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Stress Field Modeling in Context of Industrial Shot Peening

Abstract
The compressive stress field imparted by shot peening has distributed surface and depth profiles relating to media characteristics and impact conditions. While the average surface stress and depth profile may be consistent over a large area, variability depends on the local scale of scrutiny—for example, in relation to a feature size of the part being treated, or size of peening media. In this paper, we analyze datasets obtained from finite element modeling of peening with media having experimentally-measured size and shape distributions, with detailed attention to the variance of the stress fields over a range of reference scales.

Industrial shot peening – a distributed process
Considering industrial shot peening as a distributed set of discrete impacts, one can assess stress field uniformity based on spatial and temporal variation of surface impacts during the peening process. Fundamentally, shot peening is a stochastic process, with thousands of individual particles impacting each part in random positions (Miao et al., 2009). While the resulting surface stress may be fairly uniform averaged over the full part, the local variability of the stress field increases as the scale of scrutiny approaches the shot size. In this paper, we consider the systematic analysis of stress field averaging and quantification of its scale-dependent variability.

Media size and shape distributions change during the process, i.e., due to rounding, hardening, and breakage. Other machine parameters can also contribute to variability, complicating the prospect of modeling such a process. Though these sources of variability are certainly unavoidable in any shot peening process, they do not necessarily have to inhibit a practitioner's ability to make predictions about their process and parts. Through careful and thoughtful analyses, shot peening practitioners in any industry can make robust predictions about the stress states present in their parts and the variability therein.

Stress field simulation
A finite element simulation of the shot peening process was used as a reference model of the surface stress field (Figure 1). It was generated through random sampling of a shot media size and shape distributions, obtained experimentally using a SolidSizer (JM Canty, Lockport, NY) particle measurement system (Mort et al., 2022). The simulated target was a 5 mm by 5 mm representative volume element of an Almen strip; stress residuals were calculated using 65 m/s impacts with a Johnson-Cook isotropic hardening material model (Ghanbari, 2020). The flux of media was based on industrially relevant process parameters.

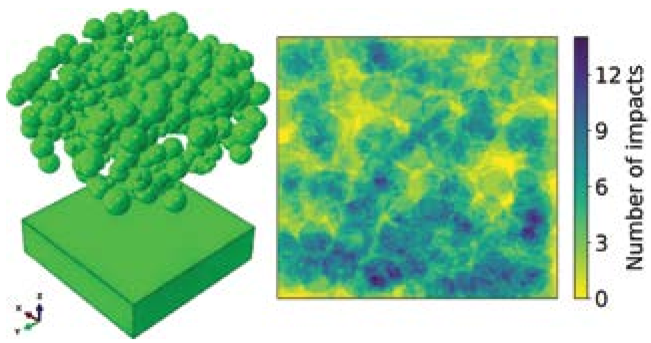

Figure 1. FEA model of shot peening process and map of spatial distribution of impacts on the surface of the substrate: a) media flux, pre-impingement; b) impingement locations.

The random placement of particles on the surface of the part creates both densely and sparsely impacted regions on the surface of the part. This is shown by the impact locations (Figure 1b) as well as the deviatoric analysis of the stress tensor in the X, or 11 direction, on the surface of the part plotted as the colormap variable (Figure 2). The average diameter of the shot particles was 0.837 mm and leaving dimples with a size of around 0.2 mm in diameter. The heterogeneous stress field suggests a need for textural model, i.e., one that predicts variation as a function of scale.

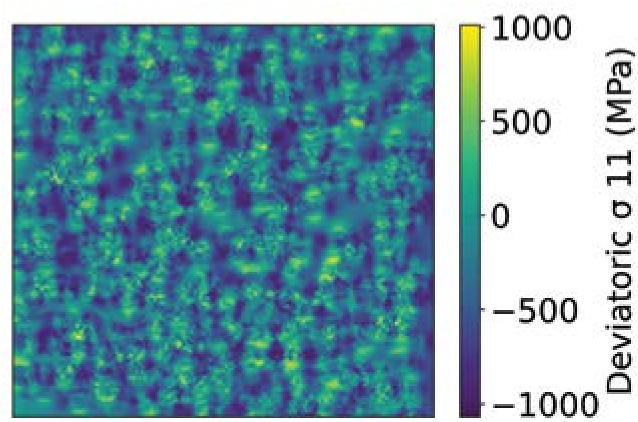

Figure 2. Spatial distribution in the deviatoric component of surface stress in the reference direction.

Experimentally, residual stress analyses of shot peened parts often employ an X-Ray diffractometer to measure the in-plane linear elastic stresses. The sin2 (ψ) method (Prevey et. al, 2020) and the cosα method (Tanaka, 2018) provide an integral of the stress over lateral spacings on the order of 2 mm diameter, depending on the specifics of the X-Ray source and fixturing. This is a standard practice for process monitoring and/or validation. In this paper, we consider applications requiring higher resolution—for example, materials having structural features and/or failure criteria (e.g., critical crack length) <2 mm. Modelling extends the stress field resolution to the grain scale, enabling residual stress analyses at relevant scales of scrutiny, i.e., detailed spatial and statistical analyses of the stress state in shot peened parts, accounting for temporal, spatial, and stochastic variability present in the process.

To mimic a physical experiment, the entire second order Cauchy stress tensor was extracted from every node in the substrate FEA model. One of the limitations of XRD residual stress measurement is a lack of the ability to measure hydrostatic, or mean, stress; therefore, the stress tensor at every point is resolved into hydrostatic and deviatoric components and only the deviatoric portion is kept. Another assumption of the XRD stress measurement system is that the stress state in the substrate is purely in-plane, so only the stress values associated with the XY-Plane are considered. Feasibly, a shot peening practitioner would define a reference orientation for the part when they measure the residual stress on the surface of the part. Since the particles in this study impact the surface of the substrate in random locations at a 90˚ angle of incidence, the X, or 11, direction was assumed to be the reference orientation for this part, and the deviatoric component of σ11 was used in the analysis.

Scale of Scrutiny

The uncertainty of stress field analysis depends on the scale of scrutiny over which the residual stress is being measured or calculated. In the case of XRD measurements, residual stress is the arithmetic average of the stress within an irradiated region, which is typically greater than the size of the media. At this scale, the variability of the stress state is relatively low. In comparison, at a scale less than a shot particle size, the stress state varies in relation to the local distribution of impacts. To perform an uncertainty analysis of the stress field as a function of the scale of scrutiny, we consider: 1) a sampling technique to pick equally sized and continuous regions of the substrate, and 2) a method for describing the stress-depth profile and associated uncertainties at each scale.

The FEA substrate was subsampled into equally sized cubic elements with nodes at each corner (Figure 3). This means that the part is a three-dimensional grid-work, consisting of discrete values for stress at equally spaced intervals throughout the body. Since the substrate is 5 mm by 5 mm, the reference or mean state is the average stress state

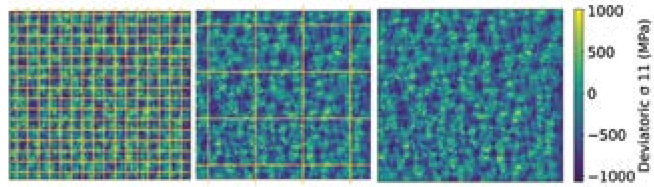

Figure 3. Slicing of the substrate into equi-sized subsections allows for the variability in stress state to be determined across scales of scrutiny.

for all nodes at each discrete depth. The sides of the substrate were divided sequentially into discrete length divisions. As the number of side divisions increased, the unit cell length decreased. The stress depth profile for each unit cell is calculated as the average stress value for the nodes at each discrete depth in each unit cell.

The stress state within each unit cell was described with equation 1, providing a continuous stress-depth profile. The ability to fit a continuous function to describe the stress depth profile greatly simplifies the shape of the stress-depth profile into interpretable coefficients. In this case, the stress-depth profile is modeled as a modified stretched exponential function (Equation 1), where, σ* is the stress on the surface of the part, x* is the characteristic depth, describing the curl or relaxation of stress close to the surface of the part, and m describes the rate of decay of the compressive stress into the thickness of the part and is related to the compressive penetration depth.

$$\sigma(x) = \sigma^* \cdot exp\left(1 - \left(\frac{x}{x^*}\right)^{\frac{x}{m}}\right) \qquad \text{Eq. 1}$$

This function has added the convenience of being linearizable (Equation 2), and since the surface stress is fixed, a traditional linear regression is sufficient to fit the characteristic depth and decay factor to the simulation stress depth profile. This equation describes the mean stress depth profile in the substrate. The breadth of the distribution of stress values as a function of scale of scrutiny was analyzed relative to the mean.

$$ln\left(1 - ln\left(\frac{\sigma}{\sigma^*}\right)\right) = \frac{x}{m}\left(ln(x) - ln(x^*)\right) \qquad \text{Eq. 2}$$

Discussion of Results

An example of the technique is shown in Figure 4, sampling the stress values at each depth across all unit cells. The mean stretched exponential fit is shown. Regardless of the scale of scrutiny, the mean remains the same. The main difference is the width or breadth of the stress values in the depth profile. The difference in breadth of the stress values is striking, when comparing a scale of scrutiny of 1 mm, similar to the XRD stress measurement scale, and 50 microns, similar to a grain scale.

In order to use this type of analysis as a quality measure in an industrial application, a user can predict the boundaries of the prediction interval for residual stress vs. depth curves

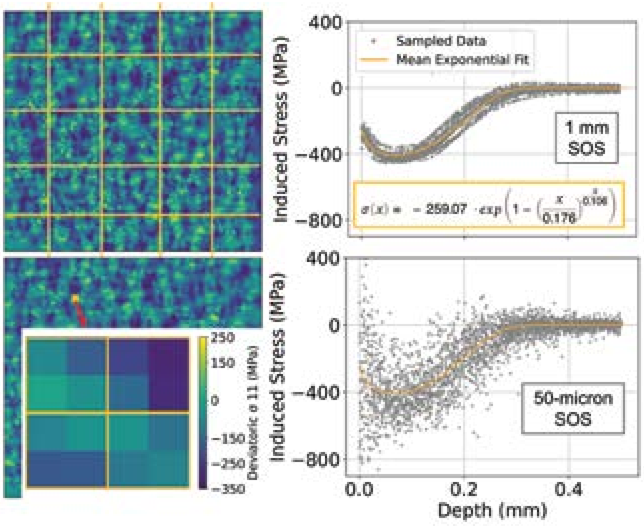

Figure 4. The breadth of the point cloud of stress values is determined by the size of the unit cell being evaluated and the depth at which the stress is measured.

in the body of the substrate as a function of the scale of scrutiny by constructing probability distributions for the stress values at each depth of the FEA model. In this case, each depth was assigned an individual Gaussian probability density function, with the mean value evaluated at the center of the mean exponential fit and the variability determined by the breadth of the prediction interval as a function of depth. Figure 5 shows the set of all stress-depth profiles from the FEA reference model, with the relative frequency of values in a particular region shown as the color. The 99% prediction intervals for the stress were based on the probability model assigned at each depth.

At a 1 mm scale of scrutiny, the entire prediction interval is in compression, and the width of the prediction interval is about 200 MPa at the surface of the part. At a 50-micron scale of scrutiny, the prediction interval for surface stress is much wider, spanning 1500 MPa. At this scale of scrutiny, localized stress fields can be tensile or compressive, ranging from 500 to -1000 MPa in residual stress. Evaluating stress field prediction intervals as a function of scale can provide insight on part quality and performance metrics. As a next step, we propose to develop work-process guidelines relating the selection of media and process parameters to quality objectives on the basis of relevant scales of scrutiny.

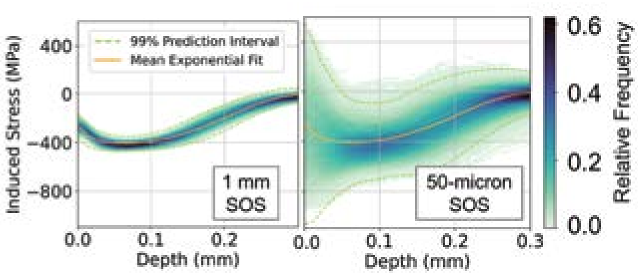

Figure 5. At a given scale of scrutiny, prediction intervals can be constructed for the stress-depth profile, showing the range of stress values present in a part at each discrete depth.

Conclusion

Shot peening researchers and practitioners continue to refine and develop understanding of the peening process. In this paper, we consider peening as a distributed process having parameters affecting the variability of stress fields in treated parts. A statistical assessment of stress field variability is a foundation for building quality models relative to critical scales of scrutiny.

This paper illustrates the scale dependency of residual stress imparted by shot peening. The effect of scale on the prediction interval is striking, especially at the surface. As a quality measure, we anticipate using this framework to inform predictive performance models of shot peened parts, enabling industrial practitioners to link selection of media and process parameters with product quality objectives.

Acknowledgments

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