I, Max Miller, hereby submit this original work as part of the requirements for the degree of Master of Science in Mechanical Engineering.

It is entitled:
An Integrated Experimental and Simulation Study on Ultrasonic Nano-Crystal Surface Modification

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University of Cincinnati
An Integrated Experimental and Simulation Study on Ultrasonic Nano-Crystal Surface Modification

A Thesis submitted to the Division of Research and Advanced Studies of the University of Cincinnati in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE in the School of Dynamic Systems of the College of Engineering and Applied Science

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By

Maxwell Miller

Advisor: Dr. Dong Qian
ABSTRACT

Ultrasonic Nano-Crystal Surface Modification (UNSM) is a relatively new material processing technology to enhance the operating service lives, or fatigue life, of engineering components. There is an increasing interest in extending this technology to metal parts such as aircraft engine turbine blades, compressor blades and medical implants such as spinal rods. In this process a ball made with tungsten carbide generates 20 - 40 KHz strikes of a few hundred Newton on the specimen surface. It works as a cold forging process; however the small ball that works itself across the specimen surface has a dynamic load added to the normal static load. The total striking force, feed, ball radius, amplitude of dynamic load and speed can vary to yield different results. UNSM induces severe plastic deformation and deep compressive residual stresses to increase surface hardness, improve surface roughness, and introduce nano-crystallization near the specimen surface. Currently there is no systematic approach to predict the material response under UNSM. Therefore the objective of this thesis is to develop a process model for predicting the material response as a result of the UNSM process. Before developing the model, experimental data is extracted from two UNSM treated coupons, one of Ti-6Al-4V and the other IN718 SPF. First a MATLAB code is developed to define the displacement history of the carbide ball on the surface of the specimen during the UNSM process. For titanium alloy (Ti-6Al-4V) a temperature, pressure, and rate dependent constitutive material model for is established to account for the high strain rates associated with UNSM. A semi-implicit forward tangent modulus algorithm is developed to implement the material and damage model, and this is linked with the FEM software LS-DYNA through a user-defined material subroutine. We use the Johnson Cook material model already within the LS-DYNA software to simulate IN718 SPF. The residual stress obtained from the simulation is compared and verified with experimental results. To further understand the UNSM process, the residual stress results are compared with Laser Shock Peening (LSP) to note the differences.
ACKNOWLEDGEMENTS

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CHAPTER 1 – INTRODUCTION

1.1 Background and Motivation

Ultrasonic Nano-Crystal Surface Modification (UNSM) is a material processing technique that was first developed at Sun Moon University in South Korea. When compared to conventional shot peening, this technique generates deeper compressive residual stresses in metallic materials. Ri-ichi Murakami at University of Tokushima compared UNSM to several other treatments [8], including shot peening (SP, laser shock peening (LSP), low plasticity burning (LPB) and deep rolling (DR), and ultrasonic shot peening (USP). The table below ranks the different treatment methods from 1 – 5, with a value of 5 being the most effective.

<table>
<thead>
<tr>
<th>Tech vs Character</th>
<th>SP</th>
<th>LSP</th>
<th>LPB, DR</th>
<th>USP</th>
<th>UNSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Source</td>
<td>Powder Injection</td>
<td>Laser Heat</td>
<td>Static Load</td>
<td>Ultrasonic Dynamic Load</td>
<td>Static Load + Ultrasonic Dynamic Load</td>
</tr>
<tr>
<td>Compressive residual stress/depth</td>
<td>1</td>
<td>5</td>
<td>4</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Hardness &amp; depth</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Nano Structure</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Surface Topology</td>
<td>2</td>
<td>5</td>
<td>1</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Surface Roughness</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>5</td>
</tr>
</tbody>
</table>

The UNSM process generates ultrasonic energy of 20 – 40 KHz strikes with a small bead (tungsten carbide) with a 2.38 mm diameter (see Figures 1 and 2 below). As the bead moves across the specimen in straight lines, it can vary with total striking force, feed (S), ball radius (r), amplitude of dynamic load (P), and speed (V (m/min)). The tool induces a normal static load, and then adds a dynamic load when traveling along the specimen. The total striking force can be written as, [9]
\[ F = P_{st} + P \sin(2\pi ft) \]  \hspace{1cm} (1.1)

where \( P_{st} \) is the normal static load on the tool, \( P \) is the amplitude of dynamic load, \( t \) is time in seconds and \( f \) is the load frequency.

Figure 1: Movement of UNSM bead [9]

Figure 2: UNSM setup [9]
From this information, the UNSM treatment is a cold working process, and the surface is not affected thermally. Permanent plastic deformation occurs in the material when the tool pressure exceeds the elastic limit. The dynamic yield strength of the material can be derived as, [10]

\[
\sigma_v^{dyn} = \frac{1-2v}{1-v} HEL
\]

(1.2)

where \(v\) is Poisson’s ratio, \(\sigma_v^{dyn}\) is dynamic yield strength of the material and \(HEL\) is the Hugoniot elastic limit. Severe plastic deformation, or dynamic plasticity, occurs as a result of the UNSM treatment which increases the life of the component significantly.

One of the main objectives of this thesis is to compare UNSM to Laser Shock Peening (LSP) process. LSP is a fairly new process which also has an advantage over conventional shot peening by generating deep compressive residual stresses in the material. Here, a high energy laser pulse is incident on the surface for 25-50ns. Temperatures in excess of 10000°C are reached on the surface which causes plasma to form. This plasma generates a shock wave with peak pressure up to the order of several Giga Pascals and propagates through the surrounding medium. The surface to be treated is coated with an opaque material with a transparent material (water) on top of it. This protects the surface from thermal damage and increases the shock wave pressure. This method is called ablation mode. The process is illustrated in Figure 3 below.
One characteristic the UNSM treatment has when compared to LSP is that the treatment creates a nano crystal layer on the first 10 microns on the surface. The severe plastic deformation caused by the UNSM treatment decreases the grain size of the material to the nano level on the first 100 microns into the depth of the material. Figure 4 below illustrates this.

Figure 3: Laser Shock Peening Process [11]
The nano structure increases surface hardness, and improves surface roughness/topology. Researchers at Sun Moon University observed increased hardness and improved roughness with IN718 SPF and Ti-6Al-4V samples with different UNSM conditions (static loads of 60, 70 and 80N), and can be seen below in Figures 5, 6 and Table 2 and 3 [9].
Figure 5: Surface roughness Micrograph of IN718 SPF treated with UNSM [9]

Figure 6: Surface roughness Micrograph of Ti-6Al-4V treated with UNSM [9]

Table 2: Surface hardness/roughness measurements of IN718 SPF treated with UNSM [9]

<table>
<thead>
<tr>
<th>Material</th>
<th>Surface hardness, HV</th>
<th>Surface roughness, μm (Ra)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated</td>
<td>447</td>
<td>0.12</td>
</tr>
<tr>
<td>UNSM-treated_1</td>
<td>502</td>
<td>0.09</td>
</tr>
<tr>
<td>UNSM-treated_2</td>
<td>514</td>
<td>0.10</td>
</tr>
</tbody>
</table>
Table 3: Surface hardness/roughness measurements of Ti-6Al-4V treated with UNSM [9]

<table>
<thead>
<tr>
<th>Material</th>
<th>Surface hardness, HV</th>
<th>Surface roughness, µm (Ra)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated</td>
<td>377</td>
<td>0.09</td>
</tr>
<tr>
<td>UNSM-treated_1</td>
<td>394</td>
<td>0.08</td>
</tr>
<tr>
<td>UNSM-treated_1</td>
<td>401</td>
<td>0.08</td>
</tr>
</tbody>
</table>

1.2 Residual Stress and fatigue life

One way to extend the fatigue life of a component is to introduce residual stresses. Materials are often subjected to cyclic operating stresses, such as turbine vanes or spinal rod implants, where tensile and compressive stresses are present. In these cases of alternating stress, failure often happens due to fatigue. UNSM treatment introduces additional compressive stress to eliminate tensile stresses during cyclic loading. Cheriff, Pyoun and Scholtes studied the effects of UNSM on AISI 304 steel and observed that the treatment increased the fatigue life when compared to an untreated specimen. [1]

Figure 7: Effect of UNSM on fatigue life [1]
It can be seen from this figure that the fatigue strength is increased when compared to the untreated sample, and shows the lifetime of the material is extended. Cheriff, Pyoun and Scholtes also performed residual stress testing with AISI 304 [1]. Figure 8 below indicates the comparison of residual stress along the depth for UNSM, deep rolled and conventional shot peened material. The maximum depth at which compressive stresses occur is much higher than conventional peening, as well as the magnitude of compressive residual stress.

![Figure 8: Comparison between UNSM, deep rolled, and shot peening residual stress [1]](image)

### 1.3 Motivations

UNSM technology is a very new process, and so far has been found in many cases to produce better results than conventional processing techniques. However, not much research has been done to study the effects of the nano crystal formation and severe plastic deformation caused by UNSM. A process model is needed to simulate the ultrasonic vibration on a material surface. Having a model could reduce the amount of time and cost in the experimental stage,
and help us understand the influence of various UNSM processing parameters such as the feed, speed, static load, and amplitude of dynamic load. The main significance of having a simulation model is it can be used as a guiding tool for validation and control.

1.4 Objective

The main objective of this thesis is to compare the LSP and UNSM processes using samples of IN718 SPF and Ti-6Al-4V, and develop a model to simulate and predict residual stress response in the UNSM process. Figure 9 below shows the flow chart for developing an LS-DYNA Solver-Simulation. The model will be compared with experimental results for verification. The specific aims are:

1. Obtain residual stress and hardness measurements from the UNSM and LSP samples
2. Characterize microstructure of UNSM samples using SEM and EBSD
3. Compare UNSM and LSP hardness and residual stress measurements
4. Develop process model for simulation of UNSM using nonlinear damage based constitutive material model for Ti-6Al-4V and IN718 SPF
5. Verify simulation results with experimental results
Figure 9: Flow chart of the project
CHAPTER 2 - EXPERIMENTAL RESULTS

2.1 Specimen Samples

Four coupon samples were processed at Sun Moon University using UNSM. Figure 10 shows the four samples, where each sample is approximately 2.04mm thick, two of them being Ti-6Al-4V and the other two are IN718 SPF.

![Figure 10: Four coupon samples treated with UNSM for experimental verification](image)

In the above figure, the movement of the carbide bead from left to right gives the feed speed and is defined as the x-axis. The movement up and down gives the feed rate and is defined as the y-axis. It is important to keep in mind the axial directions when measuring residual stress because the values vary significantly in the x and y axes.
Table 4 displays the UNSM condition used for all four specimens. In this case, the only UNSM parameter changed in the different samples was the static load. The two titanium coupons have loads of 60 and 70 N, and the IN718 coupons have loads of 70 and 80 N.

<table>
<thead>
<tr>
<th>Amplitude, μm</th>
<th>Static load, N</th>
<th>Feed speed, mm/min</th>
<th>Feedrate, mm/rev</th>
<th>Ball dia &amp; material</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>60, 70, 80</td>
<td>3000</td>
<td>0.07</td>
<td>2.38 mm (WC)</td>
</tr>
</tbody>
</table>

2.2 Surface Hardness

To measure the hardness of the material after being subjected to UNSM treatment, a CSM Micro/Nano Indentation machine was used. The CSM machine applies a load on to the indentation tool, and the Vickers hardness can be calculated by measuring the depth of indentation. Typically for micro-hardness the indenter is a diamond shaped pyramid. The Vickers number (HV) is calculated using the formula: [6]

\[ HV = 1.854 \left( \frac{F}{D_2} \right) \]  

(2.1)

where \( F \) is the applied load and \( D_2 \) is the area of indentation. For accurate results, matrices of indentations are averaged. For surface hardness, micro indentations were used with a 1-2 Newton load spaced 100-150 microns apart.

2.2.1 IN718 SPF Results

To get a good idea of how UNSM treatment increases the surface hardness, the results from UNSM are compared with the untreated part of the specimen. For the IN718 samples the UNSM conditions are listed in Table 4. A 2 Newton load with 150 micron spacing was used,
and a patch of 4x4 micro indentations was performed on the treated portion of the IN718 specimens with a line of 8 indentations on the untreated part. Figure 11 shows the resulting patch. Looking at the Vickers values seen in Tables 5 for both specimen samples, we can see a 20 – 25% increase in hardness when compared to untreated material. Figures 12 and 13 show the force vs. depth curve for both treated and untreated IN718 of the indenter from first making contact with the surface, then being loaded until reaching 2 Newton. For the treated material we can see, for both specimens, that it takes a higher force to reach the same depth when compared to the untreated.

![Figure 11: CSM image of micro indentations 4x4 patch on treated IN718 SPF sample](image)

Figure 11: CSM image of micro indentations 4x4 patch on treated IN718 SPF sample
Table 5: Vickers hardness results of IN718 SPF sample 1 and 2

<table>
<thead>
<tr>
<th>Sample 1</th>
<th>Treated</th>
<th>Untreated</th>
</tr>
</thead>
<tbody>
<tr>
<td>HV (O&amp;P)</td>
<td>Data: 1</td>
<td>615.627</td>
</tr>
<tr>
<td>[Vickers]</td>
<td>Data: 2</td>
<td>587.795</td>
</tr>
<tr>
<td></td>
<td>Data: 3</td>
<td>594.622</td>
</tr>
<tr>
<td></td>
<td>Data: 4</td>
<td>603.953</td>
</tr>
<tr>
<td></td>
<td>Data: 5</td>
<td>550.433</td>
</tr>
<tr>
<td></td>
<td>Data: 6</td>
<td>515.838</td>
</tr>
<tr>
<td></td>
<td>Data: 7</td>
<td>594.416</td>
</tr>
<tr>
<td></td>
<td>Data: 8</td>
<td>604.324</td>
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<td></td>
<td>Data: 9</td>
<td>598.842</td>
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<td></td>
<td>Data: 10</td>
<td>621.36</td>
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<td></td>
<td>Data: 13</td>
<td>573.738</td>
</tr>
<tr>
<td></td>
<td>Data: 14</td>
<td>639.75</td>
</tr>
<tr>
<td></td>
<td>Data: 15</td>
<td>633.9</td>
</tr>
<tr>
<td></td>
<td>Data: 16</td>
<td>632.837</td>
</tr>
<tr>
<td>~20% increase</td>
<td>Mean</td>
<td>597.519</td>
</tr>
<tr>
<td>Std Dev</td>
<td>28.972</td>
<td>18.379</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample 2</th>
<th>Treated</th>
<th>Untreated</th>
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<tr>
<td>HV (O&amp;P)</td>
<td>Data: 1</td>
<td>630.896</td>
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<td></td>
<td>Data: 2</td>
<td>494.786</td>
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<td></td>
<td>Data: 3</td>
<td>539.812</td>
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<td>Data: 4</td>
<td>615.55</td>
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<td>Data: 5</td>
<td>562.364</td>
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<td></td>
<td>Data: 6</td>
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<td>Data: 7</td>
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<td></td>
<td>Data: 8</td>
<td>601.065</td>
</tr>
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<td></td>
<td>Data: 9</td>
<td>600.631</td>
</tr>
<tr>
<td></td>
<td>Data: 10</td>
<td>560.424</td>
</tr>
<tr>
<td></td>
<td>Data: 11</td>
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<td>Data: 12</td>
<td>536.436</td>
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<td>Data: 13</td>
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<td></td>
<td>Data: 14</td>
<td>604.799</td>
</tr>
<tr>
<td></td>
<td>Data: 15</td>
<td>601.924</td>
</tr>
<tr>
<td>~25% increase</td>
<td>Mean</td>
<td>576.712</td>
</tr>
</tbody>
</table>

Figure 12: Force vs. Depth curve of IN718 SPF sample 1
2.2.2 Ti-6Al-4V Results

For this material, a step size of 100 microns and a 1 Newton load was used for the micro indentation measurement of surface hardness, along with a 5x5 patch for both the treated and untreated surfaces. Figure 14 shows the resulting micro indentations performed on the sample 1 specimen. Ti-6Al-4V is slightly softer than IN718, so the Vickers hardness will be lower. Looking at Table 6, we can easily see an increase in hardness compared to the untreated surface, which is approximately a 27% increase. Also, the force vs. depth curve, shown in Figure 15, displays once again a higher force on the treated surface at a higher depth than the untreated surface.
Figure 14: CSM image of micro indentations on Ti-6Al-4V treated surface sample 1

Table 6: Vickers hardness results for Ti64 Sample 1

<table>
<thead>
<tr>
<th>Sample 1</th>
<th>UnTreated</th>
<th>Treated</th>
</tr>
</thead>
<tbody>
<tr>
<td>HV (O&amp;P)</td>
<td>Data : 1</td>
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*27% increase Mean 370.615 472.644
2.3 Residual Stress

As discussed previously, residual stresses are stresses that reside inside a component after all applied forces have been removed. After treatment of UNSM, both compressive and tensile residual stresses are present. Compressive residual stresses should be seen in the first 300 microns or so into the component, with the rest being tensile. To measure the residual stress in the specimens treated with UNSM, X-ray diffraction is used with the Proto LXRD machine located in the LSP lab at the University of Cincinnati. The process uses the distance between crystallographic planes as a strain gauge, so when this distance, or d-spacing, increases or decreases, the material is in tension or compression respectively. According to Bragg's Law: [14]
\[ nl = 2d \sin q \]  

(2.2)

where \( n \) is the order of diffraction, \( l \) is the wavelength of x-ray beam, \( d \) is the distance between lattice planes inside the material, and \( \theta \) is the angle of the diffracted beam. Figure 16 illustrates this process.

![Proto LXRD X-Ray Diffraction process](image)

Figure 16: Proto LXRD X-Ray Diffraction process [14]

### 2.3.1 IN718 SPF Residual Stress Measurement Results

Several parameters were used with the Proto LXRD system to measure the residual stresses in the IN718 SPF specimens. The radiation used was Magnesium K\( \alpha \) (\( \lambda = 2.10314 \) Å), along with a 2mm circular aperture size. For the tilt axis \( \Omega \), 11 \( \beta \) angels were used on the 311 plane with a Bragg angle of 152°. To get the depth profile, an area of 10 x 10 mm in the middle of the sample was electro polished in between each measurement. Figures 17 and 18 show the resulting residual stress depth profiles compared to LSP. The LSP data uses a 2mm IN718
coupon subjected to a patch of 30x30 1.8mm diameter laser spots which are overlapped 50% in each direction, with a laser pulse energy of 8 Joules.

Figure 17: Residual Stress Profile of IN718 sample 1 compared with LSP (8J)
From the figures above we can see a significant difference between the two measurements. In the LSP sample, the depth at which residual stresses turn tensile is much higher; however the UNSM samples seem to have significantly higher compressive stresses near the surface. Measurements in the X and Y directions had to be taken in the UNSM samples because of the treatment pattern on the surface of the sample.

To get a better understanding of the differences between the measurements, we also compare the FWHM (Full Width Half Maximum) intensity of peak width from the X-ray measurement, which is shown in Figure 19 to LSP and cavitation peening. Cavitation peening is a process which uses the impact force of a shock wave induced by jet-induced cavitation bubble. This process can be compared to conventional shot peening. Again we see a large difference at the surface, with UNSM having a larger FWHM than LSP and Cavitation. FWHM is an
indication of the grain structure evolution and plasticity events. As such, UNSM seems to bring enhanced plasticity in the near surface region.

Figure 19: FWHM vs. depth comparison between UNSM specimens, LSP, and Cavitation

2.3.2 Ti-6Al-4V Residual Stress Measurement Results

Slightly different parameters were used on the Proto LXRD when measuring the residual stresses in the Titanium sample. A Cu Kα radiation tube was used with a 2mm circular aperture, and the tilt axis Ω with 11 β angles. In this case, for the 311 plane, the Bragg angle was 142°. Again, to get the residual stress depth profile, an area of 10 x 10 mm in the middle of the sample was electro polished in between each measurement. The effects of UNSM treatment on the Ti64 samples were slightly different than the IN718 samples. Figures 20 and 21 compare the residual stress results to LSP (taped 3.9J).
Figure 20: Residual stress profile of UNSM Ti64 sample 1 compared with LSP (taped 3.9J)
In both cases, mainly for the Y-direction, the compressive residual stress is much higher at the surface when compared to LSP. Unlike the IN718 SPF samples, the stresses turn tensile at a slightly higher depth, however near the surface the compressive stresses are much smaller in value.
2.4 Microscopy

To get a better understanding of the effects of UNSM treatment, microscopy is performed to take a close look at the microstructure of the treated specimen. The main area of interest when looking at a UNSM treated structure is 10 microns into the surface. After treatment, nano sized grains form near the surface, and return to original sized grains after approximately 100 microns. Two techniques were used to look at the grain structure. One was etching the sample and viewing under an x1000 microscope, and the second technique involved polishing the sample, then performing Electron Backscatter Diffraction (EBSD) under an SEM microscope.

2.4.1 IN718 SPF Sample Preparation

Using the sample 1 IN718 coupon, a small 5mm x 7mm rectangle was cut out to be used for microscopy. The cut piece was then mounted in a conductive thermosetting molding compound by its cross section to see the depth profile. To fit in the SEM machine, the mount was also cut down to a small rectangle. Figure 22 shows the resulting mount.
2.4.2 IN718 Etching Results

After polishing the cut mount down to colloidal silica, the specimen was dipped in an etchant solution of 100 ml of Hydrochloric acid and approximately 5 ml of H₂O₂ for thirty seconds. After etching, the grain boundaries, as well as slip planes, can be seen under a microscope. The IN718 mounted specimen was viewed under a CSM Indentation x1000 microscope, as well as an SEM. Figures 23 and 24 show the resulting SEM images taken at the surface of the mounted cross section. Here we can clearly see how the grains increase in size with increasing depth into the material. Figure 24 illustrates that the grains return to the original crystal structure after 100 microns. The size of the grains near the surface is too small to be visually identified, however it can be inferred that they are nano scale level. It can also be seen that after approximately 10 microns, the grains begin to increase in size. Figures 25, 26 and 27 show clearer images of the grain structure using the x1000 CSM microscope.

Figure 23: SEM Microscopy image of IN718 UNSM treated sample at 20 and 50 um resolution
Figure 24: SEM Microscopy image of IN718 UNSM treated sample at 100 um resolution

Figure 25: CSM image of etched IN718 UNSM treated sample at surface
To get a better understanding of how the UNSM treatment changes the crystal structure, another CSM image of an etched IN718 sample treated by cavitation peening was taken. Figure
28 shows the surface of the sample. The image shows grains of the same size at the surface as well as 40 μm below the surface. We observe that treating a sample with cavitation peening does not create nano sized grains at the surface, and does not have the same effects as UNSM.

Figure 28: CSM image of etched IN718 Cavitation treated sample at surface
2.4.3 IN718 EBSD Results

The cut mount was polished for EBSD microscopy. EBSD is also known as Kikuchi diffraction (BKD), which is a technique used to measure crystallographic orientation. In this process, an electron beam strikes a tilted crystalline sample and forms a pattern based on diffracted electrons which displays the crystal structure. The patterns, or Kikuchi bands, show the cones of diffracted electrons from the lattice plane at the Bragg angle. The orientation of the diffracting crystal can be calculated from the position of the Kikuchi bands. EBSD can provide many measurements such as crystal orientation, grain size, grain boundary characterization, phase identification, and many more.

When looking at Kikuchi band patterns, it must be ensured that they are only contributed by the crystal planes. To evaluate this, an equation can be used to calculate the intensity of a Kikuchi band for the plane (indexed by $hkl$): [2]

$$I_{hkl} = \left[ \sum_i f_i(\theta) \cos 2\pi(hx_i + ky_i + lz_i) \right]^2 + \left[ \sum_i f_i(\theta) \sin 2\pi(hx_i + ky_i + lz_i) \right]^2$$

(2.3)

Here, $f_i(\theta)$ is the atomic scattering factor for electrons and in the unit cell for atom $i$, $x_i$, $y_i$ and $z_i$ are the fractional coordinates. When looking at a UNSM treated crystal structure, the grain sizes are very small near the surface and it can be difficult to produce a visible Kikuchi pattern. Figures 29 and 30 below show exactly this. For the untreated surface, Kikuchi patterns are visible throughout the depth profile; however the treated surface shows the Kikuchi patterns are barely visible at the top, and then become visible at a lower depth. The only reason for this is that the grain size is too small. Looking at Figures 31 and 32 below, we can clearly see the nano sized grains near the surface, and as the depth increases, so does the size of the grain.
Figure 29: EBSD Kikuchi patterns at UNSM treated surface of IN718 SPF sample

Figure 30: EBSD Kikuchi patterns at untreated surface of IN718 SPF sample
Figure 31: EBSD Results for UNSM IN718 SPF

Figure 32: EBSD Results for UNSM IN718 SPF
2.5 Nano – Indentation Results

Nano indentation is a very delicate process, and obtaining accurate results can be difficult if not done properly. Because the indentations are so small, a large amount of data can be collected in a small area. For UNSM, the first 100 microns, and even the first 10 microns, are the areas of interest because of the nano-crystal microstructure.

Nano-indentation was performed on the IN718 sample 1 specimen. Two sets of experiments were conducted, the first being 4 rows of 5 indentations spaced 400 and 30 microns apart respectively. The second experiment looked more closely at the first 400 microns, with a matrix of 5 x 100 indentations spaced 30 microns apart. Both experiments used a 50 mN load so the Vickers hardness can be measured. Figure 33 shows the resulting indentations of both experiments viewed under the CSM microscope.

Table 7 shows the Vickers (HV) hardness and indentation depth for the first experiment. It can be seen that as the depth increases, the hardness decreases. Not to be confused with pressure, Vickers hardness can be measured in Pascals and it is the load over the surface area of the indentation. At 1200 microns, the average hardness is almost 100HV less than the surface. Figure 34 illustrates the average hardness vs. depth into the sample. We can see that the hardness is higher at the surface than the hardness from the proceeding depths, because of the nano microstructure. Figure 35 shows the average indentation Pd – Fn curves for each row. At the surface, the curve reaches the peak load value at a depth of around 600 nanometers, whereas at 1200 microns into the surface, the peak load value is at a depth of around 700 nanometers.
Figure 33: CSM microscope image of nano indentation experiments on IN718 SPF sample 1

Table 7: Vickers nano indentation results of IN718 sample 1

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Figure 34: Graph of Vickers hardness vs. depth of IN718 sample 1

Figure 35: Averaged Pd-Fn curves of each indentation row for IN718 sample 1
CHAPTER 3 – MODELING OF UNSM PROCESS

3.1 Finite Element Modeling and Analysis

To model the UNSM process, FEM analysis were performed. The activities such as meshing, model creation, boundary conditions and load application were done in LS-PREPOST, a pre- and post-processor for the commercial FEM code LS-DYNA. Once the input file was created, then the commercial FEM solver LS-DYNA was used to produce the simulation results, where post-processing was done in LS-PREPOST as well. For each simulation, the input file was run from 0-.016 seconds, with a courant number of .8. The large timescale was used to accurately model the speed and feed of the WC UNSM bead. A small patch of three .25mm UNSM lines spaced .07mm apart is applied on each simulation, with a static load of 70N, 30 micrometer amplitude, feed speed of 3000 mm/min, and 2.38mm diameter ball.

3.1.1 Contact Analysis in LS-Dyna

To accurately model the UNSM process is a challenge. The analysis can be analyzed as a ball impacting, or contacting, the specimen at 20,000 times per second. LS-DYNA contains contact algorithms for two parts contacting each other. The contact analysis uses Langrangian elements to interact with each other, which includes parts that impact/push/slide/rub against each other [4].

For the UNSM simulation, the contact algorithm used is Contact_Surface_To_Surface. This option searches for segments penetrating segments, and uses penalty based contact forces, or a finite contact stiffness calculation. For this particular case, a master segment set of shell
elements is chosen for the UNSM bead, and a slave segment set is chosen for the block specimen. The equation below shows how the stability contact stiffness is calculated: [4]

\[
k_{c}(t) = 0.5 \times SLSFAC \times \begin{cases} SFS \quad \text{or} SFS \quad \text{or} \quad \left( m_1 m_2 \right) \left( \frac{1}{m_1 + m_2} \right)^2 \end{cases} (3.1)
\]

where \( SLSFAC \) is the scale factor for segment to segment formulation, and segment masses are used rather than nodal masses. \( SFS \) is the layer shear strengths due to fiber shear failure, where \( SFM \) is the maximum normalized fracture strength, and \( m_1 \) and \( m_2 \) represent the mass of the slave and master nodes. The last term contains \( \Delta t_c \), which is the solution time step. The segment based contact (SOFT = 2) will check for contact of elements even if nodes miss [4]. This is a good option to use for ultrasonic contact and small elements. Figure 36 illustrates this theory.

Figure 36: Surface to Surface contact

Taylor and Flanagan [1989] were the first to implement the surface to surface constraint algorithm. The penetration force is computed for the slave node, here the IN718SPF or Ti-6Al-4V specimen, as a function of the penetration distance \( \Delta L \): [4]
\[ f_p = \frac{m_s \Delta L}{\Delta t^2} n \]  

(3.2)

where \( n \) is the normal vector to the master surface (WC UNSM Bead) and \( m_s \) is slave node mass.

At the contact segment \((s_c, t_c)\) between the slave node and master segment, the response of the slave node acceleration vector on a slave node residing on the master segment must be consistent with the motion of the master segment. To find the acceleration vector of the slave node we have: [4]

\[
a_s = \phi_1(s_c, t_c)a_{nk}^1 + \phi_2(s_c, t_c)a_{nk}^2 + \phi_3(s_c, t_c)a_{nk}^3 + \phi_4(s_c, t_c)a_{nk}^4
\]  

(3.3)

where each term containing \( a_{nk} \) represents the nodal acceleration of the master segment \( k \). The global master surface mass and force vector, given by equation 3.4 below, can be derived from the accumulating the nodal mass and penetration force of each slave node in contact with and penetrating the master surface: [4]

\[
(m_k + \sum_s m_s)a_{nk} = \sum_s f_{ks}
\]  

(3.4)

where

\[
m_{ks} = \phi_k m_s
\]

\[
f_{ks} = \phi_k f_p
\]  

(3.5)

Equation 3.2 can be solved for the acceleration vector, \( a_{nk} \), and therefore can be used to obtain the slave node acceleration correction: [4]

\[ a_{ns} = a_s - \frac{f_p}{m_s} \]  

(3.6)
Finally, the averaged final correction to the acceleration is found using, \( \beta \), a partitioning parameter that can be -1 or 1 that correspond to the master surface accumulation mass and forces from the slave surface, and vice versa. [4]

\[
a_{n}^{\text{final}} = \frac{1}{2} (1 - \beta) a_{n}^{1\text{stpass}} + \frac{1}{2} (1 + \beta) a_{n}^{2\text{ndpass}}
\]

(3.7)

which is used to compute the final acceleration time \( n+1 \): [4]

\[
a^{n+1} = a^{\text{rnl}} + a_{n}^{\text{final}}
\]

(3.8)

### 3.1.2 FE Mesh and Simulation

LS-PREPOST was used to create the model and mesh. The UNSM WC ball was modeled using shell elements and with a rigid material model to prevent any deformation or stresses. In the same .k file as an input for LS-DYNA, a 1.5x1.5x1 mm block of solid elements is modeled below the ball. The material used for the solid block is a user defined material for Ti-6Al-4V, where the Johnson-Cook model was used for IN 718 SPF. The user material code is implemented as a FORTRAN subroutine in the LS-DYNA solver as UMAT41 material ID. This particular model is the modified Zerilli-Armstong model solved using forward gradient method. This material model was used because it accurately models the deformation of high strain rates depending on the crystal structure. It also measures the dependence of the material response on dislocation density before yield, grain size, and hardening power law. The ZA model will be discussed more in depth in the next section. The Johnson Cook Material model is an LS-DYNA integrated model, and does not require a user subroutine. This model is discussed more in detail in section 3.1.4. The mesh of proposed UNSM simulation can be seen in Figure 37.
The UNSM patch is performed by contact analysis. To do this in LS-PREPOST, the Contact _Surface_to_Surface option is used. This option recognizes the contact between the rigid ball and the block. When the rigid ball contacts and displaces into the material surface, the nodes displace with the contact segments of the ball. As mentioned in section 3.1.1, a slave and master segment set are chosen to define the areas in contact. The rigid ball must contain elements smaller than the block to ensure that nodes on the surface do not displace through the rigid ball. For this particular model, there are 51,200 solid elements, and 29,400 shell elements. There will be three different boundary conditions (BC’s) modeled to observe the different effects, which are: no BC’s, BC’s placed on the sides of the umat block constrained in the normal direction, and finally non-reflecting BC’s placed on the sides of the block to simulate an

Figure 37: UNSM FE mesh using LS-PREPOST
infinite plane. For each case, the bottom of the block is constrained in all directions. To model the UNSM patch, three define curve cards are created for the movement of the ball in the x, y and z directions. The curves are implemented using the Prescribed_Motion_Rigid card. MATLAB is used to create the curve cards, and will be discussed in detail in section 3.1.4.

3.1.3 Modified Zerilli-Armstrong Model and Implementation

The Zerilli-Armstrong model focuses on the deformation mechanism related to the crystal structure of the material. It is found that the grain size and crystal structure will influence how the material responds. Since the UNSM process greatly alters the grain size and structure of the material, this model could accurately reflect how Ti-6Al-4V behaves. The three crystal structures described in a material are bcc (body centered cubic), fcc (face centered cubic) and hcp (hexagonal close-packed). Zerilli and Armstrong observed that the fcc lattice increases strain rate hardening and thermal softening with increased strain, where the bcc lattice, strain rate hardening and thermal softening do not depend on strain. The Zerilli-Armstrong model is given as [13]

\[ \sigma_f = \Delta \sigma_G + k \dot{\varepsilon}_d \dot{\varepsilon}^{1/2} + B e^{-[\beta_0 - \beta_1 \ln(\dot{\varepsilon})]T} + C \dot{\varepsilon}^n \]

(3.9)

where \( \sigma_f \) is the dynamic yield strength of the material, and is a function of the strain \( \varepsilon \), strain rate \( \dot{\varepsilon} \) and temperature \( T \) in the material. Dislocation density before yield is represented by the first term, where the second term represents effect of grain size. These two terms can be combined into one constant, representing yield stress, since they are unaffected by temperature, strain, and strain rate. The third term represents strain rate and temperature, where the final term is the hardening power law model. It can be re-written as
\[ \sigma_f = A + Be^{-(\beta_0 - \beta_1 \ln(\epsilon)) r} + C \bar{\varepsilon}^n \]  

(3.10) 

where \( \dot{\varepsilon} \) is the effective visco-plastic strain rate, \( \bar{\varepsilon} \) is effective visco-plastic strain, \( T \) is temperature, and \( A, B, C, n, \beta_0, \beta_1 \) are constants. The UNSM process mostly depends on the impact force, vibration, and speed of the Tungsten Carbide bead on the surface of the material. The pressure effects can be incorporated into the model by including the variation of shear modulus. A modified Z-A model can be formulated based on the pressure dependence proposed by Steinberg [13], given as 

\[ \sigma_f = [A + Be^{-(\beta_0 - \beta_1 \ln(\epsilon)) r} + C \bar{\varepsilon}^n] \frac{G(P, T)}{G_0} \]  

(3.11) 

where \( G_0 \) is shear modulus at room temperature and \( P \) is pressure. The function of the shear modulus with respect to pressure and temperature can be written as 

\[ \frac{G}{G_0} = 1 + \left( \frac{G'_P}{G_0} \right) \frac{P}{\eta^{1/3}} + \left( \frac{G'_T}{G_0} \right) (T - 300) \]  

(3.12) 

where \( G'_T \) is the derivative of shear modulus with respect to temperature, \( G'_P \) is the derivative of shear modulus with respect to pressure and \( \eta \) is compressibility factor. Using the parameters from previous work [11], we substitute \( A = 810 \text{ MPa}, B=1800 \text{ MPa}, C=250 \text{ MPa}, \beta_0 = 0.009, \beta_1 = 0.0005, n = 0.5 \) to model Ti-6Al-4V. Pressure parameters based on Ti are given as \( G_0 = 43.4 \) GPa, \( \frac{G'_P}{G_0} = 11.5 \text{ TPa}^{-1}, \frac{G'_T}{G_0} = 0.62 \text{ kK}^{-1}. \)
Since this modified Zerilli-Armstrong model is not available in any commercial software, it must be integrated with the finite element tool LS-DYNA. A user defined material code is used based on the tangent modulus algorithm [10], which is a stress update algorithm, or forward gradient methods. This thesis will not cover the derivation of the algorithm. From this, the expression of the tangent modulus matrix is given as

$$C_{0}^\text{tan} = C_{0}^\text{elas} - \frac{\xi_{\theta}}{H_{\theta}(1 + \xi_{\theta})} \left( P_{0} \otimes P_{0}^{0} \right) + \frac{(3B + 2G)\chi \overline{\sigma}_{\theta}}{\rho C_{p}} \mathbf{1} \otimes P_{0}^{0}$$

(3.13)

where the term containing $\rho$, density, represents the temperature effect. $C_{0}^\text{elas}$ represents the elasticity tensor, $C_{p}$ is specific heat capacity, and $\overline{\sigma}$ is effective stress. Subscripts $\theta$, $n$, $n+1$ indicate the corresponding states of time

$$\xi_{\theta} = \theta \Delta t \frac{\partial \hat{\epsilon}}{\partial \overline{\sigma}} \bigg|_{n} H_{\theta}$$

(3.14)

$$H_{\theta} = 3G - \frac{\partial \hat{\epsilon}}{\partial \overline{\sigma}} \bigg|_{n} - \frac{\partial \hat{\epsilon}}{\partial \overline{T}} \bigg|_{n} \frac{\chi \overline{\sigma}_{\theta}}{\rho_{0} C_{p}}$$

(3.15)

In addition, $P_{0} = C_{0}^\text{elas} : p_{0}$ and $P_{0}^{0} = C_{0}^\text{elas} : p_{0}$

$$p_{0} = \frac{3\sigma'}{2\sigma} + \sigma_{x} \frac{\partial G}{3G_{0} \partial P} \mathbf{I}$$

(3.16)

in which $p_{0} = \frac{3\sigma'}{2\sigma}$ is the direction of the plastic strains, and $\sigma' = \sigma - \frac{1}{3}(\mathbf{\sigma} : \mathbf{I}) \mathbf{I}$ is the deviatoric stress tensor, and $\mathbf{I}$ is the identity tensor. The stress tensor is used to define the specific heat
capacity as $\bar{\sigma} = \sqrt{\frac{3}{2}} \sigma : \sigma'$. In equation 3.15, $\frac{\partial \hat{\varepsilon}}{\partial \bar{\sigma}}$ is the derivative of effective visco-plastic strain rate with respect to the effective visco-plastic strain, $\frac{\partial \hat{\varepsilon}}{\partial \sigma}$ is the derivative of effective visco-plastic strain rate with respect to the effective stress, $\frac{\partial \hat{\varepsilon}}{\partial \dot{T}}$ is the derivative of effective visco-plastic strain rate with respect to the temperature [11].

The tangent modulus matrix can be used for plasticity model, and is implemented as an algorithm. The algorithm is written in FORTRAN and is a UMAT subroutine in the LS-DYNA solver.

### 3.1.4 Johnson-Cook Model

The Johnson-Cook Model is already implemented in the LS-DYNA software, and there is no requirement to implement a user defined material model. This model can accurately simulate the Inconel 718 SPF since it is most applicable to high rate deformation of most metals, and remains valid to lower strain rates [4]. From Johnson and Cook [12] the effective stress in the JC model is given by

$$\sigma_y = (A + B \varepsilon^P)(1 + c \ln \varepsilon^*)(1 - T^{*m})$$

(3.18)

where $A, B, C, n, m$ are constants, $\varepsilon$ is plastic strain, $\sigma$ is effective stress, $\dot{\varepsilon}$ is the plastic strain rate, $T$ is the temperature, $\varepsilon^P$ is the effective plastic strain, and $\varepsilon^* = \frac{\dot{\varepsilon}^P}{\dot{\varepsilon}_0}$ represents the effective plastic strain rate for $\dot{\varepsilon}_0 = 1s^{-1}$. The first term is the power hardening law behavior through the
effective plastic strain. Strain rate dependence of flow stress is covered in the second term. To account for the decrease in flow stress due to thermal softening, this is covered by the third term. The derivation of the strain required for fracture is given by [12]

\[ \varepsilon' = [D_1 + D_2 \exp D_3 \sigma^* \ln(1 + D_4 \ln \varepsilon^*)] \]

(3.19)

\( D_1 \) – \( D_5 \) are constants found out experimentally. The effect of stress is covered by the first term, where the effect of strain rate is covered by the second term. As the strain rate increases, the material will tend to fracture. Effect of temperature is covered by the third term. When the value of the parameter \( D \) exceeds 1 or when the strain in the material exceeds the fracture strain, fracture occurs. For this instance \( D_1 \) will be set to 10000 and \( D_2 \) – \( D_5 \) will be set to zero. The reason for this is we are not concerned about fracture in this particular application [12].

\[ D = \frac{\varepsilon_p}{\varepsilon_f} \]

(3.20)

\[ \sigma^* = \frac{P}{\sigma_{eff}} \]

(3.21)

The values used for IN 718 SPF can be seen below:

| Table 8: IN 718 SPF Parameters for Johnson Cook Model |
|------|------|------|------|------|
| A    | B    | C    | m    | n    |
| 1241 MPa | 622 MPa | .035 | 1.27 | .5  |
3.1.5 Static Load Displacement of Tungsten Carbide Bead

The UNSM Tungsten Carbide (WC) bead works as a cold forging process, where a static load is placed on the tool and is dragged across the material, with a dynamic ultrasonic load added on to it. In this case there is a 70N static load on the UNSM WC bead. Since the UNSM model is simulated in LS-PREPOST based on contact analysis, the 70N load is determined by how much force the rigid ball creates when displacing into the block. This is done by running a separate simulation with a single contact analysis. In this analysis, the rigid ball is displaced .002 mm into the block (Z-direction). During the simulation, the Nodal_Force_Group card is used on the bottom of the block to output Newton force on the nodes every .00001 seconds. Each output gives the total forces of all the bottom nodes at that state number, which will also tell us how much the rigid ball has displaced. Figure 38 shows the stress levels of the single contact analysis at a state where the total nodal forces on the bottom of the block is equal to approximately 70N. At this state, the displacement of the rigid ball is -.012 mm, and since the original position of the rigid ball is .01mm away from the surface of the block, it moves .002mm into the material.
The main instrument in the UNSM process is the Tungsten Carbide (WC) bead that moves across the surface of the material, creating the nano crystal microstructure, deep compressive residual stresses and increasing fatigue life. As described in chapter 1, the ultrasonic vibration can be described as a static load with a dynamic component added on to it (equation 1.1). Several parameters can be changed to vary the results of the UNSM process which includes total striking force, feed (S), ball radius (r), amplitude of dynamic load (P), and speed (V (m/min)). MATLAB is used to create a program that outputs the Define_Curve cards for the movement of the rigid ball in the x, y and z directions. Figure 41 illustrates the movement on the surface of the material. The code takes in four values. The first is feed speed (mm/s) which is the speed of the rigid ball moving across the surface of the material, and a value
of 50 is used for simulation. The second is static load, where we use 70 Newtons for this case. The third input is amplitude of dynamic load. A sine wave can be used to describe the dynamic load, and the amplitude is the displacement from the zero position to the peak of the wave. For simulation, the used amplitude is .015 mm. Finally, the last input is ultrasonic frequency (Hz) of which we use 20000Hz for simulation. The higher the frequency, the faster the rigid ball will vibrate.

Figures 39, 40 and 41 show the resulting plots of the MATLAB code with the described inputs. The displacement of the ball in the x, y and z directions are plotted against time. As discussed previously, the code generates the displacements of the rigid ball based on a small patch of three .25 mm lines which is shown in the X-displacement plot.

![UNSM WC bead X-displacement](image)

**Figure 39: X-displacement of UNSM bead**
Figure 40: Y-displacement of UNSM bead

Figure 41: Z-displacement of UNSM bead
In the X and Z direction plots, the rigid ball stops moving for a split second to allow time for movement in the Y-Direction in order to start a new UNSM line. Looking at Figure 39 of the Y-Displacement the time only goes to .016 seconds, yet the amount of periods of sine waves makes it hard to see. Figure 42 below zooms into a portion of the graph. At displacement of -.01mm the rigid ball makes contact with the block, and then the displacement goes to .002mm into the material before commencing vibration. We can clearly see the .015mm amplitude, as well as the large number of sine waves in only .0006 seconds. Figure 43 illustrates the complete movement of the ball in the X and Y directions on the specimen surface.

Figure 42: Closer view of Z-Displacement UNSM Bead
CHAPTER 4 – SIMULATION RESULTS

4.1 Ti64 Simulation Results

The LS-PREPOST .k file of the rigid ball and umat block with the three Define_Curve cards simulating the UNSM process was run in LS-DYNA using the umat41 material model subroutine for Ti64. LS-DYNA outputs d3plot files which are then used for post-processing in LS-PREPOST. This procedure was done in two different cases with the sides of the block constrained in the normal direction, and no BC’s where the sides of the block had no constraints. The element stress results for the final state of the UNSM patch through the thickness of the umat block in the X and Z directions were averaged and plotted against the experimental Ti64 results. Figure 44 shows the area of where residual stress is being evaluated:
Figures 46 and 47 show resulting residual stress plots for Ti64 compared with experimental results. This shows stress vs. depth into the material. To obtain the residual stress profile, the in-plane stresses were averaged over each layer of elements through the thickness. This average is then plotted as a function of the thickness of the coupon. Figure 45 shows the sample cut in half. As the depth increases, the compressive residual stresses near the surface can be clearly identified.
Figure 45: Ti64 Simulation Result – Depth Profile View

Figure 46: Ti64 Experimental vs. Simulation results with Boundary Conditions
Figure 47: Ti64 Experimental vs. Simulation results with no Boundary Conditions

From the figures we can see that a large spike exists at the surface of the block, and the curve doesn't match the experimental results exactly. This could be because the block size is very small, and the element size is not fine enough. The experimental residual stresses are captured by measuring a 2mm x 2mm treated area. The simulation only covers .25mm x .14 mm of the surface.

Another reason stress spikes are being observed in the material block is because of oscillations. When the specimen is subjected to hundreds of contacts, it is creating stress waves that reflect off the sides of the block. This can be mitigated by:

- Increasing the sample size (2.5 mm x 2.5 mm)
- Adding non-reflecting boundaries on the sides of the block to simulate an infinite plane (symmetry cell)
- Refining the mesh near the surface
- Adding global damping
- Adding dynamic relaxation

The effects of sample size and residual stress on overlapping LSP treatment have been studied earlier. The use of non-reflecting boundaries and increased sample size allowed stress waves to propagate through the boundary without reflection [3]. It is found that the compressive residual stresses increase as the sample size increases. Looking at Figure 48, we can see how increasing the sample size also decreases the stress spikes.

![In-Depth Stress Profiles, 2mm Diameter spot, 7GW 23ns](image)

Figure 48: Stress distributions for sample size study [3]

Figure 49 shows the new mesh refinement with all applied cards mentioned previously, with the surface treatment the same as before. After running the simulation, Figure 50 shows the extracted residual stresses compared to the experimental results.
Figure 49: Refined mesh for the simulation of UNSM process
From the results, we can see that the stress spikes have been reduced, and the data matches the experimental results more closely. Again the curves aren’t exactly matching, and this is because of the small treatment area in the simulation. The data used for the experimental comparison could also contain errors. The X-Ray Diffraction method used to read residual stresses on the specimen uses the lattice planes in the material. Because of the nano sized grains, these measurements are very difficult to obtain.
4.2 Inconel 718 SPF Simulation Results

To obtain residual stresses from LS-DYNA for UNSM treatment for IN 718 SPF, the refined mesh simulation is used. The boundary conditions for this case again use non-reflecting boundaries on the sides of the block, with the bottom constrained in all directions, along with the same cards used on the Ti64 simulation. The only difference is the material model, which is the Johnson Cook model. The material parameters for this specific case can be seen in section 3.1.4. To get an idea of what the depth profile looks like inside the specimen, a cross section was observed in Figure 51. The treated area can clearly be seen where compressive stresses occur. Figures 52 and 53 show the resulting depth profile plot vs. the experimental results of both Inconel samples. The results for IN718 SPF using Johnson-Cook material model matched the experimental results very well.

![Figure 51: IN 718 SPF Simulation Result – Depth Profile view](image-url)
Figure 52: IN 718 SPF Simulation Results vs. Sample 1 Experimental Results

Figure 53: IN 718 SPF Simulation Results vs. Sample 2 Experimental Results
A beneficial aspect of using simulation is certain variables can be changed in the UNSM process, such as the amplitude, and the results can be compared to observe the effects. Two additional simulations were run varying the amplitude of vibration on the UNSM carbide ball. Figure 54 shows the residual stress results of the Johnson Cook model with a UNSM amplitude of 7 microns, where Figure 55 shows the results using amplitude of only 2 microns.

Figure 54: Johnson Cook Simulation Results using an Amplitude of 7 Microns
Figure 55: Johnson Cook Simulation Results using an Amplitude of 2 Microns

Figure 56: Comparison of Johnson Cook Model Simulation Varying Amplitude
From Figure 56, we can see the different results from UNSM when the amplitude is changed. Although the differences aren’t significant, it can be clearly seen that the residual stress decreases at a quicker rate vs. depth at a smaller amplitude.

CHAPTER 5 - Conclusions and Future Work

To summarize, in this thesis a method of simulating the UNSM process using contact analysis in LS-DYNA has been developed. The specific efforts made in this thesis include:

- Hardness testing was done using micro and nano-indentation. It is found that the hardness increases on the surface when treated with UNSM, and the hardness decreases with increasing depth.
- Residual stress measurements with X-Ray Diffraction techniques based on treated IN 718 SPF and Ti64 samples treated by UNSM were used to compare with simulation results. It was found that the experimental results matched simulation results very closely, however a larger scale simulation should be performed for more accurate results.
- Microscopy and EBSD inspections performed on the UNSM treated samples. This helped visualize the effect UNSM has on grain size, and this observation can be connected to residual stress measurements.
- A Matlab code was developed to define the movement of the UNSM bead during treatment. This was used to simulate the UNSM treatment in LS-DYNA. After running
the simulation, it was realized this explicit method caused the run time to be very long, however produced useful results.

- The contact algorithm contained in the commercial LS-DYNA software defined the surface to surface contact of the specimen and UNSM bead. Here there are many options that can be used to increase accuracy.

- Defined parameters in simulation file and mesh refinement for accurate residual stress results. Used a user defined material model, the modified Zerilli-Armstrong model, for Ti64 material, and Johnson-Cook model for IN718 SPF.

The residual stress results from the simulation match well with the experimental residual stress depth profile. Increasing sample size and adding parameters such as non-reflection boundary conditions eliminated stress spikes due to oscillations from contact analysis.

Several issues are still present in the current simulation set up. The computation time taken for simulating the UNSM process is very long. This is mainly due to an explicit solution with contact analysis. To achieve even more accurate results, the elements contained in the mesh must be on a nano-sized scale. The sample size also must be increased to account for a larger treatment area. Due to time constraint, and long computation times, these goals have yet to be achieved.

Based on the work presented in this thesis, the following is suggested for future work to continue this effort:

- The use of a more powerful computer system can allow a larger simulation with reduced computation time.
Another way of possibly reducing simulation time is using displacement instead of contact. This method also requires a fine mesh to identify the center of each spherical hit of the UNSM bead, however would eliminate having to use a contact part. Displacement analysis can also have benefits in reducing oscillations in the material since there is no impact between segments.
References


