A Scaling Law in Shot Peening Induced Surface Material Property Deviations

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ABSTRACT

This paper presents a theory of shot-induced material property deviations near the component surface. Our analysis shows that, with shot peening being the common cause, there exists a universal scaling law among seemingly unrelated material property deviations under varying peening conditions. The main contribution of this paper is to show the existence and utility of the scaling law. We explicitly present scaling behaviors of several material property deviations under varying Almen intensities, and validate the predicted scaling relations against experimental data. Assuming the scaling law holds, we also show how to use it as a tool to control peening processes, by predicting, e.g., residual stress profiles at varying Almen intensities. The scaling law is also found useful in assuring consistency among nondestructive characterization measurements.

KEY WORDS

Shot Peening, Almen Intensity, Residual Stress, Cold Work, Scaling Law

INTRODUCTION

The physical properties of shot peened surfaces exhibit deviations from their bulk values. Depth profiles of these property deviations are functions of material and depend on the conditions of the peening process. To achieve target material states, e.g. compressive residual stress for surface protection, the peening process must be controlled with care. Use of Almen strips is the standard method of process control that ensures consistency and repeatability of the peening process. However, conventionally, it still is a task at the outset to determine, by repeated trials, how much shot peening to perform or to what Almen intensity, on the case-by-case basis. It is desirable to have a methodology that can predict necessary peening conditions from the knowledge on one material condition to another. Actually, the utility of the Almen test suggests existence of certain universality among material responses against a given peening process. Indeed, this paper expands this notion of universality, and shows that there exists a scaling law which provides the aforesaid universality among seemingly unrelated material property deviations and among different peening conditions.

EXISTANCE OF SCALING

Working assumptions

At the outset of the shot peening process, the surface will yield, experiencing plastic deformation. The plastic stretching of the surface layer is counteracted elastically by the cohesion to the bulk of the material, causing the layer material to experience compressive residual stress. We assume that, eventually, the plastic deformation of the surface layer saturates, i.e. the hardened surface will stop yielding.[1] After that, the surface reacts to the subsequent projected shot only elastically, in which case the strain induced by a single shot (in the saturated sample) can be calculated by the use of the Hertzian contact theory (H. Hertz, 1881) and energy conservation during the elastic collision.[2]

Scaling parameter

When a single spherical shot of radius R strikes the saturated free surface of a half-space, the maximum elastic strain $u_{ij}^{(1)}$ as a function of depth z takes the form: $u_{ij}^{(1)}(z) = (a/R)\tilde{u}_{ij}^{(1)}(z/a)$, where $\tilde{u}_{ij}^{(1)}(\zeta)$ is a universal function of the argument ζ (H. Hertz, 1881; L. Landau and E. Lifshitz, 1959), and the scaling parameter a is the characteristic contact radius between the shot and the peened surface given by

$$\frac{a}{R} = \left[5\pi \frac{\rho V^2}{2\tilde{E}}\right]^{1/5}, \qquad \frac{1}{\tilde{E}} = \frac{1}{2}\left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}\right). \qquad (1)$$

Here ρ and V are the shot density and velocity, while $E_{1,2}$ and $\nu_{1,2}$ are Young's moduli and Poisson's ratios of the shot and the half-space materials, respectively. It is important that the contact radius a depends on the material and process parameters while the function $\tilde{u}_{ij}^{(1)}(z/a)$ is independent of these parameters.

Given the elastic strain $u_{ij}^{(1)}(z)$, it is conceivable to compute the plastic strain $u_{ij}^{pl}(z)$, either from empirical nonlinear stress-strain curves, or by any appropriate choice of elasticity-plasticity theories (e.g. J. Li, *et al*., 1991). Since one would perform the calculation at each depth value z, $u_{ij}^{pl}(z)$ will take the form

$$u_{ij}^{pl}(z) = (a/R)^{\gamma} \cdot \tilde{u}_{ij}^{pl}(z/a), \qquad (2)$$

where $\gamma = 1$ because it should vanish equally as $u_{ij}^{(1)}(z)$ for small a, and where $\tilde{u}_{ij}^{pl}(\zeta)$ is another function but decaying as $\tilde{u}_{ij}^{(1)}(\zeta)$ does. The function $\tilde{u}_{ij}^{pl}(\zeta)$ is less universal than $\tilde{u}_{ij}^{(1)}(\zeta)$ because it generally depends on the plastic property of the material in question. As shown below, Equation (2) explains certain scaling behaviors among a given material, and will allow us to relate stress profiles at different peening intensities.

MANIFISTATION OF SCALING

Strip Bending

The contact radius a in Eq. (1) sets the scale of the problem, and thus is fundamentally important. However, it is sometimes an inconvenient parameter to use in applications because the shot velocity is usually unknown. Measurable quantities

[1] Practically, this saturation could be achieved after the first impact. Numerical calculations show that the "residual stress field is mainly influenced by the first impact" (D. Kirk and R. Hollyoak, 1999).

[2] Typical values of shot velocity are much smaller then the speed of sound in metals. Therefore, the collision between the shot and surface can be considered as an adiabatic process, and energy transfer to sound waves is negligible.

such as plate deflections d and radii of curvature r are more desirable parameters to describe the consequence of the universal scaling law (e.g. Eq. (2)) in physical properties. Here, we first establish the relationship between the contact radius a and the deflection d for a peened thin plate. Consider a thin plate (strip) of a thickness h, the length L_x, and width L_y. When $h << L_x, L_y$, the plate deflection d_α and the radius of curvature r_α are related via $r_\alpha \approx L_\alpha^2 / 8d_\alpha$ for each direction, α=x or y. When the plate is shot peened, it experiences bending, leading to the bending strain $u_{ij}^b(z)$. For a thin plate, this strain is a linear function of the depth: $u_{\alpha\alpha}^b(z) = (h/2r_\alpha)(1-2z/h)$ (L. Landau and E. Lifshitz, 1959). For the peened plate, the strain $u_{\alpha\alpha}^b(z)$ is a superposition of plastic and residual elastic strains. Therefore,

$$u_{\alpha\alpha}^{el} = -u_{\alpha\alpha}^{pl} + u_{\alpha\alpha}^{b}, \quad (3)$$

where $u_{\alpha\alpha}^{pl} = (a/R) \cdot \tilde{u}^{(\alpha)}(z/a)$. To find $u_{zz}^{el}(z)$, we use the standard relation between stress τ_{ij} and strain u_{ij}^{el} and impose the equation $\tau_{zz} = 0$, which holds near the free surface, leading to the result $u_{zz}^{el} = -(u_{xx}^{el} + u_{yy}^{el})\nu/(1-\nu)$. Now, we insert these relations to the elastic energy F of a bent strip

$$F = \tfrac{1}{2} E/(1+\nu) \cdot \int_0^h \left[\sum_{i,j} \left(u_{ij}^{el}\right)^2 + \left(\sum_l u_{ll}^{el} \right)^2 \frac{\nu}{1-2\nu} \right] dz \,. \quad (4)$$

We can minimize the energy F with respect to the deflections d_α explicitly, assuming that $u_{\alpha\alpha}^{pl}(z)$ decays sufficiently fast so that h/a can be taken infinity. We find that

$$d_\alpha \propto \left(a^2 L_\alpha^2\right) / \left(R h^2\right), \quad (5)$$

thus establishing the relationship of the radius a to the deflection d and/or the radius of curvature r that can be readily measured. Equation (5) is a corollary of the universality represented by Eq. (2).

The dependence of d (and r) on the strip dimensions L and h has been validated by direct experiments using Almen strips of two different thicknesses (A and N series strips) cut to different lengths which were shot peened at different pressures. Table 1 below shows that, in agreement with the theory, the product dh^2 is independent, within the errors of several percents, of the plate thickness h and the peening intensity characterized by the pressure or Almen deflection d. Similar data

	Small shots			Large shots		
Pressure, kPa (psi)	d_A (A)	d_N (A)	$\frac{d_A h_A^2}{d_N h_N^2}$	d_A (A)	d_N (A)	$\frac{d_A h_A^2}{d_N h_N^2}$
172 (25)	2.9	7.4	**1.06**	4.9	12.9	**1.03**
276 (40)	4.0	10.8	**1.00**	7.4	18.6	**1.08**
379 (55)	5.5	14.4	**1.03**	9.1	23.4	**1.05**
483 (70)	6.1	16.4	**1.01**	10.5	26.9	**1.05**
586 (85)	6.7	17.9	**1.01**	12	29.7	**1.09**

Table 1: Almen intensity d_A, d_N, and invariant ratio $(d_A h_A^2)/(d_N h_N^2)$ as a function of pressure. Strip thickness: h_A=1.30 mm, h_N = 0.79 mm. Shot radius: R=0.28 to 0.43 mm for small shots, and R=0.84 to 1.17 mm for large shots.

demonstrates that the radius of curvature $r \approx L^2/8d$ is independent of length L, i.e. deflection $d \propto L^2$.

Next, suppose a component is given, for which Equation (5) may not apply directly because it may not bend after peening as a thin plate. To proceed, we relate the scaling law of the component properties to the corresponding Almen strip deflections. Equations (1) and (5) provide us with the link if the Almen strip and component deformations are caused by common shot peening. Let us consider two different peening intensities “1” and “2” using the same type of shots, quantitatively characterized by the Almen strip deflections d_1 and d_2. À la Eq. (2), the scaling laws of the Almen strip and the component are dictated by the respective scaling parameters $a_{1,2}^A$ and $a_{1,2}^c$ at the two intensities. It is easy to see that

$$d_2/d_1 = \left(a_2^A/a_1^A\right)^2 = \left(a_2^c/a_1^c\right)^2, \tag{6}$$

where the first and second equalities follow Eqs. (5) and (1), respectively.

Cold work

Shot-induced cold work is driven by the plastic deformation, namely, cold work is in principle calculable from the plastic deformation at each depth z. Therefore, it is reasonable to write the cold work profile, after Eq. (2), as

$$w(z) = (a/R)\cdot \tilde{w}(z/a), \tag{7}$$

where $\tilde{w}(\zeta)$ is yet another scaling function. Published data for Waspaloy samples peened at four different Almen intensities (M. Blodgett and P. Nagy, 2004) have been used to verify Eqs. (6) and (7). The experimental data are in good agreement with theoretical prediction (Fig. 1a, b), namely all the cold work profiles can be scaled to a single profile function.

Stress

As presented above, we can readily calculate the residual elastic strain (and stress) for thin plates, thanks to the thin-plate approximation that limits the depth profile of the bending induced strain $u_{\alpha\alpha}^b(z)$ to be at most linear in the depth z. The calculations of the function $u_{\alpha\alpha}^b(z)$ for thick plates and complex geometry components are involved and hence outside the scope of this publication. Here, we instead proceed by making the following assumptions for large and thick plates, namely we assume that the affected surface layer does not bend for small values of stress because the host material prevents it from bending. Under this assumption, $u_{\alpha\alpha}^b(z)$ is negligibly small and hence we have $u_{\alpha\alpha}^{el} = -u_{\alpha\alpha}^{pl}$, allowing us to apply the scaling law to experimental stress data. The Waspaloy residual stress data (M. Blodgett and P. Nagy, 2004) plotted in Fig. 1(c),(d) support the expected scaling behaviors for small values of stress. Similar results hold for data from the IN100 samples.

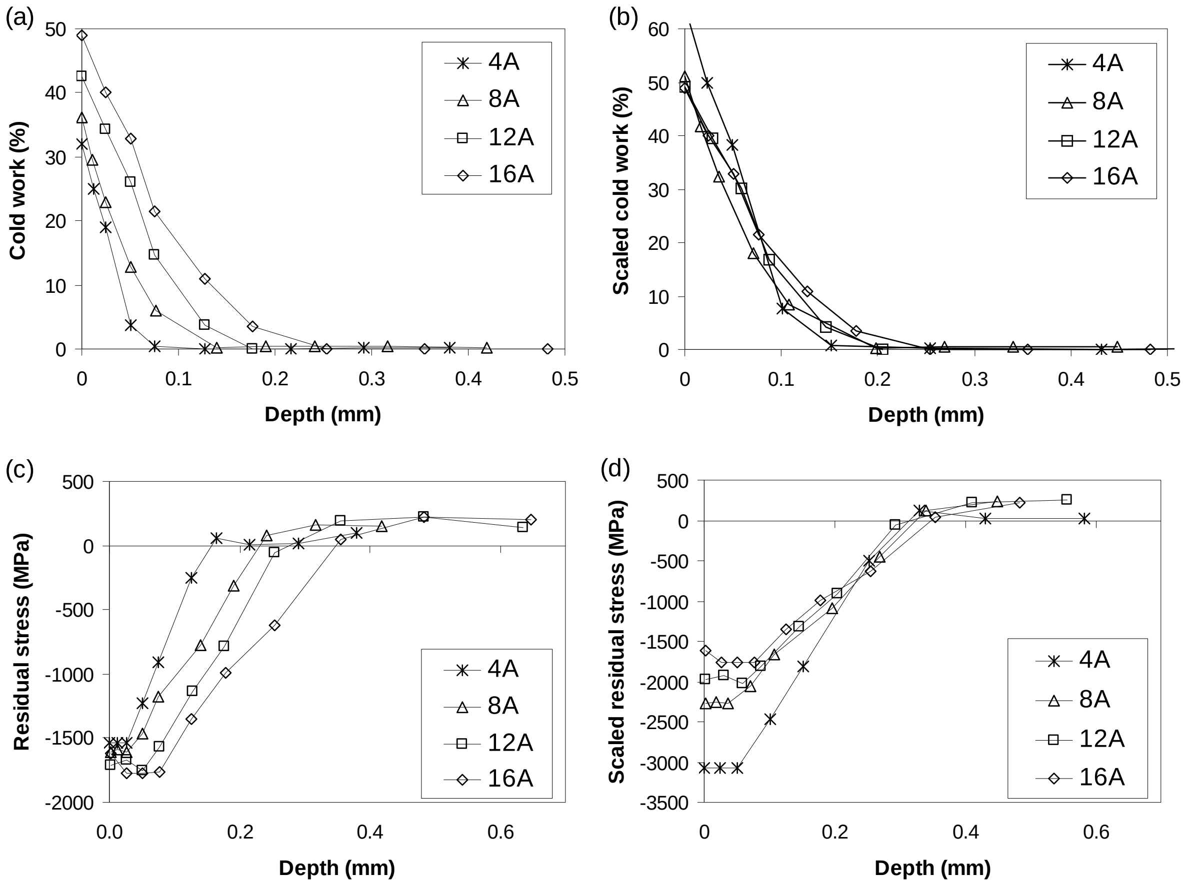

Figure 1: Cold work and stress depth profiles of Waspaloy at four Almen intensities *i*A with the strip deflections d_i, i=4,8,12,16; (a) and (c) for the cold work and stress data (after M. Blodgett and P. Nagy, 2004); (b) and (d) for the scaled cold work $w\sqrt{d_{16}/d_i}$ and the scaled stress $\tau\sqrt{d_{16}/d_i}$ as functions of scaled depth $z\sqrt{d_{16}/d_i}$.

Impedance signals of eddy current measurements

Earlier (Y. Shen, et al., 2007), we presented near-surface electrical property measurements, by the eddy current technique, on a series of Inconel 718 plates shot peened at various pressures. The sensor coils were placed over the shot-peened surfaces, yielding complex-valued impedance data. We have devised a data-processing procedure to extract so-called vertical-component signals that are free of instrumentation artifacts and directly related to surface conductivity deviations. The resulting V-component data are reproduced in Fig 2(a) as a function of frequency f. Assuming that the conductivity deviation of the shot peened surface is a linear function of stress and cold work, the theory predicts that the vertical component signals exhibit the scaling behavior, $V(f) \propto d \cdot \tilde{V}(fd)$. Figure 2(b) presents the scaled experimental stress data that show the predicted scaling behavior approximately.

SUMMARY AND CONCLUSION

A theory of shot-induced material property deviations near the material surface has been presented. Experimental data support the assumption that strain and stress as a function of depth in the shot-peened Almen strips has a universal function form depicted by Eqs. (2) and (3). The universality by way of scaling has been confirmed for the cold work in a nickel-base superalloy (Waspaloy). Residual stress and eddy current data exhibit scaling behaviors less exactly than the cold work data do. The origin of the deviation from scaling is unknown to date, but may be attributable to

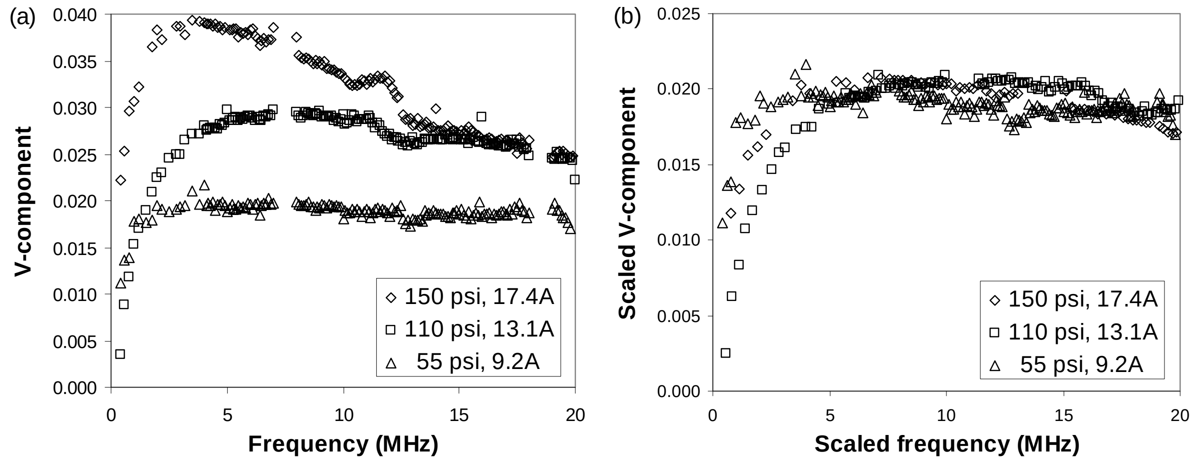

Figure 2: (a) The V-component data as a function of frequency. (b) The scaled V-component data $V_{comp} \cdot d_{9.2} / d_i$ as a function of scaled frequency $fd_i / d_{9.2}$. (150 psi etc. indicate the shot-peening pressures where $1\text{psi} = 6.90\text{kPa}$.)

bending. The scaling law could be used as a tool to control peening processes, by predicting cold work profile and to some extent the residual stress profile at varying Almen intensities. It is also useful in assuring consistency of eddy current measurement, which is currently being investigated with regards to its potential as a nondestructive technique for measuring surface and sub-surface material conditions (e.g. residual stresses) in aerospace materials such as nickel-base superalloys.

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