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Simulating shot peen forming with eigenstrains

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ABSTRACT

Shot peen forming is a cold work process used to shape thin metallic components by bombarding them with small shots at high velocities. Several simulation procedures have been reported in the literature for this process, but their predictive capabilities remain limited as they systematically require some form of calibration or empirical adjustments. We intend to show how procedures based on the concept of eigenstrains, which were initially developed for applications in other fields of residual stress engineering, can be adapted to peen forming and stress-peen forming. These tools prove to be able to reproduce experimental results when the plastic strain field that develop inside a part is known with sufficient accuracy. They are, however, not mature enough to address the forming of panels that are free to deform during peening. For validation purposes, we peen formed several 1 by 1 m 2024-T3 aluminum alloy panels. These experiments revealed a transition from spherical to cylindrical shapes as the panel thickness is decreased for a given treatment, that we show results from an elastic instability.

1. Introduction

Peen forming is a cold work process predominantly used by aircraft manufacturers to shape wing skins (Baughman, 1970). The process consists of bombarding thin metallic parts with small shots in order to plastically deform a thin surface layer of material. As a result of strain incompatibility between the surface and the core—left unaffected by the treatment—the whole structure distorts and compressive residual stresses develop near the surface. Fig. 1 shows schematically the process application on a wing skin, as well as typical peening-induced plastic strain and residual stress fields. Although the range of accessible curvatures is limited, it is possible to peen form a wide variety of shapes once appropriate parameters are set. Larger curvatures can be achieved by elastically prestraining the parts before peening to increase the effect of the treatment in a given direction (Ramati et al., 1999). This variant of the process is called stress-peen forming.

Simulating the whole process explicitly (i.e., simulating *every* shot hitting the target) is currently beyond reach. For that reason, most available publications on the topic relied on a two-step local-global approach. The local step aims at characterizing the effect of a given treatment on a given material, usually in terms of residual stresses and plastic strains. It is performed either experimentally (Levers and Prior, 1998) or numerically as in the work of Chaise (2011) on ultrasonic shot peening. Mylonas and Labeas (2011) provide an overview of recent research on local peening simulations in a non peen forming-specific context. Stresses or strains induced by the peening treatment are then post-processed to extract loads that are input in structural models of parts to compute equilibrium configurations. The local step involves contact, plasticity, and large deformations that are characteristics of a forming analysis. The global step, on the other hand, can be seen as a springback analysis, as it was demonstrated by Chen et al. (2014) that the re-balancing of the part usually involves only elastic transformations.

Several types of (idealized) loads used in global simulations were reported in the literature: Levers and Prior (1998) and Wang et al. (2006) reproduced the expansion of subsurface layers where Gariépy et al. (2011) used peening-induced non-equilibrated residual stress profiles. The main shortcoming of these approaches is that, although the choice of the loading is guided by some a priori knowledge of the post-peening state, several parameters systematically have to be adjusted by comparing simulated deformed shapes with their experimental counterparts. The workload is significant and simulations are limited to the vicinity of the process parameters for which the calibration has been performed.

We aimed to show that readily available procedures based on the concept of eigenstrain, which are commonly used in other fields of residual stress engineering, can be adapted to simulate peen forming. These tools have the potential to bypass the calibration step and to simulate peening conditions out of reach of existing procedures. To illustrate this point, we investigate the nature of a transition between spherical and cylindrical deformations observed on panels of varying thickness peen formed under identical conditions. The reason behind

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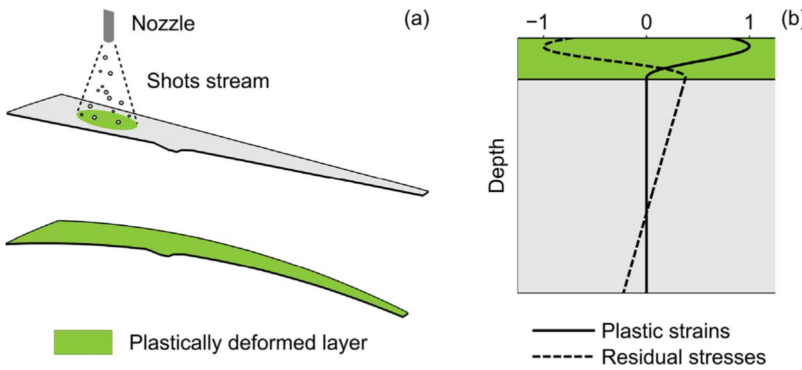

Fig. 1. (a) Peen forming of a wing panel. In-plane expansion of the plastically deformed layer causes the part to bend and elongate. (b) Typical (normalized) in plane residual stress and plastic strain profiles after uniform peening. The linear portion in the residual stress profile is due to bending.

this transition has not been explained in peening literature yet, to the best of our knowledge.

The paper is structured as follows: Section 2 reviews key results and simulation strategies from eigenstrain literature, as well as previous peen forming experimental campaigns. Materials and methods are detailed in Section 3. The proposed simulation procedure is presented in Section 4. The latter is validated against experimental results from the literature in Section 5.1, and against results generated in the course of this study in Section 5.2. Both conventional and stress peen forming are considered. The main findings are discussed in Section 6.

2. Background

2.1. Eigenstrains

The term eigenstrain, coined by Mura (1987), has been used to designate anelastic deformations inside a structure regardless of the physical phenomenon they originate from. Stress-free strains and inherent strains are equivalent designations sometimes encountered in the literature. The concept of stress-sources (initial unbalanced residual stresses) used by Niku-Lari (1981) for fast experimental estimation of peening induced residual stresses is also intimately related to eigenstrains as both quantities are proportional (Terasaki et al., 1999). Thermal strains, plastic strains, and volumetric expansion caused by phase transitions or solvent absorption are some examples of eigenstrains. In shot peened parts, only plastic strains usually contribute to the eigenstrains $\boldsymbol{\varepsilon}^*$.

In any structure free of external loads, residual stresses and distortions can always be attributed to an incompatible eigenstrain field. If the latter is known, or if it can be estimated with sufficient accuracy, then the computation of stresses and distortions—the direct problem—can be dealt with as an inclusion problem (Mura, 1987). This approach has been successfully applied to a variety of engineering problems as illustrated by Deng et al. (2007), Hu et al. (2015), and Depouhon et al. (2015) where the authors respectively investigated residual stresses and distortions induced by welding, laser peening and thermo-mechanical treatments. In all of these studies, the authors made use of a two-step procedure involving a local analysis to compute eigenstrains followed by a global springback analysis to obtain the final deformed shape. To map eigenstrains to large scale models, the source of the loading was considered analogous to a thermal expansion. Thermal expansion coefficients $\boldsymbol{\alpha}$ equal to the eigenstrains were defined over the whole domain ($\alpha_{ij} = \varepsilon^*_{ij}$) and a unit increment of temperature was applied. The validity of this procedure stems from the fact that two identical eigenstrain fields yield the same residual stresses and distortions, whatever the physical phenomenon that causes them.

It is commonly accepted that eigenstrains generated by surface treatments are insensitive to the surface's topography, provided that curvatures vary gradually and that the target is exempt of sharp geometric features (Ahdad and Desvignes, 1996). This was confirmed experimentally by Coratella et al. (2015) on laser peened Al. 7050 samples. Zhang et al. (2008) also demonstrated that eigenstrains arising in 17-4 PH steel strips shot peened in the conditions of the study were independent of the strips thickness. They suggested that this result might hold for a variety of materials and peening conditions. Similar observations by Achintha and Nowell (2011) on laser peened Ti-6Al-4V support Zhang and collaborators' hypothesis. These results further suggest that the effect of a given treatment could conveniently be characterized—either numerically or experimentally—in terms of eigenstrains on small representative volumes of the target material. For example, peening a small strip could enable estimating the post-peening state of a massive part subjected to the same sequence of operations, as was already suggested by Niku-Lari (1981).

Since eigenstrains cannot be measured directly, they have to be reconstructed from various experimental data such as elastic strains or residual stresses. It is a complex inverse problem in the general 3D case (Jun et al., 2011), but several robust reconstruction procedures have been developed for specific configurations. They include closed form relations between residual stresses and eigenstrains such as those reported by Ahdad and Desvignes (1996) and Korsunsky (2005), as well as more generic numerical procedures. Korsunsky (2006), for example, started by postulating a form of the eigenstrain field as a sum of trial basis functions, $\boldsymbol{\varepsilon}^* = \sum_{k=1}^{N} c_k \boldsymbol{\varepsilon}_k^{\text{trial}}$. The choice of basis functions was guided by some a priori knowledge of the eigenstrain field shape, and the objective of the procedure was to find coefficients c_k that minimized the squared difference between measured and simulated residual elastic strains. The latter were obtained by successively inputting each basis function in a linearly elastic model of the structure of interest. For a linearly elastic model, the solution to this least-square problem is unique.

2.2. Experimental peen forming results from the literature

2.2.1. Coverage and Almen intensity

The post-peening state of a shot peened part depends on numerous parameters, such as: characteristics of the part itself (material, geometry), properties of the shots (material, size and shape) and process parameters (type of peening machine, type of fixtures used to secure the part, velocity of the shots, angle of impingement, stand-off distance, mass flow rate, peening time and trajectories). As a consequence of the random nature of the process, many of these parameters have to be described by appropriate statistical distributions.

In industrial practice, only two parameters, namely coverage and Almen intensity, are typically used to characterize peening treatments. Coverage is defined as the fraction of the surface covered by dimples if it is smaller than 98%, and as a multiple of the time necessary to reach full coverage otherwise. (For example, 200% coverage is obtained by peening a sample twice the time necessary to reach full coverage.) Almen intensity is an indirect measurement of the energy conveyed by the shot stream. It is obtained by peening normalized SAE 1070 steel strips in the same conditions as the part for increasing peening times, and is defined as the deflection of the strips (in unit of length) read at

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