Using Simulations and Experiments to Optimize Strength and Ductility in Metals Processed by Surface Mechanical Attrition Treatment

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Abstract

Precision and Energy Controlled Surface Mechanical Attrition Treatment (PECSMAT) is a novel technique for strengthening metal parts by impacting the surface, which causes residual stresses to increase in the material and thereby increases the strength of the part. Ductility, which is the degree to which a material will permanently deform before breaking, will decrease as a part is hardened and the strength increases. This tradeoff is undesirable as retaining both high strength and ductility will allow parts to be in service longer before the part fails. This research aims to optimize the impact energy and location on a metal part to have high strength and retain ductility. Questions to be answered during the research process include: How many impacts are optimal for a given region, and where should those impacts occur? How much energy should be put into each impact? Do the experimental results agree with the simulations? Is the ductility of the impacted part higher than conventional methods while maintaining or exceeding the strength of the material? Testing will first be conducted using commercially available software Abaqus CAE, which is a simulation based finite element analysis (FEA) tool. Subsequent validation of simulation results will be carried out experimentally performing monotonic and cyclic testing. Results and conclusions have yet to be determined to date as this is ongoing research. Implications of this research include the ability to increase the strength and ductility of a metal part so it will last longer and provide a greater factor of safety.

Introduction

Residual stresses are that which remain in a body that is stationary and at equilibrium with its surroundings, can be detrimental or beneficial (depending on use case) to the performance of a material or the life of a component, and are caused by mechanically or thermally inducing the stress in the material [Withers and Bhadeshia, 1]. Fatigue failure only occurs as a result of tensile stresses whereas compressive stresses are beneficial to the fatigue life of a part. Mechanical treatment of surfaces such as impacting a surface with ball bearings (also called "shot-peening" in some cases) can cause beneficial compressive residual stresses within the material itself, in which the peak stresses occur at the surface, that can help to increase the strength and fatigue life performance of the material [Zhuang and Wicks, 2]. The main use for initiating compressive residual stresses is to induce a protective strong layer at the surface of the part where tensile loads are the dominate effect.

Precision and Energy Controlled Surface Mechanical Attrition Treatment (PECSMAT) [Scott, 3] is a novel method for precisely controlling the amount of energy and impact locations on a part material. This recent work attempts to correct some of the disadvantages to conventional shot peening such as the randomness of impacts and the intensity of the shot since there is a single numerically controlled precise impactor deforming the surface of the material. Using PECSMAT, surfaces can be precisely impacted so that the appropriate amount of energy is transferred to the surface and locations that are impacted can be optimized. Fatigue testing has yet to be performed on specimens used for testing, however, tensile testing was conducted, and from the work done, specimens that were impacted at smaller spacing intervals had a higher overall engineering strength, but lower ductility which aligns with previous research as the higher residual stress within the material would cause it to behave in a more brittle manner.

Predicting the optimal regions to impact with the PECSMAT machine on a metal specimen using FEA and experimental methods such that the stress and strain fields do not overlap during a particular impact will be of paramount importance. This minimal overlap should have the effect of maximum strength and ductility.

Johnson-Cook parameters are a set of values used to approximate a material's behavior and response to a particular strain rate and temperature. The values can be implemented into Abaqus Explicit solver to approximate the response of the plate after being impacted by the steel ball.

Since this research is ongoing, several preliminary methods have been employed while others have yet to be started. Initial research was conducted through experimental methods conducted by fellow Ph.D. student Joby Anthony III (Fig. 1). Work that was conducted by Nathan Roberts was to replicate the experimental work done by Joby through simulations (Fig. 2). This preliminary work was performed to get a better understanding of how the stresses on the plate surfaces and velocities of the ball propagate due to cyclic impact and to validate the experimental results.

Methods

- Johnson-Cook plasticity parameters were initially taken from literature values [Johnson and Cook, 5], but after those values seemed to be inconsistent, new values were calibrated based on compressive OFHC copper data (Fig. 3).
- Impact deformation results were compared to experimental deformation results for the corresponding time increments (Fig. 4).
- Each simulation was run and compared to the experimental ball impact data (Fig. 5)
- A new iteration of the simulation would be run and attempt to correct, alter, or change one parameter at a time to achieve a more accurate solution.

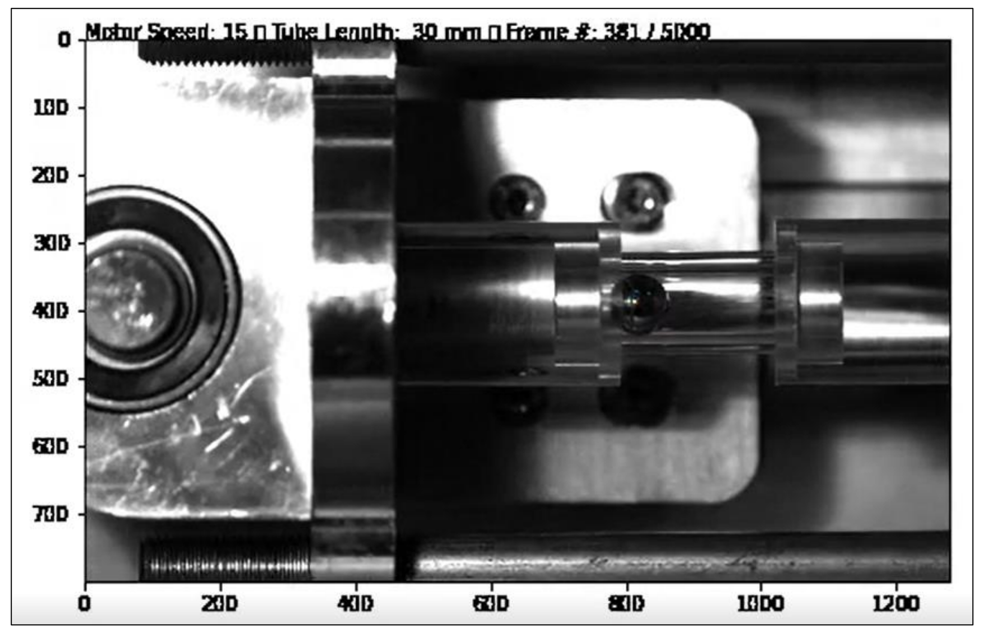

Figure 1: Joby Anthony III initial experimental work of cyclic ball impacting with ball tracking. High speed data of ball impact was captured. Tracking data gave velocity profiles of the ball impacts which simulations verified.

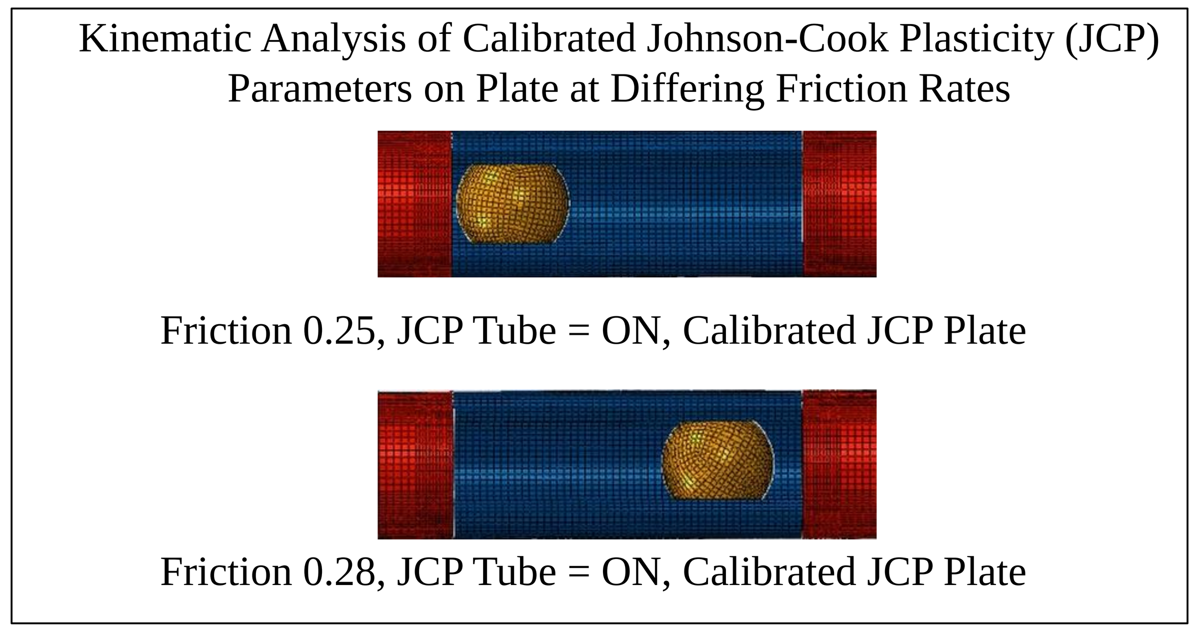

Figure 2: Simulation work using finite element analysis (FEA) software Abaqus CAE performed in an explicit analysis replicating experimental work performed by Joby Anthony III. Over 80 simulations were run comparing various contact conditions, material parameters, symmetry conditions, and mesh sizes to the original experimental data to see which correlates the best. Materials are oxygen free high conductivity (OFHC) copper plates 12.7 mm diameter and 6.35 mm thick (simulation: red); polymethyl methacrylate (PMMA) hollow plastic tube 30 mm in length (simulation: blue), 440c stainless steel ball bearing 9.53 mm diameter (simulation: orange)

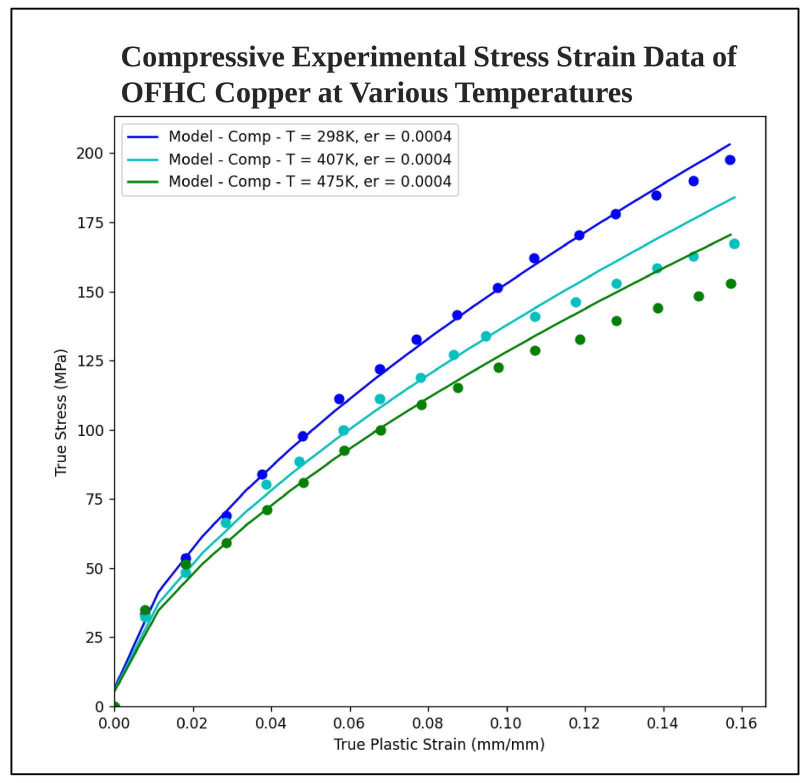

Figure 3: Compressive experimental stress strain data of OFHC copper at various temperatures and a strain rate of 0.0004 /s [Tanner & McDowell, 4]. Data from this source was used to create Johnson-Cook plasticity (JCP) parameters used in the simulations.

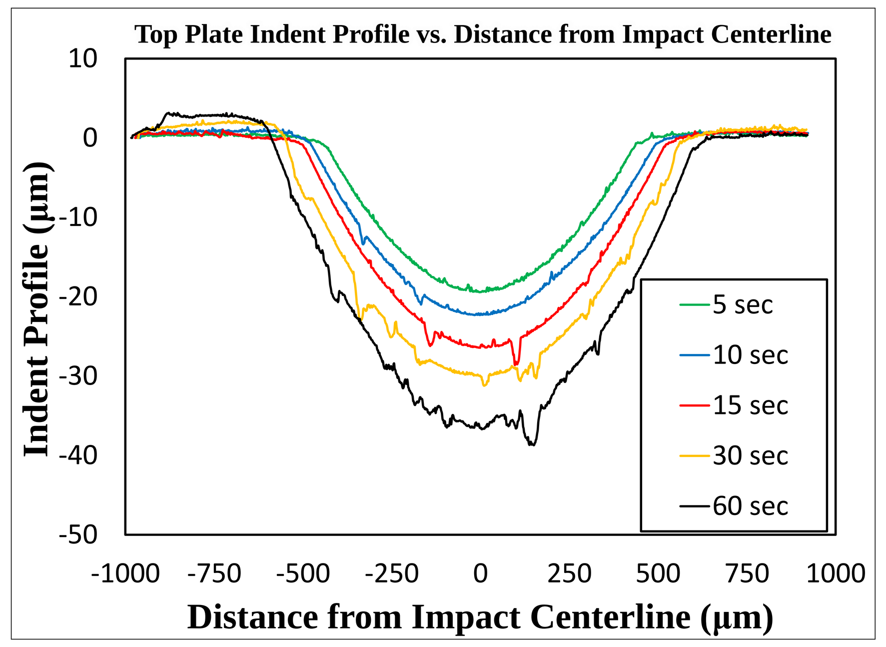

Figure 4: Experimental results of indent profile vs. distance from impact centerline at various times. Time represents how long the cyclic impactor (Fig. 1) was allowed to run for.

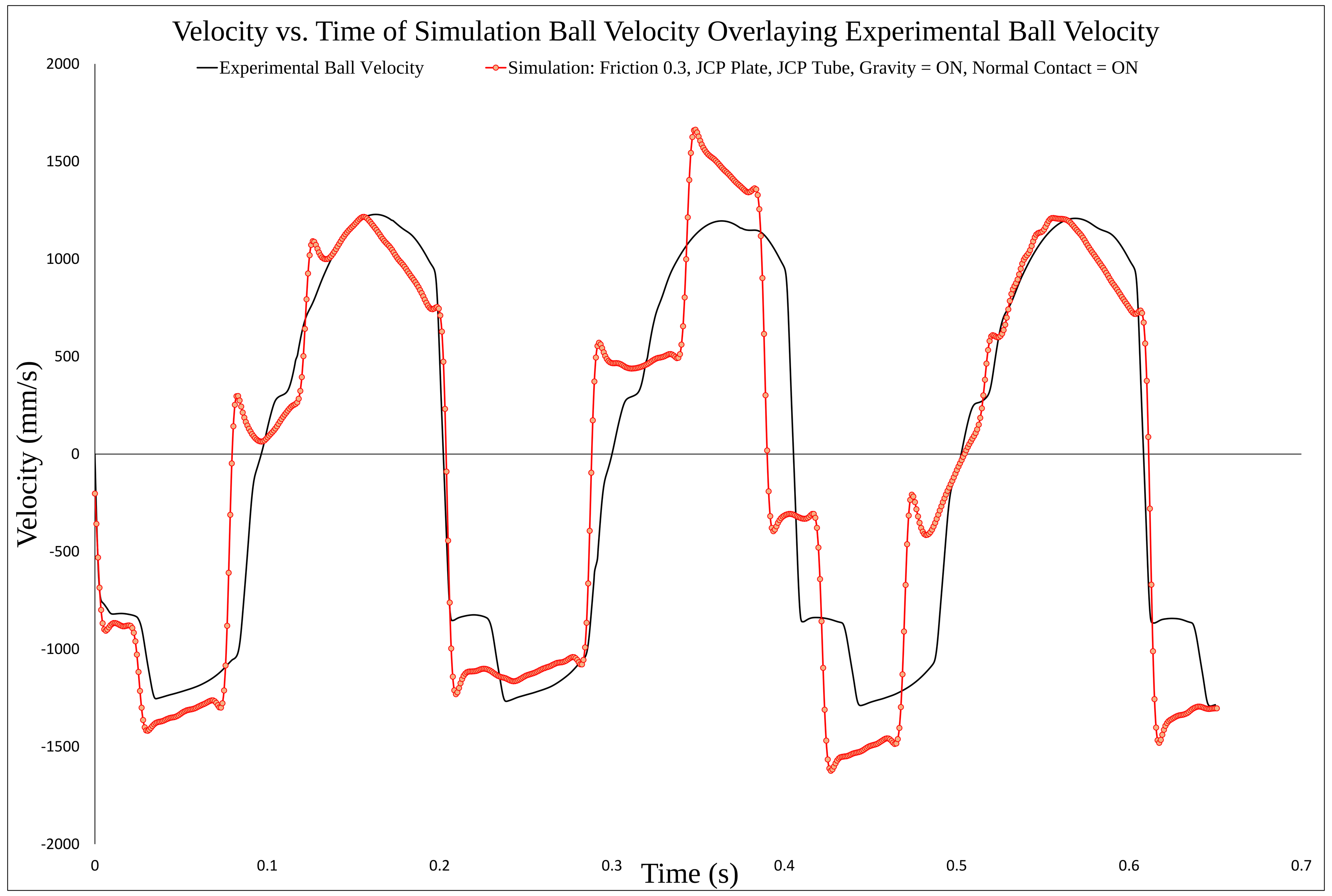

Figure 5: Simulation ball impact velocity (red) overlaying experimental ball impact velocity (black). Total time of simulation was 0.65s.

Results and Conclusions

Results

- The calibrated Johnson-Cook parameters that were used in the final calibrated simulations were A: 8 MPa, B: 828 MPa, n: 0.655, C: 0.0257, m: 1.02.
- Results from these simulations were promising as most of the impact energy was transferred into the plate surface, however, shortly through the simulation, ball lateral translation issues started to occur. Work is still being conducted to resolve these issues.
- Results that did not include lateral translation errors used JCP parameters from literature [Johnson and Cook, 5] with a tangential friction coefficient of 0.3 between the tube and ball surface with a normal hard contact condition which proved to be the most accurate (Fig. 5).
- Preliminary simulation deformation data seemed to correlate well with data from Figure 4.
- Quarter symmetry velocity impact data was more linear and less quadratic in its response, however, impacts within the simulation were at nearly identical velocities and times as the experimental data.
- Half symmetry with gravity gave accurate solutions comparable to Figure 5 data but ran at less than half the time to complete.
- The velocity curves of the simulation data overlaying the experimental data do not match up exactly, but this is more than likely due to analytically perfect calculations approximating a real-world solution.

Conclusions

- Due to various uncontrollable parameters such as imperfections within the experimental materials, grain size, metallurgical and processing defects, slight temperature fluctuations, air resistance and viscous effects of the ball inside the tube during the experiments, and approximate analytically perfect values in the simulation, it will be nearly impossible to achieve a result that is completely accurate, however, the results were close.
- This simulation work was successfully able to validate the experimental work and tracking data performed by Ph.D. student Joby Anthony III. More work would need to be done with this research to further refine the velocity curves to get a solution that follows the curve of the experimental velocity closer.

Future Work

1. Continue adjusting simulation parameters if necessary to achieve a higher accuracy solution comparable to experimental ball velocity data (Fig. 5)
2. Create multi-impact single-site simulations which should correlate well with existing simulation (Fig. 5) and experimental data (Fig. 4) to save on computational effort
3. Create simulations with multiple laterally spaced surface impacts on a plate after validating multi-impact single-site simulation data
4. Perform monotonic tensile simulations with saved stress data from laterally spaced surface impact simulations and compare to other experimental data
5. Optimize impact locations, force, and number of impacts on plate to achieve the best ductility of the material while maintaining or exceeding strength values taken from existing literature.

References

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