Shot Media Characterization and Finite Element Modeling of Peening Operations for Automotive Driveline System Components

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The goal of this project is to analyze and model the effects of shot peening process conditions on the residual stress profile of shot-peened parts to explain inconsistencies in peening times across American Axle & Manufacturing facilities. Shot samples were characterized from three plants using a Canty SolidSizer, and statistical tests were performed on the resulting volume distributions. FEA models of shot particles with size distributions from the SolidSizer data impacting an Almen strip were constructed to determine how shot size distribution affects the stress profile of a workpiece. Results indicate that machine mix and new shot have significantly different diameters and that significant differences in shot parameters exist between plants. The models showed no correlation between shot size distribution and stress profile.

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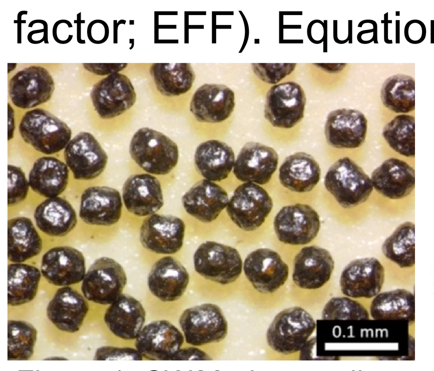
Project Background

AAM uses shot peening to refine the surface of automotive gears across its 80 facilities worldwide. Shot peening is a process used in many industries, yet few comprehensive standards for shot media size or shape degradation exist. A sample of new shot media is shown in Figure 1. During peening, shot media particles may deform or fracture upon contact with the substrate. A separator uses sieves to remove broken or undersized shot before it is used again.

A Canty SolidSizer was used to measure particle characteristics. This machine vibrates shot particles off a ledge and captures a photograph of each shot particle as it falls. These photographs can be used to determine the min. particle diameter (min. feret dia.), max. particle diameter (max. feret dia.), aspect ratio (AR), and conformance of the particle to an ellipse (elliptical form factor; EFF). Equations are shown below.



$$AR = \frac{xF_{min}}{x_{LF}} \qquad xF_{min} = min.\,feret\ dia. \qquad x_{LF} = dia. \perp xF_{min}$$

$$EFF = \frac{\beta * \pi * A}{P^2}$$

$$\beta = \left(\frac{1.5 * (AR + 1)}{\sqrt{AR}} - 1\right)^2 \qquad A = particle\ area \qquad P = particle\ perimeter$$

Figure 1: CW20 shot media.

Experimental Procedure

Samples Received

Shot samples were received from AAM plants in China, Poland, and Mexico, in sizes CW20, CW28, and CW20/28/32, respectively. Conditions of the shot provided are shown in Table 1.

Table 1: Shot condition labelling system.

Condition	Description
1	New, unused shot from the supplier
2	Shot from the hopper one day after new media added (Poland sent two days after new media added, called Condition 2*)
3	Shot from the hopper halfway between media additions
4	Shot from the hopper just before new media added

Canty SolidSizer

Particle images were taken on the SolidSizer from a distance of 530 mm, with a resolution of 10 mpp. A minimum of 5000 particles were used in each sample.

Statistics

Volume distributions of shot samples were constructed using PD Analysis software, and 95% Tukey honest significant difference tests were performed in JMP to compare the mean minimum and maximum feret diameters, ARs, and EFFs (1) across facilities and (2) for each facility across all conditions.

Model Construction

Abaqus finite element analysis software was used to construct 2-D models of spherical rigid CW28 shot particles impacting a Type A Almen substrate. The models used the material property inputs shown in Table 2.

Table 2: Material property model inputs.

	Density	Elastic Properties		Almen Strip Johnson-Cook Parameters [1] (SAE 1070 Steel)					
	(MT/mm^3)	E (MPa)	Poisson's Ratio	A (MPa)	B (MPa)	n	m	T_{melt} (K)	$T_{transition}$ (K)
Almen Strip	7.98E-09	210,000	0.31	1408	600	0.234	1	1793	0
Shot	7.98E-09	220,000	0.31	---	---	---	---	---	---

An ideal model of 20 0.7mm diameter particles[2] was first constructed, with an arrangement shown in Figure 2. Seven models were made with particle size distributions based on area equivalent diameter number frequency distributions from SolidSizer analysis. The number of particles in these models was adjusted to have equal mass flux to the ideal model (Table 3). Particles were arranged in the same spacing as the ideal model.

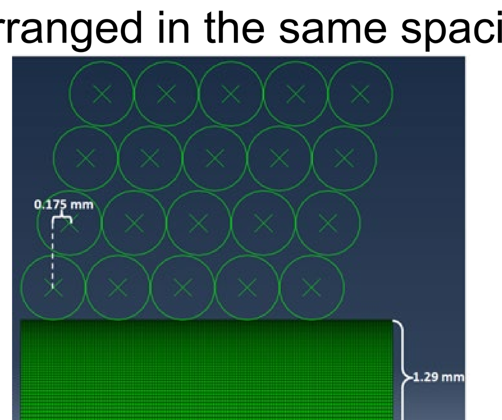


Figure 2: Ideal model arrangement.

Table 3: Model particle sizes and frequencies.

	Particle Type	Area Equivalent Diameter (mm)	Adjusted Mass Flux: # Model Particles
Mexico C1	1	0.6411	26
	2	0.0467	1
Mexico C2	1	0.7765	12
	2	0.7332	3
	3	0.1123	1
Mexico C3	1	0.7845	12
	2	0.7458	3
	3	0.0973	3
Mexico C4	1	0.7592	16
	2	0.3727	1
	3	0.0849	3
Poland C1	1	0.8292	12
Poland C2*	1	0.7959	10
	2	0.6001	8
EA C1	1	0.7848	14

Results & Discussion

SolidSizer Analysis

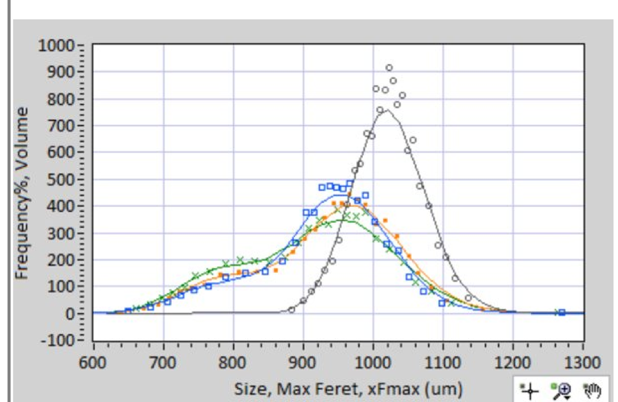


Figure 3: Volume frequency plot of maximum feret data for representative data set of each of the four conditions. Conditions 1, 2, 3, and 4 are represented by the black, blue, green, and orange curves, respectively.

The data from the frequency plots show trends related to the shot deformation between the four conditions. For example, the maximum feret plot in Figure 3 shows that there is a large amount of deformation occurring between Conditions 1 and 2, but this trend does not continue into Conditions 3 and 4. AR versus EFF plots were also made for each sample received to allow for visualization of geometric variation between each condition.

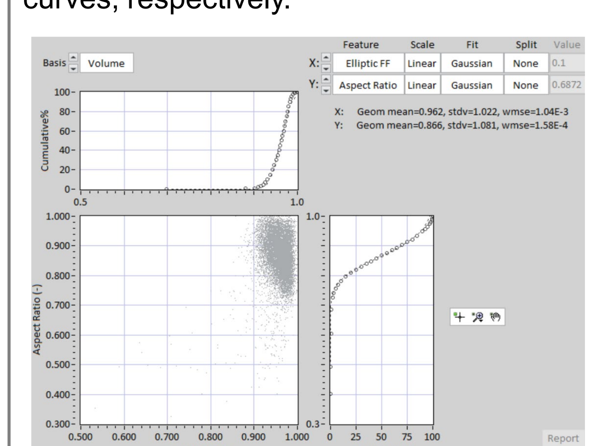


Figure 4: Representative AR vs. EFF plot.

Neither geometric variable depends on the other, but comparisons regarding trends can be made. It was determined from these plots that the AR experienced more variation than the EFF in all the samples. The AR was also more dependent on peening time than the EFF, as the variation of AR between each condition was higher than what was seen in the EFF.

Statistical Analysis

The results of comparison (1) are shown in Table 4. CW20 shot from China has a significantly different minimum feret diameter and EFF when compared to the other two facilities. For CW28, Poland and Mexico have significantly different means for all parameters except for EFF. For CW32, Mexico and China have significantly different means for AR and EFF.

Table 4: Results of the 95% Tukey tests comparing shot characteristics across plant locations, blocked by cut wire size. The difference in means, upper and lower tails of the 95% confidence interval, and P-value are shown.

CW 20	Locations	Difference	LWR	UPR	P
Min Feret (um)	EA-China	33.10	15.76	50.45	<0.0001
	Mexico-China	35.76	18.41	53.10	<0.0001
	Mexico-EA	2.67	-14.69	20.00	0.930
Max Feret (um)	EA-China	21.00	-13.94	55.94	0.3321
	Mexico-China	14.35	-20.59	49.29	0.5957
	Mexico-EA	6.65	-28.30	41.59	0.8945
Aspect Ratio	EA-China	0.0164	-0.0065	0.0393	0.2102
	Mexico-China	0.0101	-0.0128	0.0330	0.5505
	Mexico-EA	0.0006	-0.0166	0.0292	0.7931
Elliptical Form Factor	EA-China	0.0574	0.0436	0.0713	<0.0001
	Mexico-China	0.0517	0.0388	0.0645	<0.0001
	Mexico-EA	0.0058	-0.0081	0.0196	0.5918

CW 28	Locations	Difference	LWR	UPR	P
Min Feret (um)	Poland-Mexico	20.00	3.43	36.56	0.0186
Max Feret (um)	Poland-Mexico	105.74	72.38	139.10	<0.0001
Aspect Ratio	Poland-Mexico	0.0706	0.0542	0.0871	<0.0001
Elliptical Form Factor	Poland-Mexico	0.00062	-0.00652	0.00777	0.8637

CW 32	Locations	Difference	LWR	UPR	P
Min Feret (um)	Mexico-EA	14.48	-5.819	34.78	0.160
Max Feret (um)	Mexico-EA	13.58	-27.79	54.95	0.5162
Aspect Ratio	Mexico-EA	0.0684	0.0518	0.0850	<0.0001
Elliptical Form Factor	Mexico-EA	0.0249	0.0111	0.0386	0.0005

Table 5: Results of 95% Tukey test comparing shot characteristics across conditions. Similar groups are connected by the same letter, and the mean is shown.

Mexico

Times	CW 20		Mean	CW 28		Mean	CW 32		Mean
Minimum Feret Diameter (μm)									
1	A		608.53	A		813.67	A		887.32
2	A		616.43		B	770.62		B	811.15
3		B	561.44		B	777.82		B	809.20
4	A		637.29		B	754.86		B	787.77
Maximum Feret Diameter (μm)									
1	A		718.42	A		1003.33	A		1029.53
2	A		685.42		B	824.95		B	924.5
3		B	627.73		B	839.67		B	925.95
4	A		709.42		B	811.57		B	913.27
Aspect Ratio									
1		B	0.8800		B	0.8463	A		0.9744
2	A		0.9155	A		0.9484	A		0.9819
3	A	B	0.9079	A		0.9434	A		0.9818
4	A		0.9166	A		0.9454	A		0.9807
Elliptical Form Factor									
1	A		0.9772		B	0.9710	A		0.9744
2	A		0.9785	A		0.9857	A		0.9821
3		B	0.9444	A	B	0.9840	A		0.9817
4		B	0.9494	A		0.9852	A		0.9806

China (CW 20)

Times			Mean
Minimum Feret Diameter (μm)			
1	A		527.77
2		B	501.63
3		B	501.09
4		B	488.40
Maximum Feret Diameter (μm)			
1	A		704.06
2		B	613.14
3		B	612.85
4		B	596.34
Aspect Ratio			
1	A		0.8636
2	A		0.8516
3	A		0.8505
4	A		0.8488
Elliptical Form Factor			
1	A		0.9587
2	A		0.9565
3	A		0.9547
4	A		0.9568

Poland (CW 28)

Times			Mean
Minimum Feret Diameter (μm)			
1	A		793.68
2*		B	731.16
Maximum Feret Diameter (μm)			
1	A		897.59
2*		B	816.06
Aspect Ratio			
1	A		0.9170
2*	A		0.9184
Elliptical Form Factor			
1	A		0.9816
2*	A		0.9801

The results of comparison (2) are shown in Table 5. Feret diameters tend to decrease with use, with the exception of Mexico CW20. The AR and EFF are mostly similar for all conditions, but Conditions 1 and 3 are sometimes significantly smaller.

Results & Discussion

FEA Models

Stress profiles of each model were constructed by measuring the average residual stress across paths at different depths from the deformed Almen surface, like the one shown in Figure 5. Figure 6 shows the resultant stress profiles for each model.

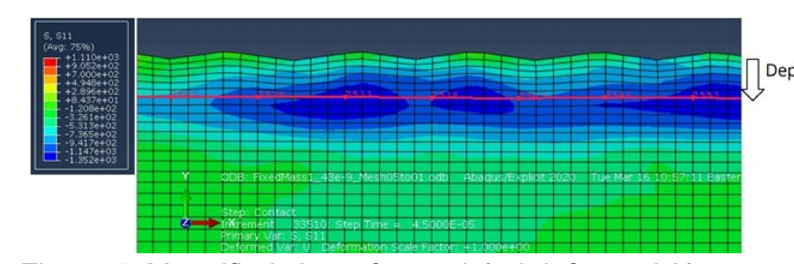


Figure 5: Magnified view of a modeled deformed Almen surface.

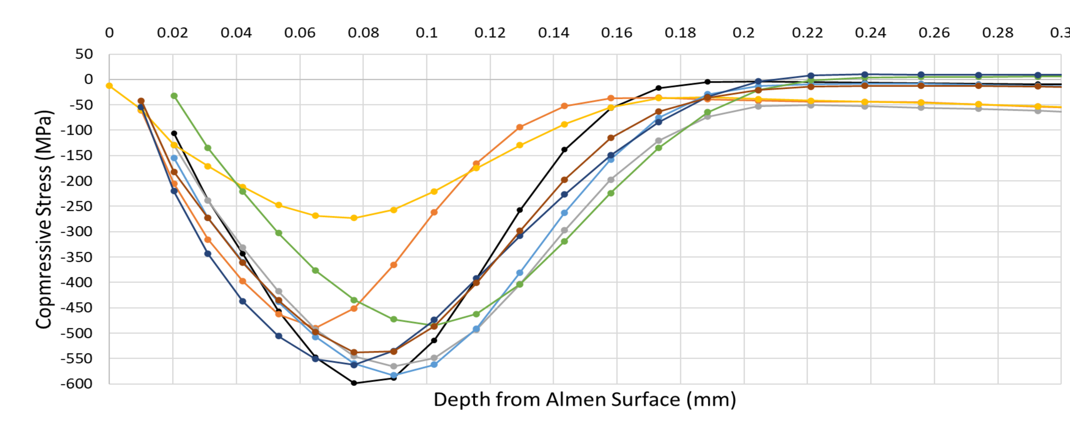


Figure 6: Stress profiles of all CW28 models with varying particle size distributions.

The stress profiles were integrated and fitted to Equation 1, a stretched exponential function of the energy stored in the impacted substrate. Figure 7 shows that models for Mexico Conditions 1 and 3 have outlying fitting parameters compared to the rest of the models.

Equation 1: Work/area as a function of depth from the Almen surface.

$$W(d) = W_{max} \times e^{-(\frac{d}{d^*})^n}$$

$W(d)$	Work/Area (Mpa-mm)
W_{max}	Total Work Flux (Mpa-mm)
d	Depth from Surface
d^*	Characteristic Depth (mm)
n	Fitting Exponent

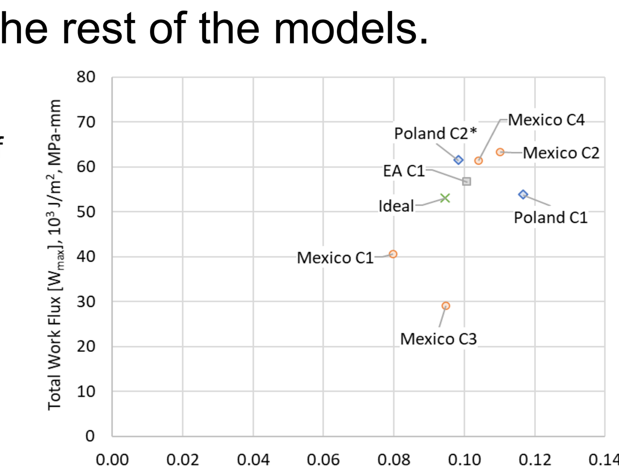


Figure 7: W_{max} vs d* from the fitted stress profiles.

It is expected that models with smaller particles have shallower stress profiles. This is consistent with Mexico Condition 1 results, but no other models followed this trend. No correlation between particle size distribution and stress profile could be identified in the models. Models with many more particles, similar to physical peening, may have shown more significant results.

Recommendations

- The shot diameters are significantly impacted by peening time. However, for future studies, shot condition should be analyzed based on amount of time shot has been used rather than time between new shot additions, and more time divisions between Conditions 1 and 2 could be studied.
- Significant differences in shot characteristics between plants were observed, so more samples should be collected to see if the trends persist. Blocking confounding factors, such as shot supplier, could also be beneficial.
- No conclusions regarding the source of peening time differences between plants could be made. Further analysis is needed.
- Future models should contain many more shot particles and a bulk gear substrate to be more realistic. Other parameters such as shot shape and substrate geometry should be considered.

Acknowledgements

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References

[1] S. Ghanbari & D. Bahr (2020). "Predictions of decreased surface roughness after shot peening using controlled media dimensions" *Journal of Materials Science & Technology* 58 pp 120-129. https://doi.org/10.1016/j.jmst.2020.03.075
[2] SAE J441, Cut Wire Shot. (2013). SAE International.