An Investigation of the Peening Intensity Limits of Shot Peened Almen Strips by Imparted Energy and Depth of Residual Stress

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Industrial Sponsors: Electronics Inc and Progressive Surface

Shot Peening is a critical metal surface enhancement process which improves the fatigue life of a part by imparting a compressive residual stress in the surface of a material. Almen strips are standardized test strips of 1070 tempered martensite steel. Our team conducted experiments seeking to **validate or modify the current specifications** of which peening intensity ranges are acceptable for use with N, A and C type of Almen strip.

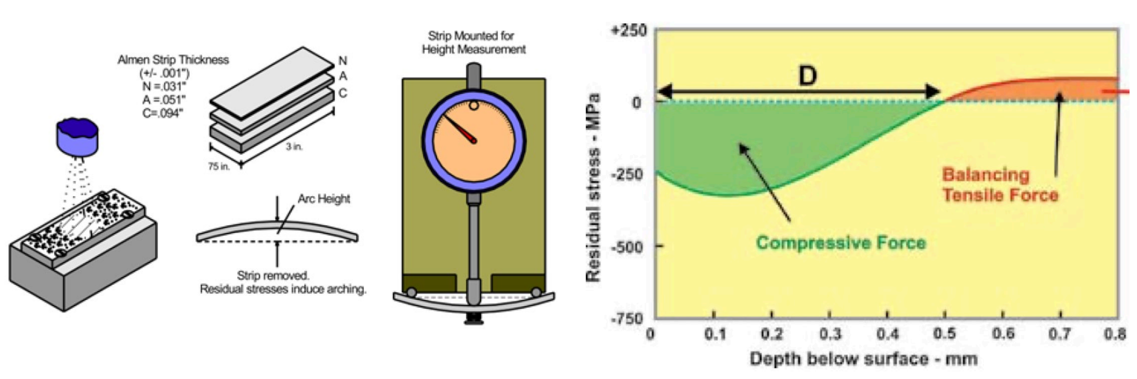
This work is sponsored by Electronics Inc. in South Bend, IN and Progressive Surface in Grand Rapids, MI

Introduction

Shot peening improves the fatigue life of a cyclically loaded part by imparting a **residual compressive stress** in the surface layer of the part, which reduces the propagation of fatigue cracks.

Almen strips are **standardized, process control test samples** used to ensure that specific peening intensities are maintained across different production setups [1]

An intensity measurement is taken as the **arc height** of the strip in thousandths of an inch (0.001") after peening. This is measured with an **Almen gauge**.



Problem Statement

There are three **thicknesses** (0.032", 0.052", and 0.095") of Almen strips that are used, and are labeled as N, A, and C, respectively.

The current 'limits' to the arc heights of Almen strips after peening, which is provided by the industry, were obtained by **qualitative observation** of the strips.

Table 1: Summary table of Almen strip types and their respective thicknesses and industry used intensity ranges.

Strip Type	Thickness (in)	Rule of Thumb limits
N	0.032	< 4A
A	0.052	4A - 24A
C	0.095	> 24 A

Relationship between peening intensity of Almen Strip [2]

C strip reading x 3.5 = A strip reading and
A strip reading x 3.0 = N strip reading.

The team objective is to provide a **quantitative reasoning** for validating or adjusting these limits, based on **measured fundamental phenomena** inside of the compressive stress layers, and using **statistical modeling**.

Shot Peening Experiment

Table 2: Experimental peening conditions that conducted at Progressive Surface.

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

The highlighted section in green denotes the strip that displays intensity values within the accepted industrial standard limits for N, A, and C strips.

Experimental Peening Conditions

The team used a CNC robotic arm shot peening machine built by Progressive Surface and an Almen gauge and Almen strips from EI. The strips were peened using S230 shot.

Experimental Rationale

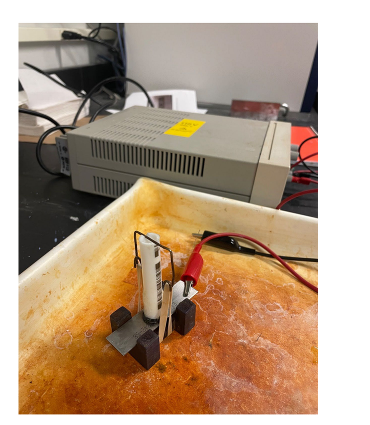
Started on high end of intensity, and worked the pressure down until reached a lower limit to produce saturation curves **above and below** A limits (4A-24A). The same conditions were used on N and C strips.

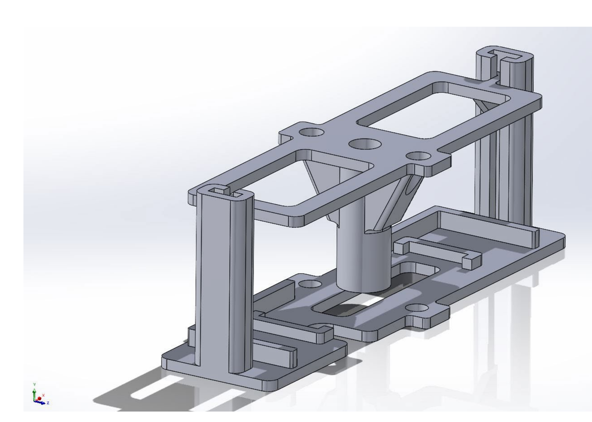
X-Ray Analysis & Stress Profiling

The next step to our experiment was to measure the residual stress profile in the strip as a function of depth below the surface of the strip. There are two main processes that are used to produce this profile – **electro-etching** and **X-Ray Diffraction (XRD).**

Electro-etching

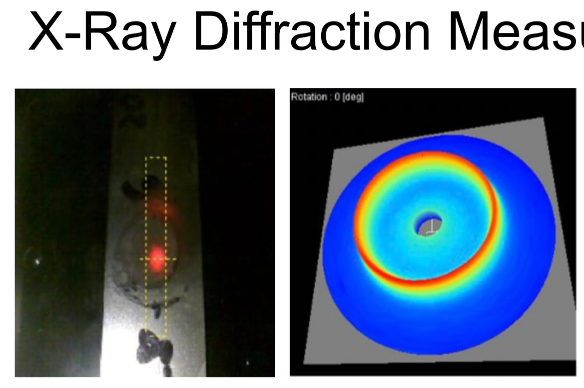
Electro-etching is used to removing material from the strip to access the inside of the Almen strip for layer by layer. The etching medium was 3 wt% NaCl solution and attach to the power supply with **22.4V**. The radius of the etched spot is around 0.5 cm and etches approximately 0.015 mm every 2 minutes of etching.



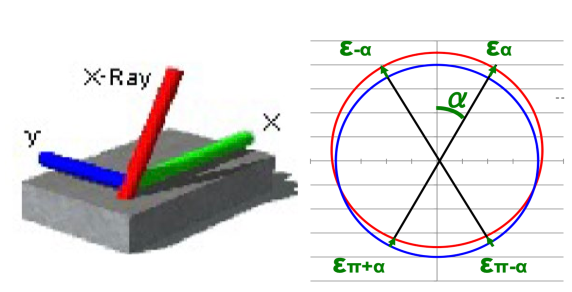


The image above on the left shows the electro-etching setup that was inherited from last year's project by our team. Due to the lack of positional constraining features in that old setup, a new design was created, and **3D printed** by this year's team, which is shown above on the right.

X-Ray Diffraction Measurements



The team used the **Pulsetec μ-x360s** residual stress analyzer, which measures the **reflection of X-rays** at a 35 degrees and compares it with the typical steel XRD reflection data.

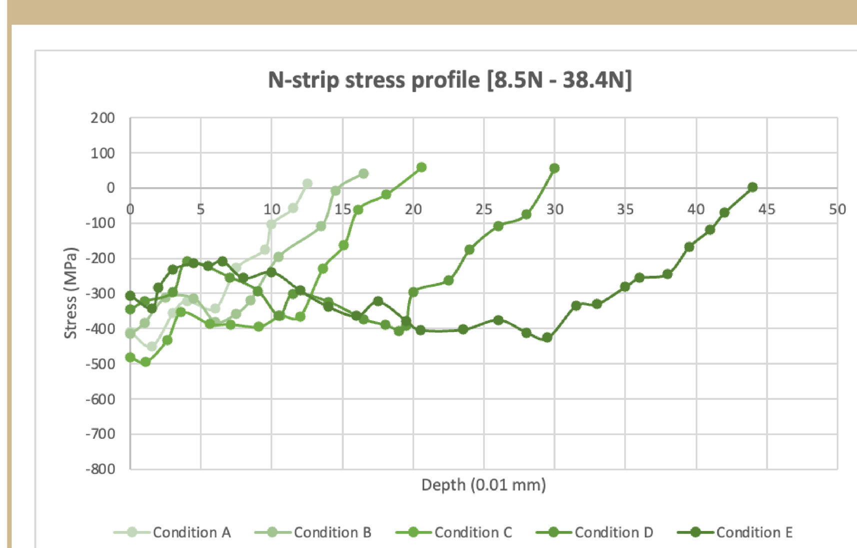


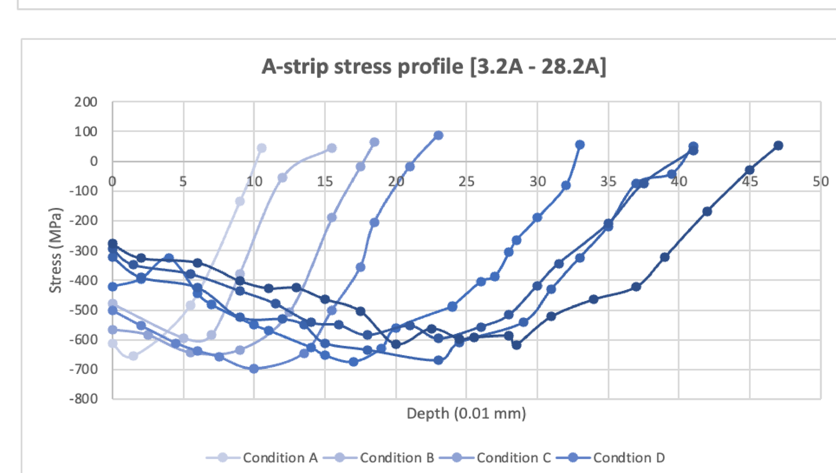
Stress is then calculated by detected position of the **Debye-Scherrer ring.**

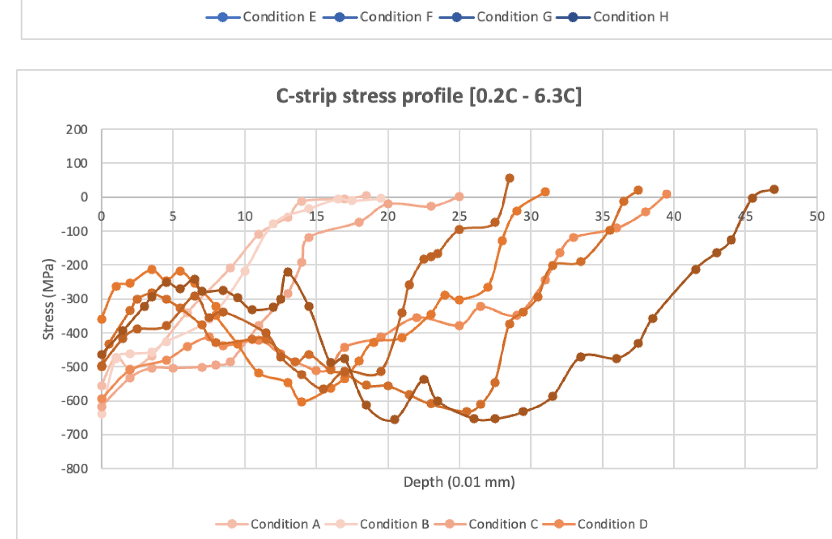
$$\sigma_x = -\frac{E}{1+\nu} \cdot \frac{1}{sin2\eta} \cdot \frac{1}{sin2\psi_0} \cdot \left(\frac{\partial \varepsilon \alpha_1}{\partial cos\alpha}\right)$$

Elastic constant K   Slope M

Residual Stress Profile Result







Measured stress-depth profiles for N, A and C strip types under all experimental conditions.

The stress profile is a graph that shows the **compressive stress (in MPa) versus depth (in 0.01 mm)** inside the surface of the peened strip.

Compressive stress depth is defined as the **distance** that compressive (negative) residual stresses have penetrated the Almen strip.

The primary difference caused qualitatively by increasing peening intensity is the driving deeper of the peak stress and tensile crossover points.

Data Analysis

Now, with all these stress profiles, data processing must be undertaken to determine what the limits should be, if it is possible with the tests that we have.

Calculating Cumulative Work and Depth

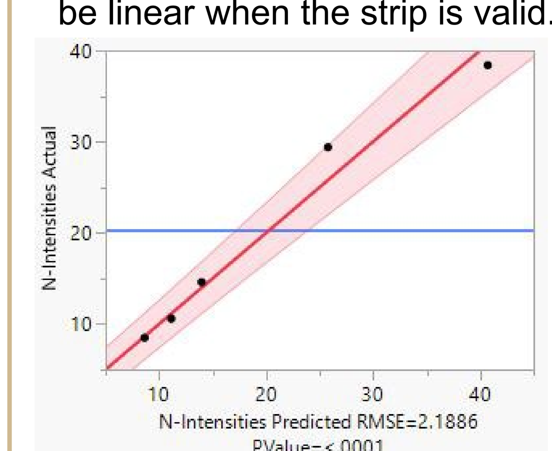
- Cumulative work *(w*)* is calculated by taking the **trapezoid Reimann sum** of a **cubic spline interpolation** of each stress profile
- Modeling as a **Weibull distribution**, calculate the characteristic depth *(x*)* as the depth where 63% of the cumulative work has been completed

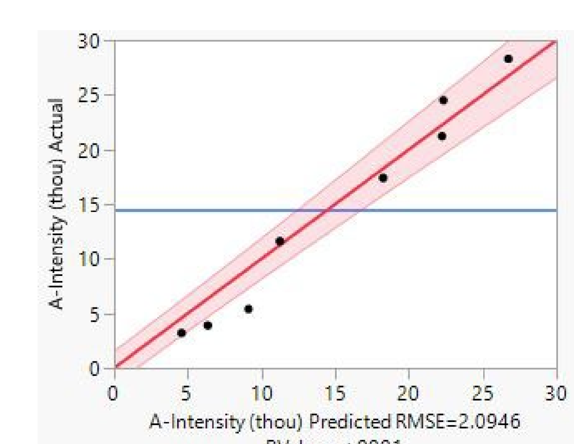
$$w(x^*) = 0.367 \cdot w^*$$

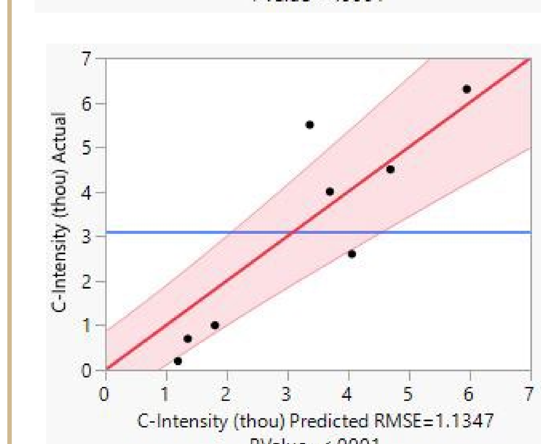
Table 3: Summary of all tests and the calculated depths and cumulative work values

Consolidation of All Calculated Characteristic Depths and Cumulative Work Values								
N-Intensities (0.001")	N-Depth (micron)	N-Work (kJ/m^2)	A-Intensities	A-Depth	A-Work	C-Intensities	C-Depth	C-Work
8.5	55.1	33.6	3.2	45.8	45.5	0.2	55.7	40.8
10.6	71.0	39.0	3.9	63.4	51.4	0.7	63.2	45.4
14.6	89.0	57.7	5.4	91.1	88.4	1	84.1	69.2
29.4	164.2	76.8	11.6	112.3	110.0	2.6	189	139.0
38.4	259.3	130.0	17.4	182.4	152.0	4	172.1	107.0
			21.22	222.2	185.0	4.5	218.5	151.0
			24.5	223.2	195.0	5.5	156.7	100.0
			28.3	267.2	192.0	6.3	277	191.0

Next, linear regressions were calculated predicted the resultant intensity from the calculated characteristic depths. Modeling Almen strips as 3-point bending suggests that these relationships should be linear when the strip is valid.

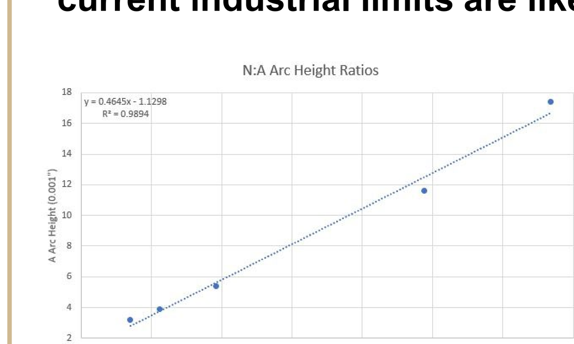






These parity plots suggest that the Almen strips are far more capable than the industrial limits suggest they are. The only data points that can be fairly determined to be **out of spec** are the **lowest 3 intensity C tests**.

Below are two graphs which show the ratios of arc heights between different strips at the same peening conditions. The two ratios of interest are the N:A and A:C ratios, as rules of thumb for those were suggested alongside the peening limits in the problem statement. Since these plots have strongly linear fits, the above assertion that the **current industrial limits are likely too strict** is further supported.



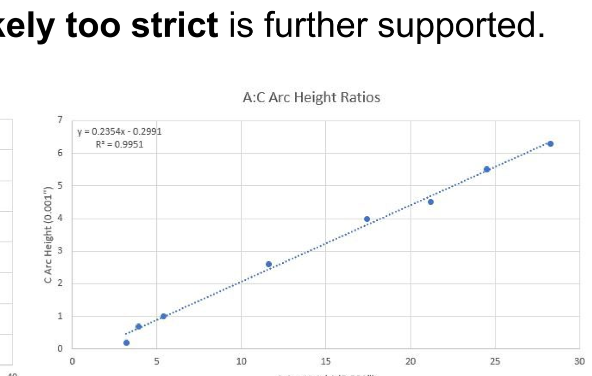


Table 4: Suggestions for New Peening Limits, Along with Old Limits

Peening Limits: Old & New						
	N-Lower	N-Upper	A-Lower	A-Upper	C-Lower	C-Upper
Current Limits	0	12	4	24	6.8	--
New Limits	--	38.4	3.2	28.3	2.6	--

References

[1] Kirk, D. (2018). *Back to Basics: Shot Velocity.* shotpeener.com. from https://www.shotpeener.com/library/pdf/2020028.pdf

[2] Satti, M. (2022). *Shot Peening - process, machines, applications, and advantages.* Punchlist Zero. from https://www.punchlistzero.com/shot-peening-process-machines-applications-and-advantages/

[3] E. I. (2021). *A, N and C certified Almen strips.* Electronics Inc. from https://www.electronics-inc.com/products/almen- strips

[4] Kirk, David. (2014). Estimate Compressed Layer Depth by using Almen Peening Intensity. shotpeener.com.