder metallurgy polycrystalline Ni-base superalloy IN100 are on the order of 10–100 μm [6,23,24]. For inclusions of these sizes, the gradient in residual stress (RS) field due to shot peening (Ref. RS profile in [25]) can have a significant effect on stress/strain response and should be considered when analyzing inclusion and RS effects in Ni-base superalloys. Therefore, a simulation approach that accounts for the entire distribution of residual stress, and not just at discrete surface depths, is warranted. Hence, we aim to develop a framework to assess (1) the effect of microstructure on the entire residual stress profile due to shot peening and (2) the effect of cyclic loading on residual stress relaxation in polycrystalline Ni-base superalloy components.

This section begins with a brief overview of previous methods to impose residual stresses within components. Next, the eigenstrain application of residual stresses within a FEM framework is discussed and a J_2 plasticity model is presented for calibrating this model. Finally, the method by which crystal plasticity is incorporated is presented with results for variability of initial residual stress and retained residual stress due to a single load/unload sequence.

1.2. Previous methods for simulated application of residual stresses

Techniques to simulate the shot peening process can be divided into two methods: (1) Simulation of the impact response between the shot bead and the shot peened surface by quasi-static or explicit dynamic analyses to predict the resulting residual stress and/or Almen intensity as a function of shot peening parameters (shot size, speed, coverage, material properties, incident angles, etc.) [26–42] and (2) Simulation of the overall induced mechanical response due to shot peening through a deformation process [20,43,44]. Some examples of relevant works regarding these two methods are discussed below.

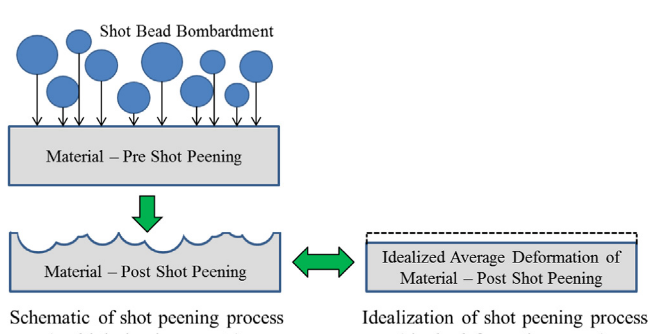

Fig. 1. Schematic showing idealization of shot peening process as a single deformation event.

1.2.1. Simulation of single and multiple impact events

The first means to model the high-velocity impact shot peening process focused on single impact events on an elastic-plastic target substrate. Chen and Hutchinson [27,28] and Boyce et al. [26] found that explicit dynamic simulations incorporating effects of strain-rate sensitivity, inertia, and elastic wave propagation resulted in a better prediction of residual stresses than quasi-static analyses. Frija et al. [29] used an energy equivalence expression and 3D quasi-static FEM analysis to find good correlation between the predicted residual stress along the shot bead impact centerline and experiments. Zion and Johnson [34] studied the impact of a hard and soft shot bead and a high-strength steel and found that the most highly significant input factor was the value of friction coefficient assumed between the shot bead and target material. While these single impact simulations can unveil key relationships between shot peen input (e.g. shot diameter, impact velocity, incident angle) and residual stress output [32], multiple impact events should be used to simulate more realistic peening conditions.

One means to model multiple impacts is to combine discrete element modeling (DEM) and FEM to determine RS profile. DEM simulates spatial interactions/collisions among multiple discrete particles within the shot stream. DEM exports particle/substrate impact velocity, location, and contact forces into a FEM model to calculate resulting plastic strains and residual stresses. Multiple researchers [39–42] have used this combined DEM-FEM approach to link the effect of complex part geometry on the overall shot peening process, including the effects of impact angle, impact density, and coverage on location-specific residual stress formation.

These combined DEM-FEM simulations of multiple impingement events are certainly noteworthy. However, it is hard to discern how much variability in local residual stress is attributed to (1) the localized inhomogeneous deformation due to the stochastic impingement events inherent in the shot peening process and (2) the effect of local microstructure, especially grain orientation. Therefore, to isolate the effect of local microstructure, we propose to use a uniform average “amount of impingement” within a crystal plasticity finite element model. In this approach, the individual shot peen events that were modeled in the previous method(s) are not modeled. Instead, the resulting material deformation and hardening states due to shot peening are (1) induced explicitly within an implicit or explicit FEM model and (2) used as initial conditions for subsequent relaxation/fatigue analysis simulations.

1.2.2. Techniques to induce overall mechanical response due to shot peening

One way to induce residual stresses explicitly within an FEM model is to deform the FEM model in displacement-controlled constrained compression. This method mimics the collective mechanical means in which biaxial residual stresses are imposed within a component during the shot peening process and traces the evolution of the material state throughout the deformation process. For example, Prasannavenkatesan et al. [20,21] used a simple displacement-controlled method in conjunction with isotropic plasticity [20] and polycrystal plasticity [21] to induce residual stresses [20] and reproduce experimental trends in