Practical Examples and Implications of Almen Strip Physics

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Introduction

For several decades, Almen strips have been valuable tools to provide shot peeners insights and expectations pertaining to the peening conditions they are employing. During the same time period, several excellent models have been proposed and developed which provide physical and mathematical bases for the interactions between the impinging media and the strip. Since one of the guiding principles at Purdue's School of Materials Engineering (MSE) is to "intersect" industrially relevant research with "real world" engineering education, multiple studies have been undertaken to examine the relationships between fundamentally developed models with conventional shot peening practice.

An appropriate place to start is Kirk's discussion of the physics that lead to the bending of shot peened Almen strips [1,2] which involves the plastic deformation of a peened Almen strip surface and the subsequent formation of a compressive residual stress. The imparted peening intensity is proportional to the depth of this compressive residual stress region. Thus, if the residual stress versus depth curve is known, then the corresponding arc-height (H) can be estimated from a simple elastic bending analysis. For this case, the estimate arc-height (H) for bending along the length of the strip is [1]:

$$H = 3ML^2/2Ewt^3 \qquad (1)$$

Where M is the bending moment, L is the Almen gage reference distance, E is Young's modulus, w is the width, and t is the thickness of the strip. The bending moment is then proportional to the area under the compressive stress versus depth curve. Taking an average value for this area as σ·d where σ is the average compressive stress induced from the peening, and d is the average depth, the bending moment (M) can then be written as [2]:

$$M = w(\sigma \cdot d)(t-d)/2 \qquad (2)$$

As noted by Kirk [1], "the problem is greatly simplified by assuming that all of the required energy is for elastic bending." Thus, for a given induced stress versus depth curve, the arc-height can be estimated using equations 1 & 2. These curves are typically not measured with respect to the Almen strip itself. The standard Almen strip thicknesses are specified in SAE J442 [3] (N vs. A vs. C), and the recommended intensity limits (SAE J443) [4] for A strips are from 0.1 mm A (0.004 in A) to 0.60 mm (0.024 in A). However, intensity ranges for N and C strips are not specifically given in a SAE specification. As part of a senior design project, MSE students investigated the response of Almen strips of different thickness for the same peening intensity. This article will briefly summarize those results as related to the above described "Almen strip physics".

Experimental

A series of tests were made using A-1S, N-1S, and C-1 Almen strips that were provided by Electronics, Inc. Peening was done at Progressive Surface with a CNC robotic arm equipped shot peening machine. The goal was to achieve a set of peening conditions to produce a complete range of intensities for A-strips extending beyond that specified by SAE J443 [4]. The selected peening conditions are listed in Table 1. At each intensity, the arc-height for C and N strips were also measured.

Stress versus depth profiles were measured for the peened Almen strips with measurements made at the center of the peened face. Residual stress at a given depth was measured with a Pulstec μ-x360s residual stress analyzer which employs the cosine(α) method [5]. Material was removed by electro-etching with a 3 wt% NaCl solution at 130 mA over a 5 mm diameter for 2-minute intervals. The depth of the resulting impression was then measured with a 0.01 mm precision dial indicator.

Results and Discussion

The stress versus depth profiles for all the peened strips listed in Table 1 are shown in Figure 1. These results show the expected strong correlation between the peening intensity and the depth of the compressive stress for N, A, and C type strips. Figure 2 shows a schematic stress versus depth profile for a fully constrained strip (or one that has a semi-infinite thickness). The area under this curve (units of work/area) represents the average area (σ·d) denoted in equation-2. Assuming an Almen strip is fully constrained in the holder, once it is removed after peening, the strip is free to elastically bend and stretch [6]. These stresses are also schematically shown in Fig. 2 which result in the final residual stress state in the strip. Thus, the stress profiles shown in Fig. 1 (or any appropriately derived residual stress-depth profile) correspond to the residual stress profile as marked in Fig. 2 where the "net" work ($W_{residual}$) is the result of the induced work ($W_{induced}$) less the work that is associated with bending and stretching.

In order to determine if the work performed for identical peening conditions is the same for all three strips (once their thickness is taken into mathematical consideration), the first step is to quantify the area under the residual stress curves ($W_{residual}$) for given strip intensities. Next is to estimate the work for the induced stress curve ($W_{induced}$) for all three strip types. A spline fit and the trapezoidal method with MatLab [7] were used to find $W_{residual}$ for all the residual stress curves shown in Fig. 1, and these values are listed in Table 2. For each strip type, the work ($W_{residual}$) increases with increased peening intensity.

To find an average work value (σ·d), appropriate average values of σ and d should be determined. Noting that the shape of residual stress curve resembles a Weibull distribution function as shown in Fig. 3, the properties of the complementary cumulative Weibull distribution can be used. This can be written as:

$$w(x) = (w^*)\exp(-x/x^*)^m \qquad (3)$$

where w^* is the total cumulative work, the constant m is the Weibull modulus, and x^* is characteristic depth defined as 63% of the total area under the residual stress profile for the case when $x=x^*$ and $w(x)=37\%$ as shown in Fig. 3. This method provides a consistent numerical approach to find the characteristic depth between curves and peening conditions. Using this procedure, x^* was found for all the residual stress depth curves, and these values are also listed in Table 2.

To estimate the area under the induced stress curves ($W_{Induced}$ per area) for the conditions listed in Table 1, equation 2 can be rearranged as:

$$W_{induced} = (\sigma \cdot d) = M/[(w(t-d)/2] \qquad (4)$$

where M is found from equation-1 using the measured arc-heights and $d=x^*$ (the characteristic depth) values. For example, an A-strip peened at condition D from Table 2 has a measured arc-height of H=11.6 [in/1000] or 0.295 mm and a characteristic depth of $d = x^*=112.3 \times 10^{-6}$ m. Then using L=31.75 mm from the Almen gage, a strip width of w=19 mm, thickness t=1.295 mm and an elastic modulus of E=200 GPa, the bending moment is found to be M=1.61 Nm which gives a work value of $W_{induced}$= 143 kJ/m^2. Figure 4 shows the comparison of the A, N, and C strips for the different peening conditions. As noted above, the same value of $W_{induced}$ is expected for the A, N, and C strips for the same peening condition as this represents a strip that is fully constrained in the holder. This is observed when comparing N and A strips as shown in Fig.4(a) since the slope of the ratio between the induced work is one. Conversely, this is not the case when comparing the A and C strips. Here, the slope is approximately 0.70 which implies that arc-heights for C strips would be overestimated using the current analysis. This can also be shown by comparing the ratios of the arc-heights between strips. Using the values from Table 1, $H_N/H_A \approx 2.65$ and $H_A/H_C \approx 4.5$. These ratios are similar to those reported earlier [8]. From equations 1 and 2, these ratios should also approximate the inverse ratios of thicknesses squared when d is small. For example taking the values in mm, $(t_A/t_N)^2 = (1.295/0.785)^2 = 2.72$ which reasonably agrees with ratio above, but conversely the ratio $(t_C/t_A)^2 = (2.385/1.295)^2 = 3.38$ is not as close.

A possible explanation for the somewhat departed calculated peening response of the C-strips may be related to the degree that the strip is constrained during peening. The calculation of the induced stress assumes a fully constrained strip (e.g., a semi-infinite strip thickness). In practice, the strip is constrained only by the 4 set screws of the Almen strip holder. Thus, it may be possible for the strip to elastically distort while in the holder, for example the formation of a cross-bow curvature, to relieve the stress. Since the C-strip is thicker than the A and N strips, it should naturally be more fully constrained. As peening is a continuous operation, the formation of the induced residual stress can be considered a pre-existing compressive elastic stress at later times. If a greater pre-existing compressive elastic stress develops in the C-strip, this could reduce the indent size and result in a smaller arc-height.

Lastly, the average work from the residual stress curves ($W_{residual}$) can be estimated by subtracting the work needed to bend the strips flat (W_{bend}) from the $W_{induced}$ values. These values can then be compared to the measured ones listed in Table 2. Here, W_{bend} can be found by integrating the bending equation, as plotted in Figure 2, over the distance d. The resulting equation is:

$$W_{residual} = W_{induced} - W_{bend} \qquad (5)$$

where $W_{bend} = \sigma_{bmax}[(d)(1-d/t)]$ and σ_{bmax} is the bending stress at the peened surface. Considering case D from Table 2 for the A-strip again, the surface bending stress is simply $[M(t/2)]/I$ where I is the second moment of area ($wt^3/12$). Substituting the values from above gives σ_{bmax} = 302.8 MPa and W_{bend} = 31 kJ/m^2 so that $W_{Residual}$ = (143 – 31) kJ/m^2 or 112 kJ/m^2 which corresponds well with the measured value listed in Table 2.

Figure 4(b) shows a comparison between the estimated and measured values for the A and N strip showing reasonable agreement between the two. Furthermore, since the range of peening conditions in this study extended beyond that recommended in SAE J443, the linear correlations shown in

Figure 4 suggest that useful information can still be obtained from strips peened beyond these limits for the current peening conditions.

Summary

These results and analyses were from a MSE senior design project which used industrially relevant peening protocols and gave students practical shot peening experience. Two key outcomes were: 1) understanding and documenting the effect of thickness on peening response and 2) comparing the measured correlations between standard Almen strip types as a function of peening intensity using well-founded physical materials science as its basis.

Acknowledgements

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References

1) David Kirk, "Quantification of shot peening intensity rating", *The Shot Peener*, Winter 2015, p. 24.

2) David Kirk, "Strip factors influencing Almen arc height", *The Shot Peener*, Fall 2009, p. 26.

3) SAE International Standard J442, "Test Strip, Holder, and Gage for Shot Peening," 2022.

4) SAE International Standard J443, "Procedures for Using Standard Shot Peening Almen Test Strip," 2017.

5) Keisuke Tanaka, "The cosα method for X-ray residual stress measurement using two-dimensional detector," *Mechanical Engineering Reviews*, 6 (2019) p. 18-00378.

6) H.Y. Miao, S. Larose, C. Perron, M. Lévesque, "An analytical approach to relate shot peening parameters to Almen intensity," *Surface & Coatings Technology*, 205 (2010) p. 2055.

7) The MathWorks Inc. (2022). MATLAB version: 9.13.0 (R2022b), Natick, Massachusetts.

8) David Kirk, "Relationships between Almen strip thickness and arc heights", *The Shot Peener*, Winter 2003, p. 22.

Peening conditions and Variables						Arc-height Intensity (1/1000")		
Condition	Incidence Angle (°)	Air Pressure (psig)	Media Feed Rate (lbs/min)	Transverse speed T1 (in/min)	Nozzle Type	N-type	A-type	C-type
A	35	9	28	22.73	(3/8)" venturi	8.5	3.2	0.2
B	45	9	28	22.73	(3/8)" venturi	10.6	3.9	0.7
C	90	9	28	20.83	(3/8)" venturi	14.6	5.4	1
D	90	10	5	21.28	(3/8)" venturi	29.4	11.6	2.6
E	90	20	5	31.25	(3/8)" venturi	38.4	17.4	4
F	90	30	5	37.04	(3/8)" venturi	N/A	21.22	4.5
G	90	40	5	33.33	(3/8)" venturi	N/A	24.5	5.5
H	90	55	5	33.33	(3/8)" venturi	N/A	28.3	6.3

Table 1: Arc-height intensity results for N, A, and C strips. Highlighted cells are strips within the recommended range of SAE J443.

	N-Strips			A-Strips			C-Strips		
Peening Condition	N-Intensity [in/1000]	N-Depth [μm]	N-Work [kJ/m²]	A-Intensity [in/1000]	A-Depth [μm]	A-Work [kJ/m²]	C-Intensity [in/1000]	C-Depth [μm]	C-Work [kJ/m²]
A	8.5	55.1	33.6	3.2	45.8	45.5	0.2	55.7	40.8
B	10.6	71.0	39.0	3.9	63.4	51.4	0.7	63.2	45.4
C	14.6	89.0	57.7	5.4	91.1	88.4	1.0	84.1	69.2
D	29.4	164.2	76.8	11.6	112.3	110.0	2.6	189.0	139.0
E	38.4	259.3	130.0	17.4	182.4	152.0	4.0	172.1	107.0
F	--	--	--	22.2	222.2	185.0	4.5	218.5	151.0
G	--	--	--	24.5	223.2	195.0	5.5	157.7	100.0
H	--	--	--	28.3	267.2	192.0	6.3	277.0	191.0

Table 2: Listing of the $W_{residual}$ values found from the measured residual stress vs. depth curves (from Fig. 1) and the associated characteristic depth values (x).*

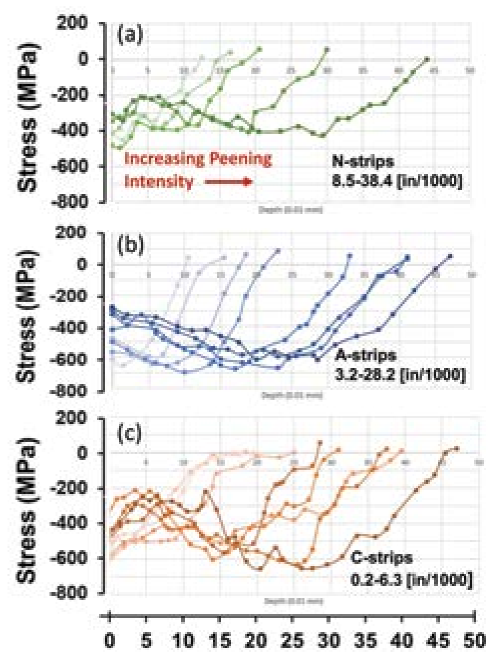

Figure 1: Compressive residual stress versus depth curves for the set of strips listed in Table 1.

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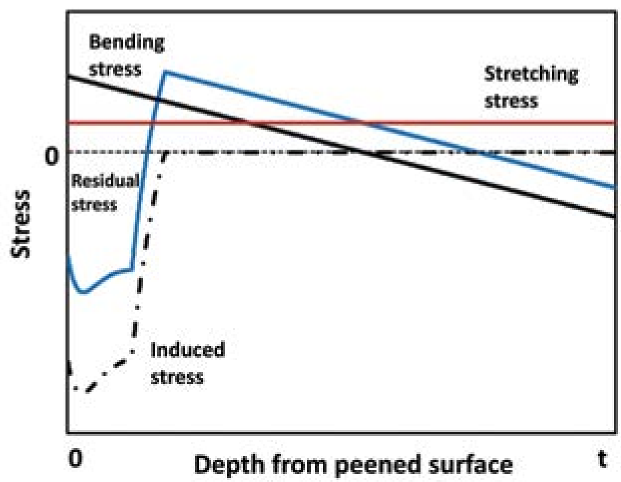

Figure 2: Schematic compressive stress versus depth curves for a fully constrained strip (induced strip) and the resulting residual stress curve for the unconstrained strip, after [6].

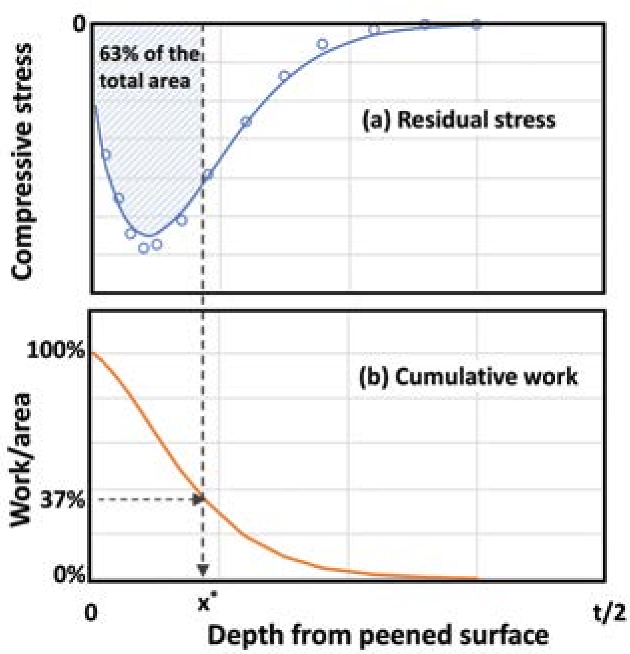

Figure 3: Schematic representation of using a Weibull distribution function to represent the stress vs depth curve and the location of x.*

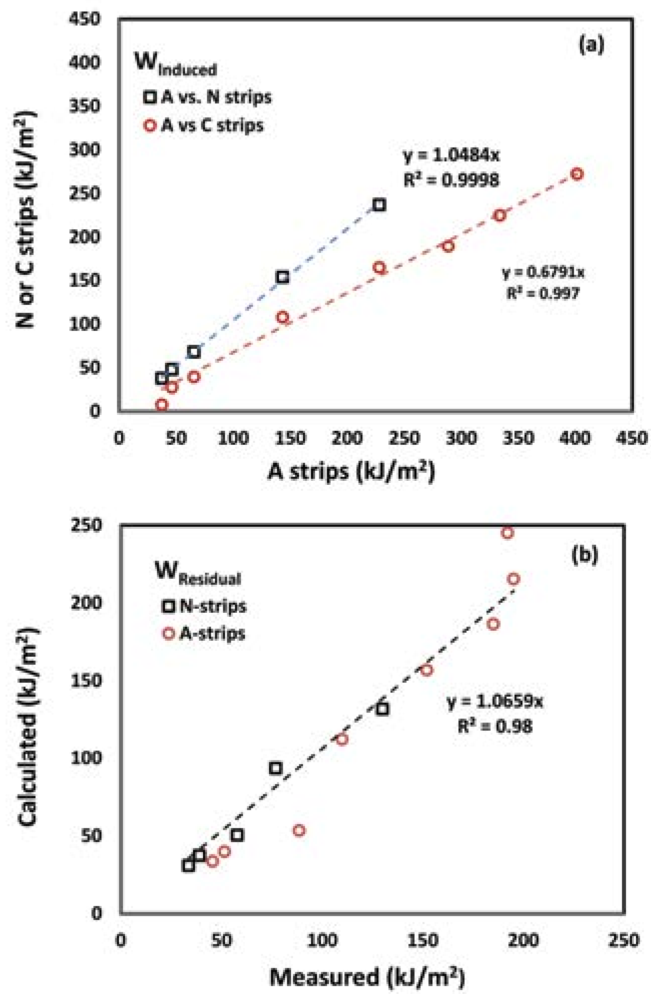

Figure 4: (a) Comparison of the work ($W_{induced}$) values calculated for a given peening condition for A, N, & C strips, and (b) a comparison of the associated work from the residual strip vs. depth curves with the measured values from Table 2.