Residual Stress Evaluation and Modelling for Axle Gear Applications

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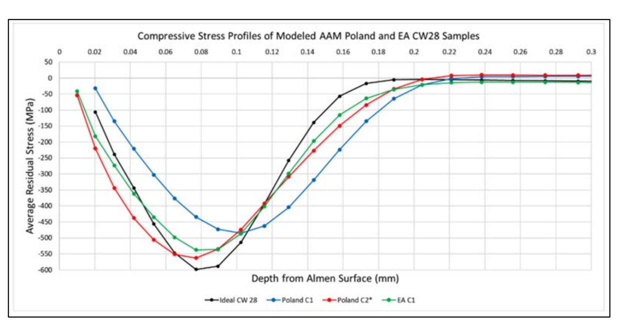
American Axle & Manufacturing (**AAM**) utilizes **Engineered Abrasives** (**EA**) shot peening equipment to induce **compressive residual stress** (**CRS**) in gear parts. The project aims to investigate and model/simulate induced stress states of Almen strips and AAM gear parts over a variety of applicable peening conditions. Good comparisons between the experimentally measured and computer-generated models of the CRS were found.

This work is sponsored by American Axle, Engineered Abrasives, Toyo Seiko, and Electronics Inc.

Project Introduction

- Shot peening introduces CRS on and immediately below the treated surface to increase fatigue life.



EA peening machine

Almen Strip Information		
Material		
1070-Steel		
Thickness (mm)		
N	A	C
0.785	1.295	2.385

- **Almen strips** are used to test shot peening parameters in situ.
- The induced CRS on the strip causes bending, measured as the maximum **arc height**.
- The simple geometry means CRS can be measured with **XRD**.
- Due to the complex geometry, stress in axle gear parts can be significantly more difficult to measure.

Experimental Methods/Results

Processing Parameter Effects

Shot Peening (table) was done with cut-wire (CW) 20, 28, & 30 shot on A, C, and N strips with differing flow rate and pressure. Low, standard and high parameters are set by EA.

Table. Selective summary of collected shot peening data

Characteristics		20 CW		28 CW	32 CW	
Strip Type		N	A	A	A	C
Gear Type	Pinion			✓	✓	✓
	Ring	✓	✓	✓	✓	✓
Flow Rate (N/min)	LOW			✓	✓	
	STANDARD	✓	✓	✓	✓	✓
	HIGH				✓	
Blast Pressure (kPa)	LOW		✓	✓	✓	
	STANDARD	✓	✓	✓	✓	✓
	HIGH		✓	✓	✓	

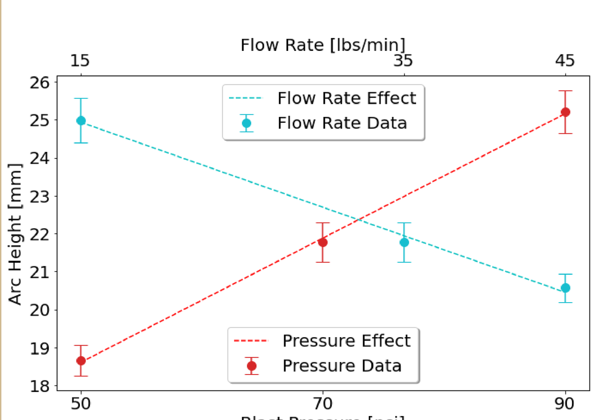
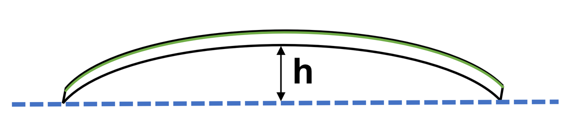


Fig. A strip arc height vs blast pressure and flow rate from experimental shot peening.

In addition to the compressive stress layer in the Almen strip, an **"arc height, h"** is imposed onto the strip due to the bending stress caused by plastic strain.



X-Ray Diffraction Residual Stress Analysis

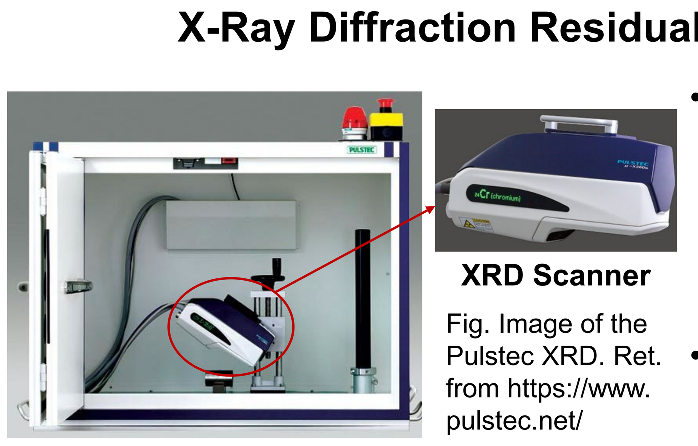


Fig. Image of the Pulstec XRD. Ret. from https://www.pulstec.net/

- Each Almen strip underwent intensive XRD quantitative stress state analysis over the **depth of the compressive layer.**
- Depth intervals are associated with a single residual stress.

Experimental Residual Stress-Depth Profiles

As pressure increases
- The depth of compressive layer increases.
- The stress peak maximum is lower and shifted deeper.

As flow rate increases
- The depth of compressive layer decreases.
- The stress peak maximum is higher and shifted shallower.

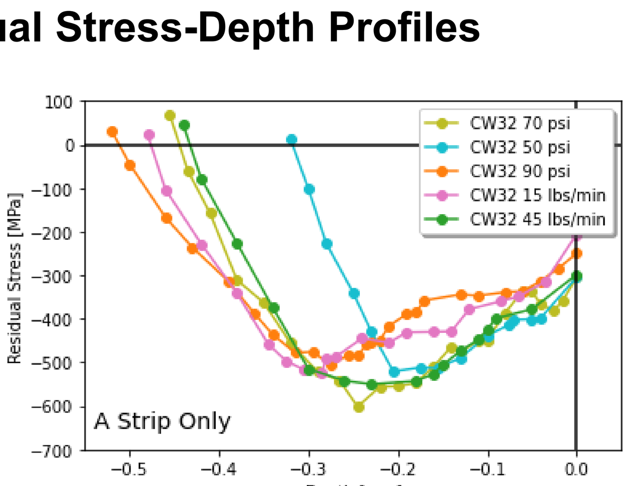
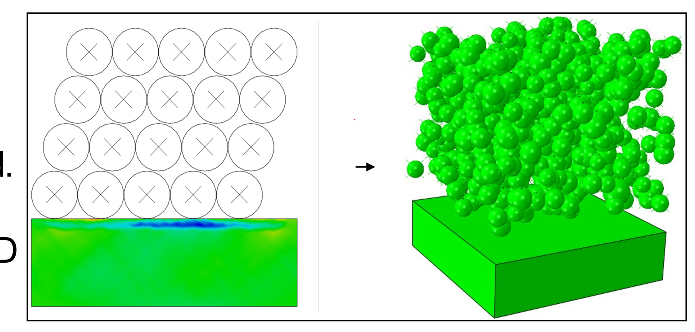


Fig. Experimental stress depth profiles with CW 32 on A strips

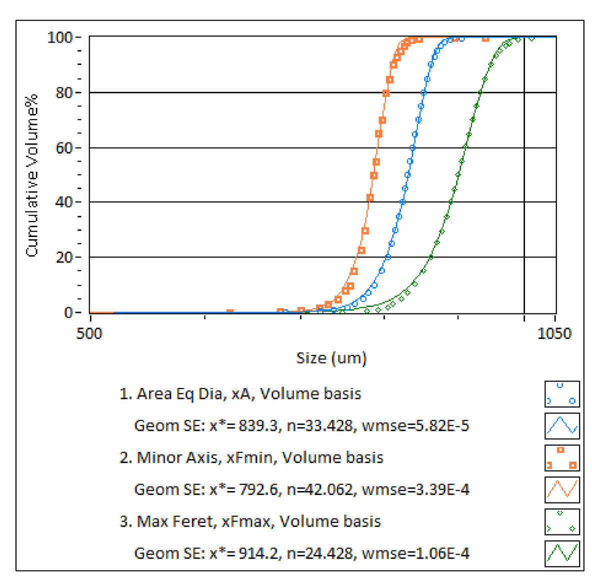
At high peening intensities
- Experimental profile depth and maximum residual stress demonstrate convergence to an average residual stress value.

Simulation Development

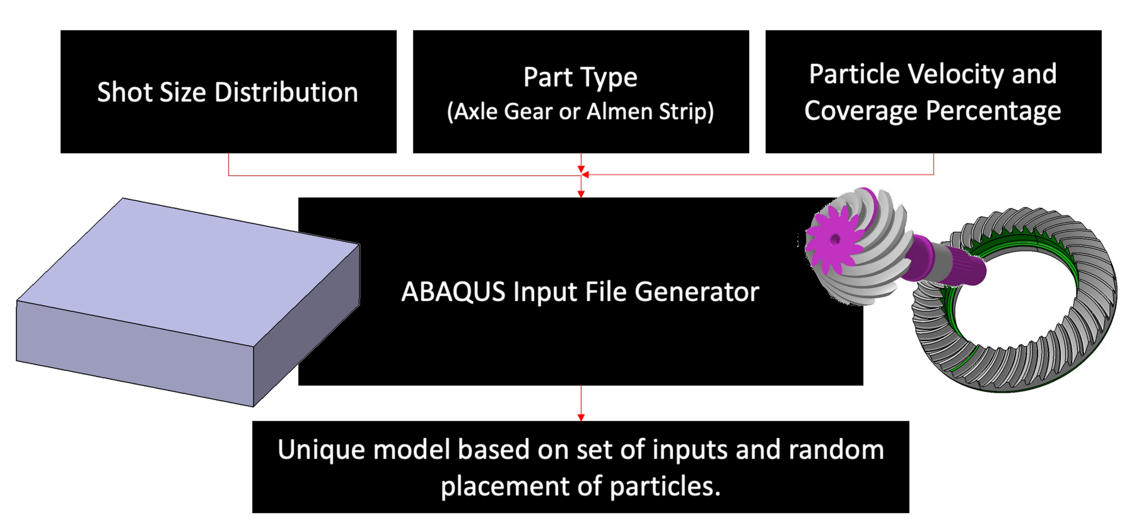
- To create a simulation of the shot peening process, the **ABAQUS** finite element modelling software was used. A simple 2-Dmodel was developed into a complex 3-D model accounting for particle size distributions.

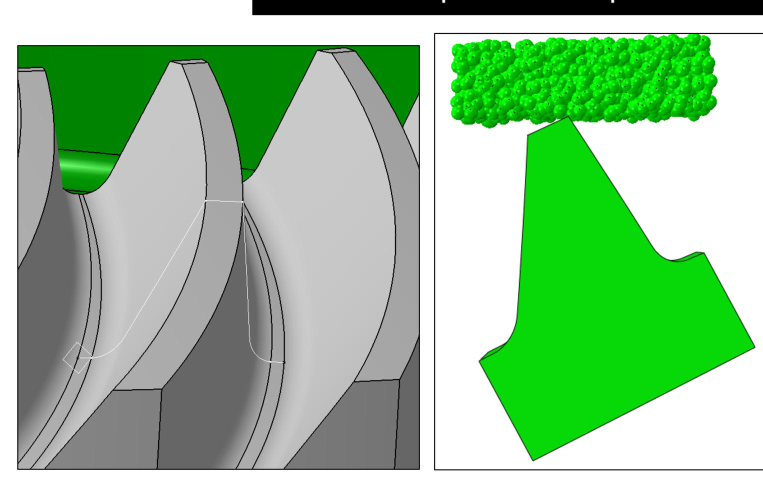


- Simulation input files were created through an **ABAQUS input file generation script** that was written as part of the scope of this work.
- The input file script reads shot particle size data, as collected from a **CANTY SolidSizer** particle measurement system.



Area equivalent diameter is used as the size descriptor for the particles since it is a balance between the minimum and maximum axes of irregularly shaped particles.





This same process flow was used to develop models of the complex axle gear geometries being shot peened with the same process parameters.

Experimental Data Analysis

Stress State and Cumulative Work

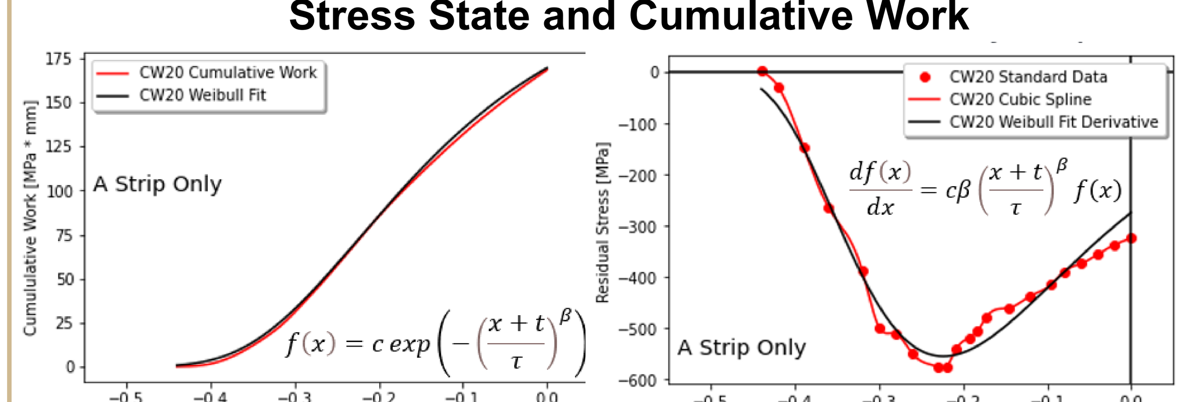


Fig. Graphical representation for Weibull statistical fits for cumulative work (left) and stress-depth (right).

Weibull stress state fitting improves conclusive comparisons. First, Raw data exhibited rigid curvature, impeding comparison. Second, **cumulative work** profiles, via trapezoidal **integration**, depicts the evolution of effective work.

Comparable Results

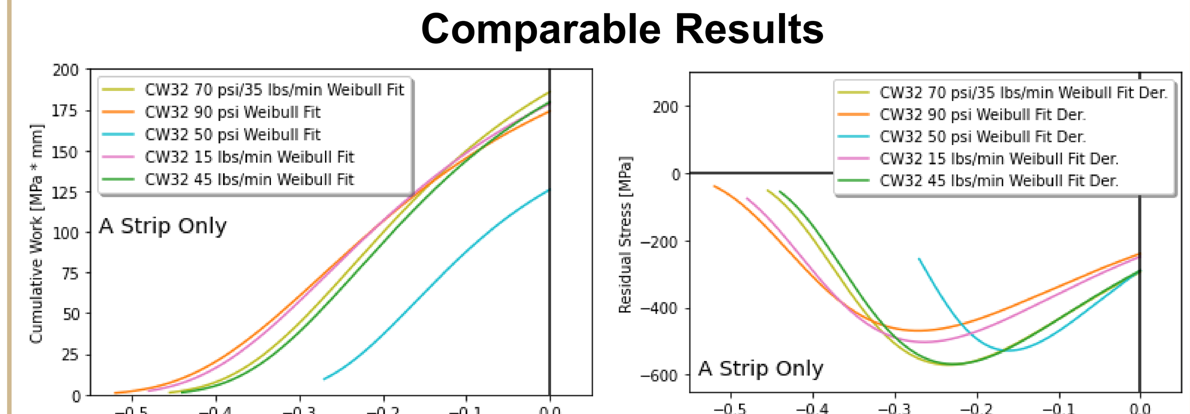
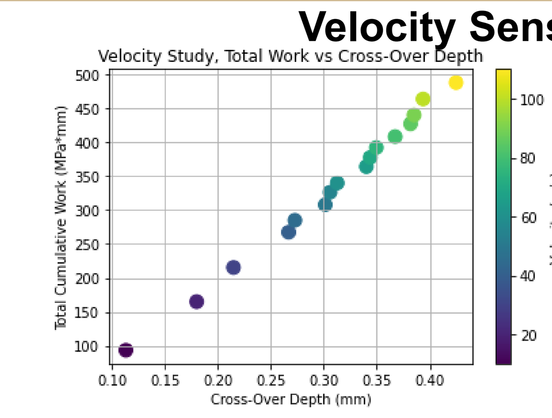


Fig. Weibull Fit experimental data for CW32 comparison of effects.

- As **peening intensity increases**, work converges and evolves at a slower rate maintaining high work values over the compressive depth.
- As **peening intensity decreases from convergence** (50 psi), maximum cumulative work is significantly reduced. The work evolution reduces to a less-intense but similar shape.

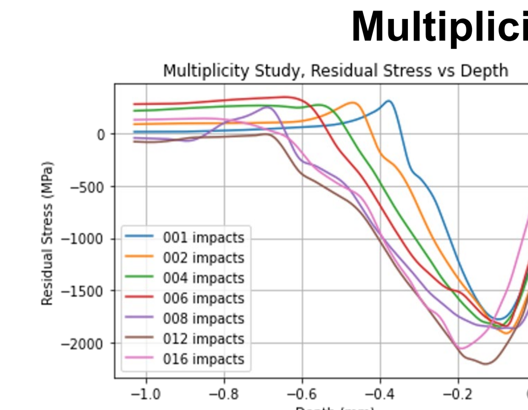
Simulation Results

Velocity Sensitivity Study



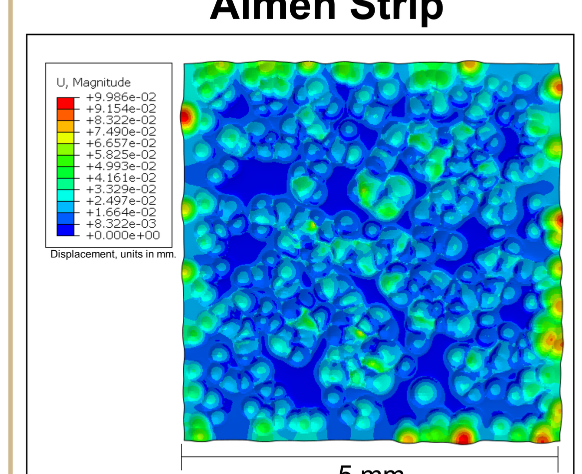
- Both **total work and cross over depth increase as a function of velocity**, for a stress state taken at the center of a single impact.

Multiplicity Sensitivity Study



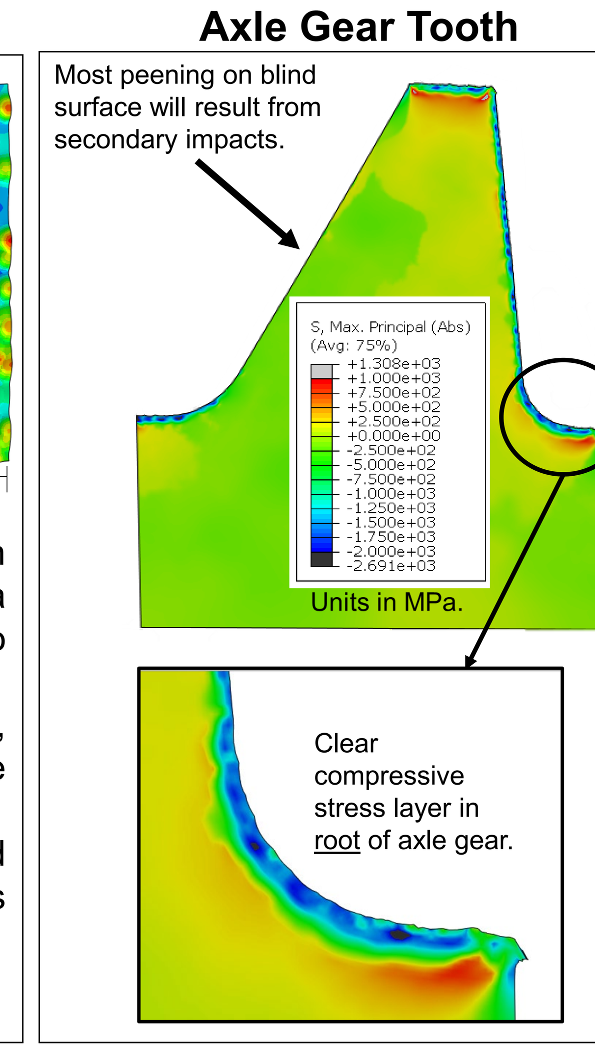
- Suggests that **convergence in stress state is reached after 8 impacts** in the same location.
- Damage to the substrate begins to occur after 16 subsequent impacts.

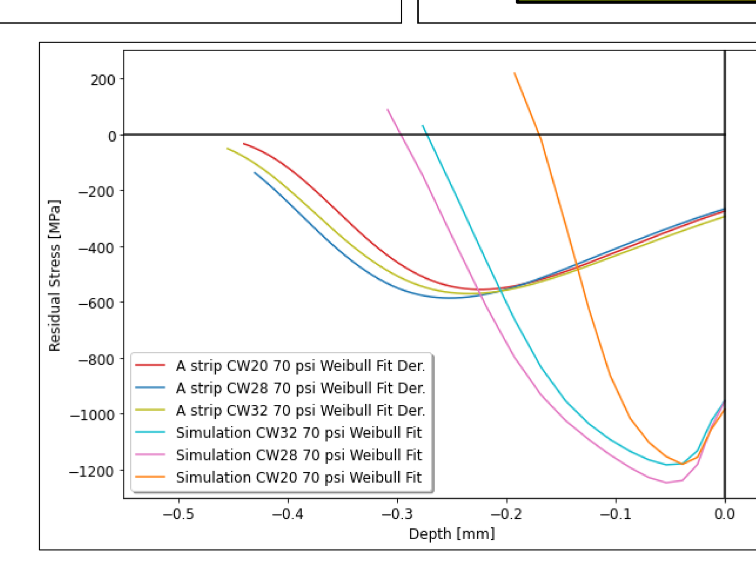
Almen Strip



- Dimples are formed in random locations and have a size distribution according to shot size distribution.
- Coverage can vary locally, but effect diminishes as size of substrate increases.
- Residual stress is measured as the average of all nodes at each discrete depth.

Axle Gear Tooth





The simulation shows **qualitative trends** with the CW28 experimental results. Both demonstrate CW28 has the deepest cross over depth and highest maximum stress.

Conclusions/Recommendations

- According to the experimental results, the stress state quantified by the cumulative work shows **convergence between standard, high blast pressure, and flow rate parameters.**
- Preliminary simulations of axle gear geometries show a **clear compressive stress layer at the root of the gear**. On the substrate's blind face, most peening will occur through secondary impacts.
- There is a **qualitative agreement between simulation and experimental results** for the induced stress state in Almen strips. CW28 shot induces the deepest compressive layer with the highest maximum compressive stress.

Future Work: Correlation between the experimental and simulation results can be improved through characterizing and validating the material properties of both Almen strips and axle gear components. Further development of sensitivity studies on the relationship between coverage percentage and stress state could also inform further simulations.

References

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