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FROM STRAIN TO STRESS: STRESS MAP TESTING OF ALMEN STRIPS

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Abstract

Almen strips have long been used to evaluate shot peening intensity, with arc height serving as a proxy for compressive residual stress. Stress mapping tests (SMT) in this work involve the controlled flattening of an Almen test strip onto a spatial pressure sensor, acting as an inferential measurement for the net bending moment caused by the relaxation of the peened strip. This work explores how stress mapping tests add insight into the stress state of Almen strips, potentially offering a fast and practical alternative to residual stress depth profiling. SMT data analysis provides a framework for relating Almen gauge height with internal stresses. We aim to use SMT as a bridge between strain and stress measures, with implications for both scientific understanding and industrial applications.

Keywords: Almen strip, Residual stress anisotropy, Bending moment, Stress mapping

Introduction

Shot peening is a surface treatment technique that has a long history in manufacturing. Peening gives many benefits to products including but not limited to increased wear resistance, corrosion resistance, fatigue resistance, and surface texture. Many of the benefits are derived from the compressive residual stress on the near-surface of the peened part. Almen strips are used as a standard tool to indicate the combined effects of all peening parameters into a single measure of peening intensity, or arc height at saturation measured using a standard Almen arc height gauge [1]. Saturation is defined as the arc height at time T, $h(T)$, such that $h(2T) = 1.1 \cdot h(T)$ [2, 3].

Arc height is a summation of the contributions from the resulting arcs formed across the length (i.e., longbow), and width (i.e., crossbow) directions. The lengthwise direction is the primary contribution to arc height due to its longer dimension [4]. The residual stress from peening is equal in both directions while the strip is clamped flat, i.e., residual stress is isotropic during peening of a sample with effectively infinite thickness. Unclamping the strip allows for relaxation in both directions, resulting in an anisotropic residual stress field, with the magnitude of the relaxed compressive residual stress being larger in the crossbow direction. The Almen strip arc height measurement represents this relaxed anisotropic condition.

Arc height is a standardized strain measurement used as a proxy for residual stresses applied to a part, but it is inherently an ill-posed problem because multiple residual stress states can produce the same arc height. As a result, information about the depth and magnitude of residual stress cannot be determined from arc height measurements alone. To obtain the values of residual stress, X-ray diffraction (XRD) depth profiles are typically used. There are several techniques for using XRD to measure residual stress, including $cos(\alpha)$ and $sin^2(\psi)$ [5].

- The cosine alpha method, $cos(\alpha)$, (Pulstec, Novi, MI, USA) measures residual stress in a single measurement, collecting data for the entire Debye ring at once.

- The sine-squared psi method, $sin^2(\psi)$, (PROTO, Taylor, MI, USA) is a multiple exposure technique taking measurements at different angles of x-ray incidence. While this takes longer, it provides information about residual stress along the direction of measurements. When measuring an unclamped Almen strip along the length of the strip (i.e., longbow), the measured values of stress are lower than in the crossbow direction.

Tactile sensors work by having arrays of sensels measuring an electrical property calibrated to different stress states. The Tekscan 4201 (Tekscan, Norwood, MA, USA) is a resistive sensor having an 11x24 array of sensels which can collect data at high frequencies. The stress measured can then be analyzed looking at the full array, or averaging stresses over different sub arrays. The uncompressed thickness of the 4201 sensor is ~178 μm; it has significant compliance in response to compression.

During peening, the part absorbs some of the imparted kinetic energy as plastic deformation, causing accumulation of residual stress in the material. When unclamping an Almen strip, it deflects to relax some of the residual stress. Energetically, it reduces the energy state in the material to balance the moments of the residual stress gradients. Assuming elastic deformation, the work of flattening the strip should equal the energy difference between the clamped and unclamped states.

Information regarding the bending of Almen strips can be inferred using beam bending theory. Assuming the flattening of the strips follows similar behavior to a 3-point bending test, the change in load by the vertical displacement should follow equation 1 for the general bending, where dF/dy is the slope of the applied force, F, with respect to vertical displacement, y. I is the second moment of area, E is Young's modulus, t is strip thickness, L is the distance between points of force, and b is the width of the bent area. Equations 2 and 3 show the formulas for the beam bending in the longbow and crossbow direction respectively, for variable strip thickness, t, where strip width is 19 mm and distance between contact pins in the test rig is 25.4 mm. The assumption for these relationships is that the bending or flattening is purely elastic [6, 7].

$$\frac{dF}{dy} = \frac{48EI}{L^3} = \frac{4bEt^3}{L^3} \tag{1}$$

$$\frac{dF}{dy} = \frac{4(19\ mm)Et^3}{(25.4\ mm)^3} = 0.0046Et^3 \tag{2}$$

$$\frac{dF}{dy} = \frac{4(25.4\ mm)Et^3}{(19\ mm)^3} = 0.015Et^3 \tag{3}$$

The above beam bending analysis suggests a crossbow stiffness of about 3x the stiffness of the longbow direction. Assuming a model having crossbow and longbow "springs" in series, initial flattening occurs primarily in the longbow, followed by combined flattening in both longbow and crossbow directions.

Experimental Procedures

A series of experiments having a range of Almen strip thicknesses (N, A, and C) was done over a range of peening conditions. The Almen strip grades were 1S for N and A strips and 1 for C strips. Two peening conditions were used varying the air pressure and angle of incidence from the lengthwise direction, Table 1. All peening was done on the Sentenso Process Master (Datteln, Germany). The saturation curve as well as the calculated saturation point can be seen in Figure 1. Samples used in subsequent testing were collected at times $1/2 \cdot T^*$, T^*, and $3 \cdot T^*$ where T^* is the time corresponding to the saturation point. In experimental design, a reduced factorial of the sample thicknesses at the varying points of coverage was implemented to focus on ranges of arc heights that would be reasonable with respect to the range and precision of the Almen Gauge. N and A strips were used for the low coverage point, $1/2 \cdot T^*$; all strip thicknesses were tested at T^*; C and A strips were peened at the high coverage point, $3 \cdot T^*$.

Table 1. Shot peening parameters for the samples tested and the resulting intensities.

	Air pressure	Angle	Media rate	Media	Intensity
Condition A	2 bar (19.4 psi)	76 degrees	2 kg/min	CCW32 (63 HRC)	17.7A
Condition B	1 bar (14.7 psi)	45 degrees	2 kg/min	CCW32 (63 HRC)	7.5A

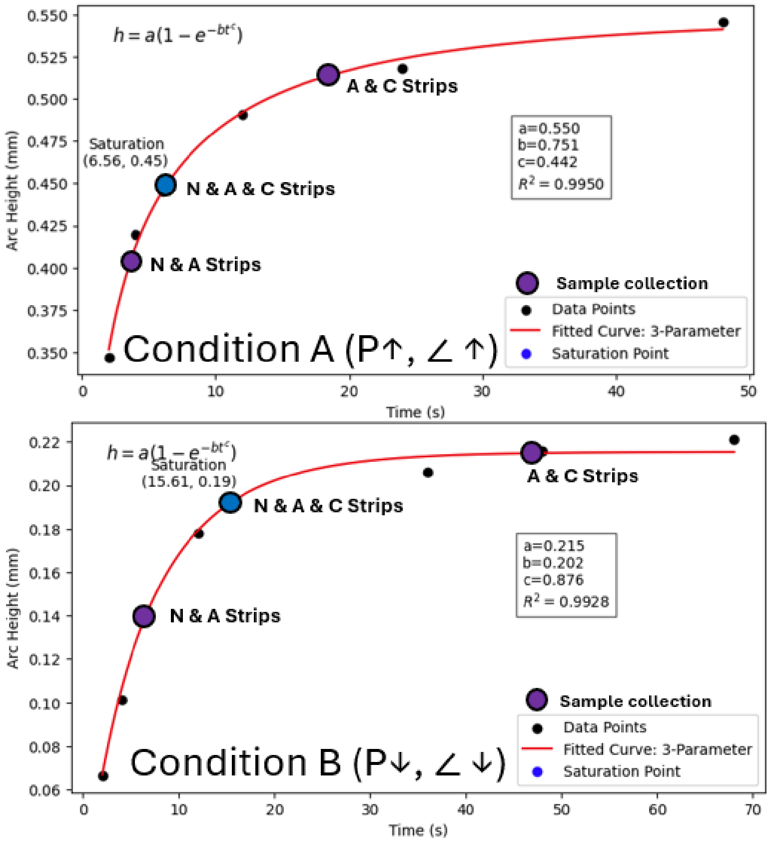

Figure 1. Saturation curves of A strips for conditions a) A, and b) B. The experimental samples were collected at three coverage points as marked on the saturation curve corresponding to half, full, and three times the saturation time.

Surface residual stress measurements were performed in both longbow and crossbow directions. To measure stress anisotropy, the $sin^2(\psi)$ multiple exposure technique was used with the strips oriented vertically and horizontally with respect to the axis of incident x-rays.

An experimental compression testing rig was designed to measure the position and load using a test frame (Electroplus E1000, Instron, Norwood, MA, USA), Figure 2. Additionally, stress arrays were measured using Tekscan 4201 sensor during the compression cycle. The two datasets were synchronized manually. The load data were interpolated to match the data rate from the stress measurements, Figure 3. The compression for each strip goes down to about the same depth relative to the thickness of the strip, but not relative to its arc height. In some cases, C and A strips were compressed significantly compared to their arc heights, including compliance of the tactile sensor.

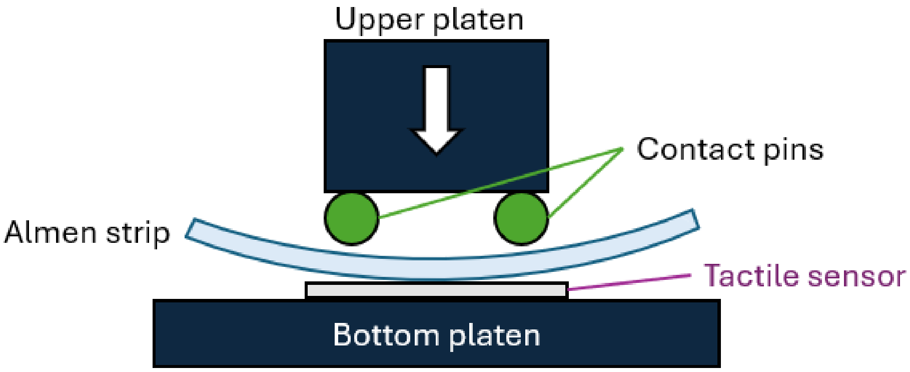

Figure 2. Compression rig for stress mapping test using an Instron load frame. The contact pins are spaced 1 inch center to center. Bottom plate remains fixed, while upper fixture will lower to flatten the peened Almen strip. Tactile sensor is a 4201 Tekscan sensor with 11x24 arrays of measured stress. Instron collects load and position measurements.

Experimentally, there was some uncertainty in the Instron Electropuls control program, which overshot the intended load-control limit and proceeded to what appeared to be a hard-stop displacement limit. Despite the control issue, data were obtained and analyzed for this report. Future work should consider transitioning to an updated and supportable test frame.

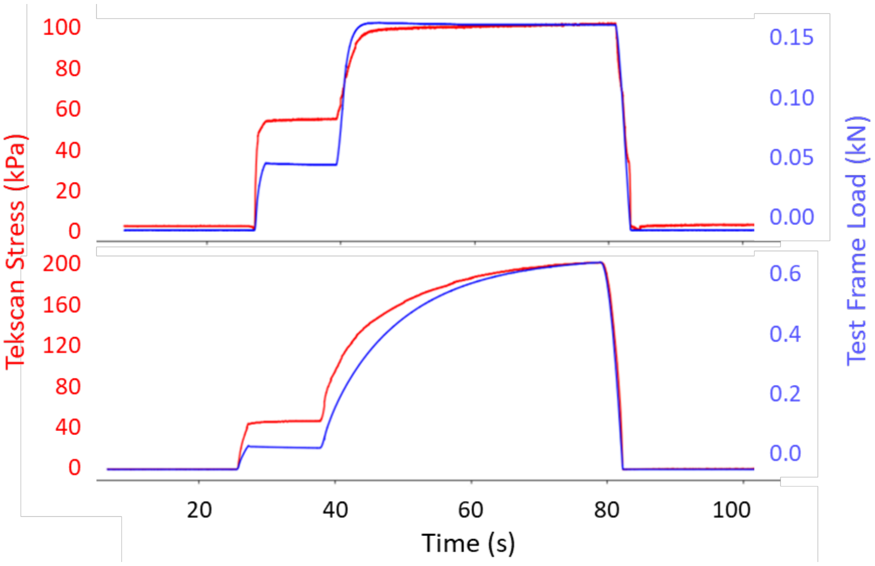

Figure 3. Graphs showing example curves of the measured load from the Instron, blue, and stress from the Tekscan, red, synchronized across time for a) N and A strips, and b) C strips.

Results and Discussion

The measured surface residual stress of peened Almen strips should be isotropic prior to releasing the strip off the Almen block. While unclamped, the Almen strip will have an arc height in both directions, with a higher contribution of the arc across the length of the strip compared to the width. The measured residual stress appears to depend on the degree of arcing in each direction of the strip, being lower in the longbow and higher in the crossbow, Table 2. When flattened completely and clamped as initially peened, the values of residual stress should be higher and about equal in both directions, but when clamping down a bent strip, there is some difficulty in flattening it out in the crossbow direction, causing the anomally in the residual stress of the clamped N strip in Table 2.

Table 2. Measured residual stress in both directions, clamped and unclamped, on the surface of Almen strips peened at the same time using condition A. All the strips were unclamped after peening and were later re-clamped for the measurement.

		Unclamped residual stress		**Clamped residual stress**	
Strip	Arc height	Longbow	Crossbow	Longbow	Crossbow
N	0.989 mm	-229 MPa	-323 MPa	-450 MPa	-259 MPa
A	0.440 mm	-252 MPa	-506 MPa	-471 MPa	-495 MPa
C	0.127 mm	-296 MPa	-480 MPa	-427 MPa	-415 MPa

During compression and subsequent relaxation of the strips, multiple slopes can be seen in Force vs Displacement graphs, Figure 4. The different slopes correspond to the long direction flattening first, followed by flattening in the crossbow direction. In the relaxation, the order is reversed where the crossbow will relax before the longbow. The slope of each region can be related to stiffness in each direction.

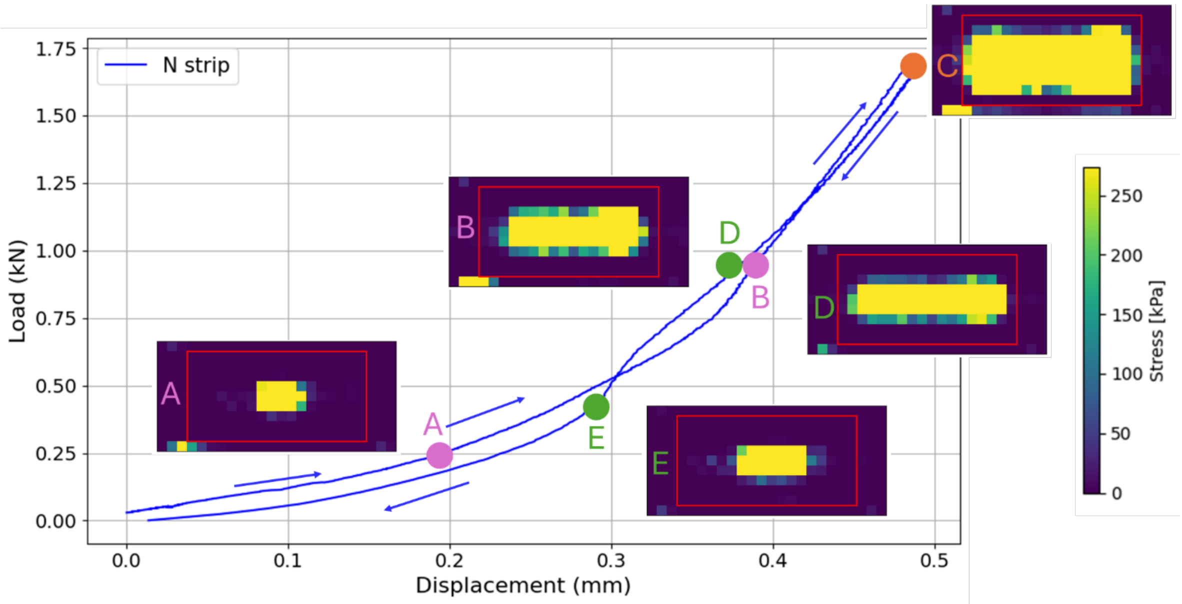

Figure 4. Load vs displacement for N strip peened at T^*. Spatial map of stress at various stages in the compression (A, B), maximum stress (C), and relaxation (D,E).

Linear regressions for the load and position can also be used to map out the linear regions of the longbow and crossbow flattening, Figure 5. For consistency in the analysis, a script was implemented to parse the two linear regions by minimizing the squared error. An experimental summary is given in Table 3.

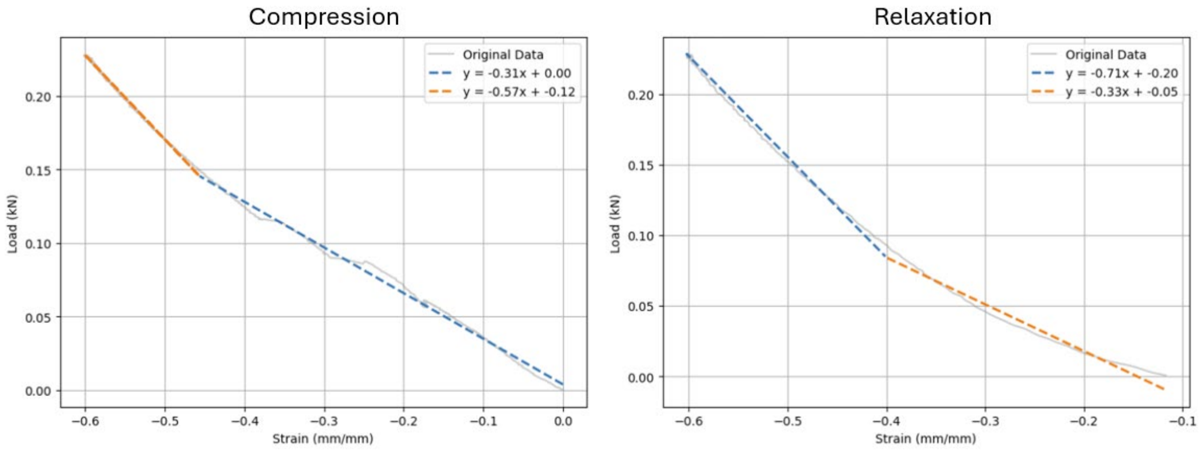

Figure 5. Example load and strain curves for A-strip flattening. The strain is the displacement relative to the arc height of the strip.

Table 3. Compression and relaxation slopes for conditions A and B, degree of coverage (US, S, OS), and strip type (N, A, or C). The slope ratios relate crossbow/longbow flattening.

	COMPRESSION					**RELAXATION**				
SAMPLE ID	Slope 1	R2	Slope 2	R2	Slope ratio	Slope 1	R2	Slope 2	R2	Slope Ratio
CA-S-A	-0.66	0.97	-3.22	0.99	4.87	-2.95	0.98	-0.72	0.94	4.09
CA-S-N	-0.60	0.97	-2.51	0.98	4.20	-5.62	0.94	-1.44	0.92	3.90
CA-S-C	-0.16	0.98	-0.82	0.99	5.21	-1.03	0.99	-0.23	0.89	4.40
CA-S-C	-0.16	0.98	-0.71	1.00	4.41	-0.76	0.99	-0.22	0.92	3.49
CA-OS-C	-0.16	0.98	-0.73	1.00	4.54	-0.78	1.00	-0.21	0.90	3.66
CA-OS-A	-0.37	0.99	-0.71	1.00	1.92	-0.98	0.98	-0.44	0.97	2.25
CA-OS-A	-0.38	0.99	-0.69	1.00	1.81	-0.98	0.99	-0.45	0.97	2.21
CA-US-N	-0.35	1.00	-0.41	1.00	1.15	-0.51	0.99	-0.34	0.99	1.51
CA-US-A	-0.31	0.99	-0.57	1.00	1.84	-0.71	0.99	-0.33	0.97	2.15
CB-US-N	-0.44	1.00	-0.89	1.00	2.05	-1.27	0.97	-0.36	0.98	3.54
CB-US-A	-0.41	0.99	-1.83	0.99	4.45	-2.39	0.99	-0.53	0.94	4.52
CB-S-N	-0.41	1.00	-0.86	1.00	2.09	-1.29	0.98	-0.39	0.98	3.32
CB-S-A	-0.45	0.99	-1.39	0.99	3.10	-1.95	0.98	-0.51	0.94	3.83
CB-S-C	-0.17	0.98	-0.85	1.00	5.04	-1.01	0.99	-0.26	0.89	3.91
CB-OS-A	-0.44	0.99	-1.53	0.99	3.50	-2.14	0.98	-0.55	0.96	3.89
CB-OS-C	-0.16	0.98	-0.84	1.00	5.30	-0.97	0.99	-0.27	0.92	3.61
AVERAGE					3.47					3.39
STDEV					1.45					0.88

The stress mapping data showed regions of compression that varied in shape and magnitude (up to a saturation pressure). The pattern of compression varied by sample. Figure 6 shows the differences in the stress map for same peening conditions and coverage at the point of maximum stress across the sensor. The region of interest (red rectangles) for each strip was selected to focus on the active sensels: i.e. in direct contact with flattened strip. The borders of the sensor measure values of stress due to the fixture holding the strip in place.

The arc height of the C strip in Figure 6 is a value of 0.125 mm. In the experiment, the sample was deformed beyond this point due to the tactile sensor compliance. In the cases of the A and N strips, the final displacement was around 51% and 35% percent of the arc heights respectively.

The degree of crossbow compression differed depending on the final load reached. In the case of the C strips, crossbow was flattened significantly, but in the N strips, the crossbow flattening was significantly smaller and reached a much smaller final load.

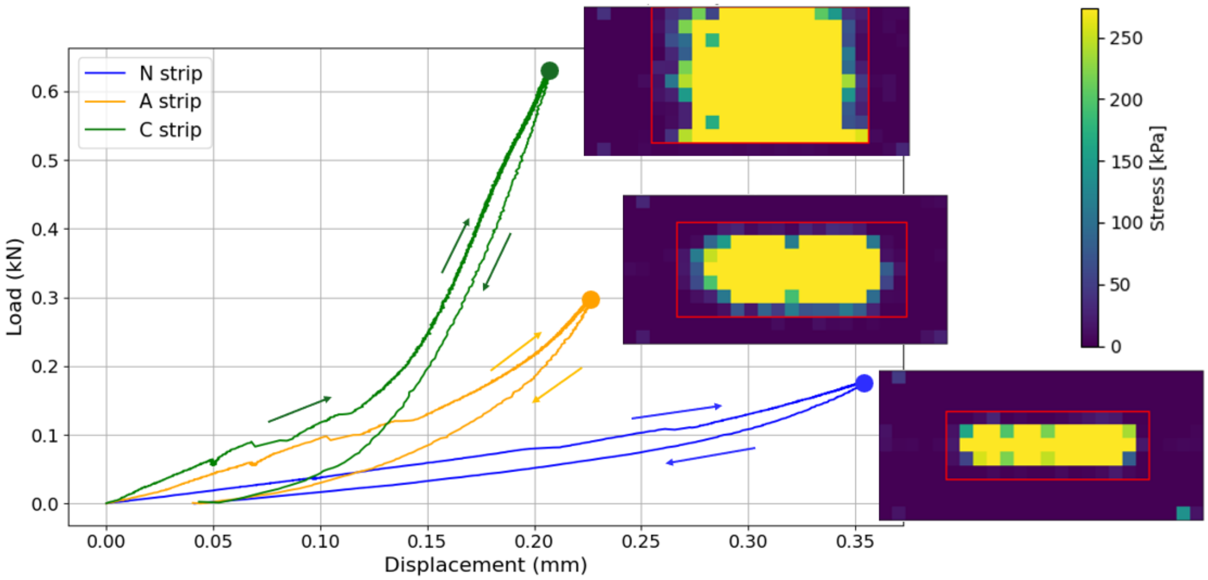

Figure 6: Load vs displacement curves for three samples (N, A, C) peened at the same condition and coverage. The spatial map corresponds with the points of max stress per experimental run.

Summary and Conclusions

Shot peening induces residual stress in treated parts, in this case, Almen strips. Post-peening, Almen strips relax to minimize the interplay between the bending moments and residual stresses. The remaining residual stress is a function of the amount of relaxation and is anisotropic due to the difference in the dimensions of the strip. The higher value of surface residual stress is in the crossbow direction of the unclamped peened strip. During SMT, the applied stress will counter the residual stresses, thus the strip will first flatten across its length at a lower stiffness than the subsequent crossbow flattening. Experimentally, the ratio between the stiffness of longbow and the combined longbow-crossbow flattening is about 3.4. The amount of work required to flatten a strip in the SMT should be equal in magnitude to the change in internal energy when deflecting to the arc height.

In standard shot peening characterization methods, the Almen strips deflect and provide a strain measurement (i.e., arc height) that can be used to infer the stress state, but there is more information that can be gathered. Residual stress XRD depth profiles provide detailed information about the internal stresses in the system but take time, capital, and experience to perform. The flattening of an Almen strip requires a load frame and is relatively simple to perform. The information collected provides the force and stress data needed to analyze the anisotropic residual stress state. The Tekscan sensor provides additional information about where the strip is in the flattening process, but it is not necessary to perform the experiments if the load frame collects position and force information.

The SMT is pertinent to industrial peening applications. In large parts such as gears or axles, macroscopic deformation due to peening is minimal, and the residual stress state is most related to the clamped or flattened state of the Almen strip. In peen forming applications, the goal is to deform the part to the desired end state. The change in residual stress profiles due to the deformation is directly connected to the results from the SMT. Additionally, information can be correlated between the results from the SMT and the amount of force the peen-formed part can withstand before yielding.

The study will continue to investigate the connection between the work to compress the sample (area under the Force-Displacement curve), and the arc height of the material to infer information about the residual stress depth profile. Knowing the geometry of the strip and the arc height, the information regarding the bending moment can be predicted. The moment information combined with the work required to flatten the strip, informs the depth profile, which can take the form of the profile itself or its work integral. In theory, there may be multiple depth profiles that could result in the same deflection and moment, so surface residual stress information may be required for accuracy of the prediction.

Acknowledgements

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