The Pennsylvania State University
The Graduate School
Engineering Science and Mechanics Department

OPTIMIZATION OF HIGH SPEED WIRE DRAWING USING FINITE ELEMENT ANALYSIS

A Thesis in
Engineering Mechanics
by
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Submitted in Partial Fulfillment of the Requirements for the Degree of

Master of Science

December 2008
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ABSTRACT

The process of pulling a wire through a series of conical shaped dies which incrementally reduces its cross sectional area is known as wire drawing. These wire drawing dies are subjected to extremely high stresses while at the same time expected to survive long service lifetimes. Finite element modeling is used to model the interactions of these materials throughout the wire drawing process. These models show that during the drawing process the wire at the exit of the die can reach local stresses of roughly 150% of its yield strength. The required drawing force and die stress are monitored at many different drawing conditions. As the drawing speed of the wire is increased there must also be an increase in die approach angle in order to maintain a minimal stress state.

The bearing length and reduction ratio of the die must be optimized for different hardening exponents. Brittle materials with low hardening exponents contain strain gradients throughout the thickness of the wire which results in tensile stresses in the outer edges of the wire and compressive stresses near the center. Materials with higher hardening exponents contain less significant strain gradients but exhibit more elastic rebounding after drawing. Optimized die geometries are specific to a desired application and understanding the relationship between the die geometry and the resultant stress states allows improvements on existing drawing techniques as well as the possibility for drawing new materials.
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ACKNOWLEDGEMENTS

I would like to thank Dr. Smid for all of his help throughout my graduate work and also Dr. John Keane and Allomet Corporation for financial support. I would also like to thank the Engineering Science and Mechanics Department at Penn State as well as the Center for Innovative Sintered Products. Lastly, I would like to thank Dr. Heaney, Kristina Cowan, Erik Bryne, Craig Shaffer, Eric Gift, Minna Ranjeva, Anthony Kmetz and Paul Sauter for their help with experiments and other work around the lab.
Chapter 1

Introduction

The first hard metals were patented in 1923 and were comprised of tungsten carbide and cobalt [1]. These early materials were primarily marketed for wire drawing dies and other high-wear applications. In the past three quarters of a century many improvements have been made, but the basic principle remains the same [2-3]. Most of these changes can be attributed to the decreasing powder particle size and complying with stricter quality control standards. The microstructure of Tough Coated Hard Particles (TCHP) is unique in that it is comprised of hard “core” particles surrounded by a tough tungsten carbide cobalt shell. By combining $\text{Al}_2\text{O}_3$, WC, and Co in this way, a new composite material is produced which has an extremely high wear resistance and still maintains a high toughness [4].

Wire drawing is the process in which a wire is pulled through a series of dies in order to reduce its cross sectional area. TCHP is an impressive candidate for wire drawing due to its inherent wear resistance; as its surface wears, new wear resistant material resurfaces. At the exit region of the die, the stress in the wire exceeds its yield strength and local plastic deformation takes place. When the wire is pulled through a die, small dislocations in the wire are shifted and the material is work hardened. Wires, such as those used in radial car tires, are pulled through a series of eight to fifteen dies. Many factors such as the hardening exponent of the wire material and drawing speed become important in maintaining control in the plastic region. If either factor produces excessive
stress, then uncontrolled deformation can occur in the wire. This uncontrolled deformation can result in wire breakage or an elongated wire that does not meet final dimensional tolerances.

The die itself is another factor influencing success throughout wire drawing. Die longevity is crucial in industrial applications because of the costs related to die failure. Die wear and fracture are common modes of failure. Certain parameters such as the approach angle, reduction ratio and bearing length influence the amount of stress acting on the die face and corresponding to the amount of die wear. It is important to consider both the die and the wire when simulating the wire drawing process. Since the optimal drawing apparatus will vary depending on the application it is important to understand the relationships all of these parameters have with one another so that the necessary corrections can be made. To date there have been only limited finite element simulations of this process due to its computationally demanding nature [5].
Chapter 2

Background

2.1 Wire Drawing

The earliest formal documentation of wire drawing began in the 12th century by a German monk by the name of Theophilus. His description of the process was, “Two iron [plates] three fingers wide, narrow at the top and bottom; thin throughout and pierced with three or four rows of holes [of diminishing size] through which wires may be drawn”[6]. Although this was the first formal procedure for the drawing of metal wire the process had been done for thousands of years before in the making of jewelry. As the range of materials being drawn began to expand it was necessary to move from hardwood drawing plates to something with an increased hardness [6]. Today the most common drawing die materials are comprised of tungsten carbide (WC), tantalum carbide (TaC) and several other carbides mixed with a ductile binder which is commonly cobalt (Co) or nickel (Ni). These materials generally have a high hardness and resistance to wear which is required under their extreme loading conditions.

Carbides have been in use since the early 1920’s when they were designed to replace costly diamond dies used in drawing tungsten incandescent filament wire for light bulbs [7]. Tungsten carbide has since become the most widely used carbide in cutting and wear applications. This is due in part to its ability to be alloyed, not only with cobalt and other ductile binders, but with other carbides. The type and amount of the alloy
depends on the specific application. In the case of high stress and high wear applications pure WC-Co is used, however depending on which property is more important the level of Co addition can be varied to produce either a higher hardness and wear resistance or higher strength. When thermal properties are important an addition of TiC or TaC can increase the material’s resistance to thermal deformations or cratering along with maintaining its material properties at high temperature [7].

<table>
<thead>
<tr>
<th>Carbide</th>
<th>Crystal Structure</th>
<th>Melting Point (°C)</th>
<th>Hardness HV (50 kg)</th>
<th>Modulus of Elasticity (GPa)</th>
<th>Coefficient of Thermal Expansion (m/m•K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiC</td>
<td>Cubic</td>
<td>3100</td>
<td>3000</td>
<td>451</td>
<td>7.7</td>
</tr>
<tr>
<td>VC</td>
<td>Cubic</td>
<td>2700</td>
<td>2900</td>
<td>422</td>
<td>7.2</td>
</tr>
<tr>
<td>Cr3C2</td>
<td>Orthorhombic</td>
<td>1800</td>
<td>1400</td>
<td>373</td>
<td>10.3</td>
</tr>
<tr>
<td>WC</td>
<td>Hexagonal</td>
<td>2800</td>
<td>2200</td>
<td>696</td>
<td>5.2</td>
</tr>
<tr>
<td>TaC</td>
<td>Cubic</td>
<td>3800</td>
<td>1800</td>
<td>285</td>
<td>6.3</td>
</tr>
</tbody>
</table>

When compared to other carbides it can be seen that WC does not have the highest hardness, however it has a lower coefficient of thermal expansion and the higher modulus of elasticity. Another property which sets WC away from the rest is its high resistance to fracture. This resistance comes from the cobalt binder work hardening itself as the applied load exceeds its yielding strength.

The current popularity of WC-Co is due to the diverse applications that it can be tailored to. Today it is used in cutting tools, mining and metal forming just to name a few. For each of these applications the grain size of the WC can be varied in order to
increase or decrease hardness, toughness, wear resistance, thermal properties, etc. For wire drawing the current standard is fine grain WC with a 6% Co addition. This composition provides a high wear resistance while at the same time giving the material the ability to resist impacting that occurs during drawing.

Figure 2-1: Wire Drawing Diagram

Wire drawing is the process of drawing a wire through a series of conical dies and in so reducing the diameter of the wire as seen in Fig 2-1. The drawing die consists of four different stages. The first is an entrance angle which is usually has no direct contact with the wire unless uncontrolled oscillations or fracture in the wire occur. The second is the approach angle which ranges from 10° to 15° and is where most of the interaction between the wire and the die initially occurs. After the wire is pulled through the approach angle it moves into the bearing channel where no further reduction occurs. This
section is used to form the wire to a uniform diameter. The approach angle and bearing channel undergo the highest stresses and the most wear. The last is the back relief angle which is usually between 60° and 90°. In most cases the die is thermally fit into a steel casing which is customized to fit a desired drawing machine.

A steel wire for example may be reduced in diameter by up to 95% throughout a series of 8-15 dies. In each one of these dies a diameter reduction of between 10-30% can take place.

---

**Figure 2-2: Wire Drawing Process**

As the wire is pulled through these dies it undergoes plastic deformation. In this application the plastic deformation is known as work hardening, wherein dislocations in the wire are shifted in order to increase its material properties. The yield strength of the
wire is the most common measurement used to track the material properties throughout the stages of this process.

The most common drawn material is 0.6% carbon steel for radial car tires. Over 12 million miles of steel wire are drawn each day in order to produce 300,000 radial car tires [8]. Other popular applications are the drawing of superconducting wires, tungsten filaments, copper and niobium wire, and steel wire for construction.

2.2 Finite Element Analysis

Since its creation, mathematics has been used to describe the physical world that surrounds us. Early mathematicians such as Isaac Newton and Claude-Louis Navier related mathematics to natural phenomenon of the earth. The finite element method was developed as a way to apply these theorems to complex situations, which without simplification would be impossible to solve analytically.

The earliest developments of finite element analysis can be credited to Alexander Hrennikoff and Richard Courant, both in the early 1940’s. Although these two men worked independently they shared one key factor in their work. This was mesh discretization of a continuous domain which today is known as elements [9]. Courant’s approach, which was found to be more universal since it was based on earlier work done by Rayleigh, Ritz and Galerkin on partial differential equations, was based on dividing a surface into triangular elements for a solution of second order elliptic partial differential equations that arise from the problem of torsion of a cylinder [9].
Commercial development of finite element analysis for civil and aircraft industries began in the late 1950’s at the NASA Langley Research Institute. Computer Sciences Corporation was contracted by NASA to develop the first generic finite element software program. Since its creation there has been constant exponential growth due hand in hand to an increase in computational ability and increased understanding of the systems being analyzed. The first text book popularizing FEM was published in 1957 and contained 270 pages. The current edition of this same book is now split into two volumes with a total of 1400 pages [10].

The construction of the geometry of a model and the positioning of its nodes play a significant part in the accuracy of the system being analyzed. The size, shape and orientation of the discretization must coincide with both the structure of the model as well as the information being drawn from the analysis. These discretized elements are bounded by nodes as their corners. Mid-nodes as shown in Fig. 2-3 can be used in some cases to improve accuracy between nodes by simulating quadratic relationships in the areas separating nodes.
Many techniques inside of the topic of finite elements analysis are available to solve problems such as this. The solving technique depends on the desired data being extracted from the problem. For example, if a simple static structural analysis of a system is performed the required inputs would include material properties, motion constraints and applied loads. This information can then be converted into a force matrix and a global stiffness matrix shown in Eqn. 2-1. From this the displacements functions at each one of these nodes can be found and used along with the material properties of the structure to determine the stress-strain state inside of the system.

\[
\begin{bmatrix}
k_1 & \cdots & k_i \\
\vdots & \ddots & \vdots \\
k_j & \cdots & k_{ij}
\end{bmatrix}
\begin{bmatrix}
u_1 \\
\vdots \\
u_n
\end{bmatrix}
= 
\begin{bmatrix}
F_1 \\
\vdots \\
F_n
\end{bmatrix}
\]

Equation 2-1.

**Figure 2-3:** Quadrilateral Mesh Discretization Containing Mid-nodes
2.3 Yielding and Strain Hardening

When materials undergo small loads with respect to their maximum yield strength the relationship between the applied stress and strain is linear. If the applied stress is removed from the material it can return to its original size and shape. When the applied stress exceeds the yield strength this linear relationship is lost and permanent deformation in the structure occurs. In materials such as steels there is a region after yielding where the material is actually hardened with increasing stress and therefore increasing its strength. This process known as strain hardening continues until a critical ultimate stress is reached [11]. At this point strain hardening no longer occurs and the material's ability to support the stress is lost.

Tensile testing is the most common example of this type of deformation. As the load on the sample increases stress concentrations occur at the region of the sample with the smallest cross sectional area (assuming no defects or sharp edges). When these localized stresses exceed the yield strength, permanent deformations begin to occur and elongation takes place in the sample. Although these deformations are taking place the sample is still able to withstand stress increases until the ultimate load is reached and fracture occurs. This process is called necking and can be seen if Fig. 2-4 as the non-linear region of the stress-strain curve.
Figure 2-4: Stress-Stain Diagram for Ductile Materials [Hibbeler]

Figure 2-5: Simulation of Tensile Test Sample Necking [SRI]
This phenomenon of strain hardening can be traced back to an atomic level. Dislocations in the form of point imperfections, line imperfections, planar imperfections and bulk imperfections can be found in any material. These material imperfections can be thought of as voids in the lattice structure both on a small scale of a single missing atom and on a larger scale of a three dimensional void in the microstructure of the material. When a load is applied to a material shear stresses build up and entire atomic planes are shifted relative to one another. “When these dislocations move, they are encountered by other dislocations intersecting the slip plane as well as by other imperfections such as impurity atoms, twin boundaries, grain boundaries and particles of secondary phases with which they interact” [12]. By these dislocations having the ability to shift within the material it avoids brittle fracture and allows deformation to occur. Eventually, when many of these dislocations have moved to a grain boundary the stress at these boundaries becomes too great and fracture begins to occur.

Knowledge of these dislocations and what factors cause them to shift can be used to tailor material properties, such is the case with wire drawing. Prior to being pulled, a steel wire may contain many small dislocations throughout its volume. As the wire is pulled through the drawing die these dislocations shift and in doing so increases the hardness and also the yielding strength of the wire. All of this comes at a loss of ductility in the material. Therefore, by varying the amount of reduction at each pass and the number of passes, the steel wire can be tailored to the required material properties for its application.
Figure 2-6: Atomic Line Dislocations [Callister]
Chapter 3

Tough Coated Hard Particles

3.1 Introduction

TCHP is part of a family of sintered composite pseudoalloys that can combine hardness approaching that of diamond with fracture toughness greater than tungsten carbide, and weight approximately that of titanium [2-5]. The material structure is comprised of a refractory hard core particle which is coated with WC and Co using chemical vapor deposition (CVD). These produced particles can be looked at as a spherical particle roughly 1-2\( \mu \)m encapsulated by a WC-Co shell. When these particles are combined during hot-pressing a homogeneous cellular structure is formed throughout the material which can be seen in Fig. 3-1.

The combination of these hard core particles and the WC-Co shells produce a material which can essentially “self-heal” itself as wear progresses. Most WC-Co machining tools are simply coated at the outer surface with micron thick layers of wear resistance materials to increase the usable lifetime of the part. In the case of TCHP however, each wear resistant particle consists of this “coating”. This allows for the wear resistance of a material to be constant throughout the entire part, bringing the usable lifetime all the way to its geometrical limits.
3.2 Powder Fabrication and Sintering

The production of TCHP powder begins with 2-3µm spherical Al₂O₃ particles. These particles are then coated with a thin layer of WC using chemical vapor deposition. This process takes a gaseous tungsten precursor and which is heated to decompose and deposit WC on the Al₂O₃ particles and a film is deposited on the surface. The last step in the production of TCHP powder is to again place the particles in a CVD furnace and deposit a thin coating of cobalt. This exterior layer of cobalt is prone to oxidation and for that reason all TCHP powders are stored under argon or another inert gas.
3.3 Material Characterization

The hardmetal industry in general has well established standard characterization practices. Unfortunately, since TCHP is a particulate reinforced hardmetal it cannot always undergo the same means of testing as conventional hardmetals. For this reason it is hard to quantify the hardness and microstructural uniformity of a given sample. Also, identifying and describing possible defects in the material become more complex since there is now an internal interaction in the WC-Co matrix but also a surface interaction between this matrix and the core particles. Although these pose new challenges, consistent data was obtained and used to monitor process improvement and to compare with current products.

3.3.1 Particle Size Analysis

Particle size analyses were performed using a Horiba LA-920 Laser Scattering Particle Size Distribution Analyzer which carries a sensitivity of 0.6% for NIST-traceable standard particles. Laser scattering particle size analysis uses a powdered sample dispersed in a dispersion media. A representative cloud or ‘ensemble’ of particles contained in this solution passes through a broadened beam of laser light which scatters the incident light onto a Fourier lens [14]. This light is then focused on to a detector array which can be transformed in a particle size distribution. To ensure consistency, a dispersant of isopropanol was used to sufficiently disperse the TCHP solution.

The particle size distribution in most TCHP samples is fairly consistent with a smooth “bell” slope and only a small presence of spiking. As seen in Fig. 3-2, the
distribution spectra are consistent for all three analyses. In some cases the appearance of ultra-fines produces a spike in the distribution in the region under 1µm. The addition of these ultra-fines has been found to increase the materials performance in flexural testing. This particular lot of TCHP has an average particle size of 2.882µm. Also, 90% of the particles in the spectra are under the size of 5.331µm. One of the most useful features seen in these spectra is the identification of agglomerated particles, although not present in Fig. 3-2, these particles would be represented by small spikes 10 µm region. Despite the scarcity of these particles they play a large role in the overall performance of the material. These agglomerated particles are generally in the range of 5µm to 20µm and composed of carbon and agglomerated alumina particles. A more detailed examination of these particles can be seen later under SEM Characterization.
3.3.2 Vickers Micro-hardness

A Leco hardness testing machine along with an Akashi video line micrometer was used to determine Vickers Micro-hardness. In this test a Vickers Diamond Pyramid indenter is used under a force of 1kg. This Vickers Diamond Pyramid indenter is cut down from a cube and has 136° between faces as seen in Fig. 3-3.
Vickers Micro-hardness testing has become the standard means of hardness testing on TCHP materials. This method has proven to be the most appealing due to its minimal cost and rapid turnaround rate. The downside of using this technique on TCHP is that it does not contain a homogeneous microstructure. The microstructure, as can be seen in the SEM imagery, is composed of a matrix of alumina particles surrounded by WC and Co. Due to this there can be large variations in hardness values depending on the placement of the indenter. As a means to counteract this effect, hardness measurements are taken at five locations throughout the surface of the material and then averaged.

Hardness measurements of TCHP vary mainly due to two factors; carbon content and sintering conditions. If the material is heated to an excessive temperature or for an
extended period of time the resulting hardness will generally be decreased. Also, if the powder is carbon deficient then the $\text{WC}_{1-x}$ is not able to transform fully to WC therefore reducing the hardness of the material. In contrast, if the powder contains excess carbon it can hinder the bonds between the core particles and the WC matrix. A relationship between carbon content, rupture strength and hardness can be seen in Fig. 3-4.

---

**Carbide Properties vs. W-Carbon Balance**

*Bernhard*

**Figure 3-4:** Effects of Carbon Addition on Mechanical Properties [Bernhard]
3.3.3 Transverse Rupture Strength

Three point bending tests were conducted using an MTS Qtest 100 Elite tensile testing machine. All specimens were prepared using electrical discharge machining to final dimensions of 7mm by 7mm and a length of at least 1 inch. These tests were conducted using a vertical ram speed of 1.2 mm/min until failure. The results recorded on this machine have been verified with results from a separate tensile machine and those results were comparable.

Due to the fact that hot pressed TCHP samples are small in size and expensive to produce, transverse rupture strength testing has become the standard for flexural testing. These tests allow for a smaller sample size and simplified machining. Many factors affect the performance of TCHP in these flexural tests. The most prominent of these are the presence of microstructural defects and particle agglomerations. A direct correlation can be made between the microstructural analysis of these materials and the flexural testing. This relationship shows that these small inconsistencies play an enormous role in the overall performance of the material. The general range of TRS values for a TCHP sample is around 1400MPa.

3.3.4 Scanning Electron Microscopy

SEM characterization was performed using a Philips XL30 ESEM scanning electron microscope capable of EDS x-ray analysis through EDAX. This machine is capable of imaging in secondary electron as well as backscatter electron modes with x-ray voltages ranging from 5 to 40kV. For the imaging provided in this paper a voltage of
15kV was used. The EDAX measurements of surface composition were collected using Genesis analysis software. This software has the capability to produce qualitative spectra as well as quantitative analysis of those spectra. In the case of TCHP a focus is put on the main elements present such as Al$_2$O$_3$, C, Co and W.

SEM analysis is the most essential tool for characterizing the microstructure of TCHP. The following section contains analyses of flat polished surfaces as well as fracture surfaces. All flat surfaces have been prepared by polishing on diamond wheels. The roughness of these wheels starts at 20µm and finishes at $1/4$µm. These surfaces are cleaned with acetone prior to analysis. Fracture surfaces shown are from transverse rupture strength testing. These fracture surfaces are not cleaned with acetone prior to analysis.

A typical TCHP microstructure at a magnification of 5000x can be seen in Fig. 3-5. The darker regions represent Al$_2$O$_3$ particles which are roughly 2µm in size and spherical. These particles are distributed uniformly throughout the microstructure with minimal particle to particle contact. These points of particle to particle contact produce high stresses when the material undergoes compressive forces. The lightest regions of Fig. 3-5 represent the WC matrix. The grain size of these WC particles are much smaller than the Al$_2$O$_3$ particles. Lastly, the light grey regions of Fig. 3-5 represent the Co
binder. These cobalt regions are spread uniformly throughout the material and act as crack diffusers.

Prior to any heat treatment, these Al₂O₃ particles are completely coated with a layer of WC-Co. Once these particles are pressed into a green state they are sintered to obtain the microstructure shown in Fig. 3-5. As the material is sintered, these external WC-Co coatings bond together in order to produce a WC-Co matrix surrounding the Al₂O₃ particles. This is the reason for the dense region of WC seen around the edges of many of the Al₂O₃ particles.
As cracks propagate through the TCHP microstructure the Al$_2$O$_3$ particles act as crack arrestors by blunting crack growth. When a crack approaches one of these particles it is forced to move through the particle. This effect continues to occur as a crack growth increases. The results is an overall decrease in the crack growth rate.

**Figure 3-6:** Fracture Surface of TCHP at 5000x
Chapter 4

Finite Element Analysis

4.1 Introduction

In practice today, finite element analysis is one of the most common techniques for studying stresses, deformations and vibrations due to structural or thermal loading. Wire drawing is a unique application of this process due to the fact that it contains high strain rates, permanent deformations, and thermal variations in the wire, and therefore requires a transient solution. To make the analysis more complicated, TCHP wire dies are not a uniform material containing homogeneous material properties; it contains a micron scale matrix of Al$_2$O$_3$, WC and Co. The computational requirements for implementing all of these factors into a finite element analysis would be immense, therefore certain key parameters have been chosen to include in the analysis and others have been ignored. These excluded parameters are the thermal variations and the discontinuity of the TCHP material properties. Although these factors do play a role in the overall result of the model they were chosen because their influence is minimal in comparison to the others. Since an understanding of the influence of applied stress on the TCHP matrix is still needed, even if not included in the overall analysis, a separate finite element analysis has been performed on a micron-scale level. In order to accurately model the behavior of TCHP under these complex loading conditions found in wire drawing, ANSYS 11.1 finite element modeling software is used [11].
4.2 Micro-scale Modeling Procedure

4.2.1 Assumptions

- The bond strength between all materials is infinite. Only small applied loads are analyzed to minimize the effects of this.
- Although some aspects of this model are on the scale of 50 to 100nm a continuum model is used since under small applied loads the diffusion effects play a small role.

4.2.2 Model Formulation

Due to TCHP’s composite composition, a particulate model of a TCHP is simulated. A cross section of a sphere is placed inside several spherical shells in order to model the encapsulated Al₂O₃ core particles inside of the WC-Co matrix. The composition and thicknesses of these layers are shown in Fig. 4-1. The binder shell is made up of pure Co with a small thickness of roughly 200nm. The transition layer is comprised of an even weight percent mixture of Co and WC and has a thickness of 300nm. This layer provides a more uniform stress distribution by removing the abrupt interface of pure Co and WC. All of these structures are then placed inside a matrix of WC containing 6wt% Co. When combined, these elements represent the fully sintered TCHP structure. Mesh sizes vary between layers depending on thicknesses. The interfaces between these layers are assumed to be in complete contact throughout the simulation.
4.3 Wire Drawing Modeling Procedure

4.3.1 Assumptions

- Material Properties are elastic for both the die and wire materials. Material properties for TCHP have been generalized to model the wire die as a continuum material.
- The outer edge and bottom of the wire die as well as the cross section of the wire are assumed to be rigid and do not displace under loading.
- Loading above the yield strength of the steel wire is modeled using a bilinear kinematic response.
Although the wire is modeled using a bilinear kinematic, the wire die is modeled as an elastic material. This simplification is made since peak stresses during drawing are below 70% of the yield strength of the TCHP wire die.

4.3.2 Model Formulation

The geometry of the wire drawing model is set up in such a way that the height and width of the wire die are a constant size, but the approach angle and bearing length can be modified. The length of the wire being drawn is also a fixed size, however the initial and final diameters can be modified. This allows a large range of diversity in simulations such as the ability to model each pass of a wire drawing apparatus from start to finish. The material properties of the die are assigned as homogenous and elastic, and can be varied to fit any material which falls into those specifications. The material properties of the wire are assigned as non-linear and are able to account for stress above the yielding point of the material. This relationship is defined by a bilinear-kinematic stress strain curve as seen in Fig. 4-2. The elastic modulus of the curve defines the relationship between stress and strain when the stresses are below the yielding point. After this yielding point is exceeded the tangent modulus defines the relationship. This is an idealistic approximation since for any ‘real’ material there would be some polynomial function describing the relationship between stress and strain after yielding begins.
The FE model uses Plane183 2-D triangular elements containing mid-nodes. Mid-nodes allow for a quadratic response in displacement between the two defining nodes. The element size increases with increasing distance from the die-wire interface, as seen in Fig. 4-3. A fine mesh is present at the die-wire interface to prevent problematic stress irregularities and nodal penetration that can arise from too few contact nodes. The size of this fine mesh was determined through trial and error based on the presence of uniform stress distributions surrounding the interface as well as time required to perform the calculation. The optimal mesh edge length size was found to be roughly 10% of the diameter of the wire being drawn. The total number of elements in this model varies with geometry between 2500 and 2800 with 5000 to 5600 total degrees of freedom.

Figure 4-2: Bilinear-Kinematic Material Properties for Wire

<table>
<thead>
<tr>
<th>$\varepsilon$ (mm/mm)</th>
<th>$\sigma$ (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope 1: Elastic Modulus</td>
<td>186 GPa</td>
</tr>
<tr>
<td>Slope 2: Tangent Modulus</td>
<td>25 GPa</td>
</tr>
</tbody>
</table>
Figure 4-3: Geometry of Wire Drawing Model
Contact surfaces were assigned on all inner faces of the wire die as well as all exposed faces of the wire as shown in Fig. 4-4. These surface contact elements are created at the defined lines by overlaying new contact elements on the existing elements at the contact surface. The die is defined as the target surface using Targe169 elements. The target surface is generally the larger of the two surfaces and it is stationary. The wire is defined as the contact surface using Conta172 elements. The contact between these two surfaces is calculated at the edge nodes perpendicular to the target surface (die) as shown in Fig. 4-5. Although there is a small radius on the die at the interface between approach angle and the bearing channel there should not be overlapping at this point. If there is a large amount of overlapping then the deformation in the wire is more gradual and the strain rate is not an accurate representation of real world wire drawing.
Displacement boundary conditions were placed on the left face of the die constraining it in the x-direction and on the bottom face constraining it in the y-direction. These two conditions simulate the die being shrink fit into a larger steel casing where no slipping is assumed. Since this analysis is only one half of a two dimensional analysis it will be mirrored about the y-z axis. Therefore, a displacement boundary condition was placed on the right face of the wire constraining it in the x-direction. As the wire is pulled through the die this condition prevents all deformation in the x-direction from crossing into the right half, or in the case of extremely high drawing stresses, deformation in the die. Lastly, a displacement boundary condition was placed on the bottom face of the wire setting a negative displacement of 5mm in the y-direction. This displacement moves roughly 25% of the wire through the exit of the die.

Figure 4-5: Interface of Conta172 and Targe169
This model was performed using a transient analysis and an augmented Lagrange solver. In order to accurately calculate the large plastic deformations of the wire 1000 substeps were used to model 25% of the wire being drawn. Also, since a permanent deformation of 8-20% is seen in the wire it is necessary to activate the large deformation key option. Lastly, due to large plastic deformations in the wire and its non-linear material properties, it is necessary to use stabilized finite elements. A constant energy dissipation value of 0.1 is used. Since the potential energy in the system is much greater than this ratio, its effects are minimal [16].
Chapter 5

Results and Discussion

5.1 Microscale Modeling Results

For a small case such as the 10µm by 10µm block shown in Fig. 5-1 a two dimensional analysis is possible as well as a three dimensional analysis. The three dimensional analysis is more realistic and will produce more ‘life-like’ results. As shown in Table 5-1, the number of degrees of freedom per element in a 2-D analysis is 12. For the same structure in a 3-D analysis using tetrahedral elements, each element contains 30 degrees of freedom. Another effect of a 3-D analysis is an increase in the overall number of elements. The increase in element number from a 2-D model to a 3-D model with the same geometry is roughly 10 fold. All of this increase in accuracy comes at an increase in computation time. To determine how dramatic this loss in accuracy truly is in a analysis of TCHP a comparison was made between two identical TCHP structures under the same loading conditions with one being 2-D and one being 3-D.

Table 5-1: Effect of 2-D vs. 3-D Analysis

<table>
<thead>
<tr>
<th>Element Type</th>
<th>2–Dimensional</th>
<th>3-Dimensional</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Plane 183 (6 nodes), LST</td>
<td>Solid187 (10 nodes), T10</td>
</tr>
<tr>
<td>Degrees of Freedom</td>
<td>2 (x &amp; y)</td>
<td>3 (x, y &amp; z)</td>
</tr>
<tr>
<td>(per node)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of Elements</td>
<td>1400</td>
<td>16000</td>
</tr>
</tbody>
</table>
The 2-D analysis shown in Fig. 5-1 has uniform stresses applied to both ends of the block which are much lower than the yield strength of the material. Since, for this analysis, we are interested in modeling the particle interactions on a continuous scale, all amplified stresses near the edges of the model will be ignored. The stresses seen throughout the core particles are almost completely uniform and moreover this uniformity occurs continues between particles in the direction of the applied load. On the other hand high stresses are above and below these uniform stress channels. The magnitude of the variation in these two sets of stresses is roughly a factor of 2. The interface between these higher loads and the uniform loads on the core particles is divided by the pure Co shell. In between this interface, the Co shell actually displays the lowest stresses of anywhere in the structure. This is due to the fact that Co has the lowest modulus of any material in the structure and is least affected by small deformations. It is in part because of this that the Co binder is crucial in providing TCHP the required toughness.

Figure 5-1: 2D Stress Distribution in Particle Matrix Due to Tensile Stresses
A 3-D analysis of the same structure under the same boundary and loading conditions is seen in Fig. 5-2. The stress distribution is similar to that of the 2-D analysis and as stated prior, all amplified stresses near the edges of the model will be ignored. The stress is not completely uniform throughout the core particles, however the variance is only about 20%. The ‘flow’ of these stresses through the structure from particle to particle along the direction parallel to the applied stress is interrupted by lower stresses in the Co shell than were seen in the 2-D analysis. This shows that there is a 3-D absorption of stresses due to the Co shell, again proof of its’ ability to increase toughness. Similar to the 2-D analysis, the stresses on the upper and lower surfaces of the particle are roughly twice those on the sides. The most important part of this analysis is that the stress distributions across the face of the structure are similar to the distributions through the thickness. This along with the fact that the stress distribution were within a 10% range from the 2-D to the 3-D analysis, it can be assumed that a 2-D analysis sufficiently models the structural displacements of TCHP with reasonable accuracy. This assumption allows the possibility of further modeling of TCHP on a larger scale such as a full size wire die with a TCHP particle interface at the location of the die where the highest stresses are seen.

In order to fully understand the particle interactions in the TCHP matrix a shear loading condition was applied to the top face of the 3-D structure. The peak stresses at the lower endpoints are negligible and are caused by boundary conditions. It can be seen in Fig. 5-3 that there are not high stress regions throughout the core particles, shell layers or the matrix interface. This demonstrates TCHP’s ability to uniformly distribute shear loading.
Figure 5-2: 3D Stress Distribution in Particle Matrix Due to Tensile Stresses

Figure 5-3: 3D Distribution of Shear Stresses Through Particle Matrix
5.2 Wire Drawing Modeling Results

The dynamic die-wire system contains many factors which can be varied depending on the material being drawn and the production needed. The most prominent of these factors are the drawing speed, approach angle and hardening exponent. Although not as significant, factors such as friction coefficient, bearing length, final wire diameter and exit angle still play a part in the state of the system. In this section each of these parameters are analyzed separately to determine what effect they have on the overall system. Once these relationships are determined it is possible to optimize a drawing apparatus which will be most beneficial for a specific application.

5.2.1 Stress and Strain Deformation During Drawing

The resultant stresses and permanent strains are studied at various stages in the drawing process. Figure 5-4 shows the stress distribution after a significant amount of wire has been drawn. The peak stress distributions occur in Fig. 5-4 where the die transitions from the approach angle to the bearing channel. This location is where the highest strain rate in the wire occurs. As such, this is the area of the die with the highest wear and the most potential for fracture.

It can be seen that at this interface there is a small stress concentration in the die equaling almost 1.5 times the wire’s yield strength. At increased distances, the stress decays to a small uniform value. Although the stresses at this point are one and a half times the yield strength of the wire, this value is still well below the yielding point of the die material. Furthermore, Fig. 5-4 shows that the stresses are distributed up the wire a
distance roughly equal to the width of the wire. The stresses at this distance up the wire are significantly less than the yielding strength of the wire. If these stresses were to exceed the yielding strength of the wire then necking would occur prior to the contact with the die and would most likely result in fracture of the wire. Lastly, residual stress fluctuations can be seen throughout the length of the wire after it has exited the die. These residual stresses are caused by stress fluctuations during drawing.

As expected, the permanent strain has a similar pattern to the stresses, shown in Fig. 5-5. Severe plastic deformation of 14% takes place locally at the die exit. This deformation decays throughout the width of the wire coming to a uniform strain at the midsection. Similar to the stress state, there is plastic deformation in the wire before it reaches the final reduction into the bearing channel. For this case, the deformation is small and would not likely have an affect the performance of the drawing system.

Figure 5-4: Von Mises Stress Distribution Surrounding Exit of Die
Figure 5-5: Plastic Strain Deformation in Drawn Wire

Figure 5-6: Oscillations in Drawing Force During Drawing
Throughout drawing there is a variation in the force required to pull the wire through the die. Figure 5-6 shows an example of these fluctuations in the drawing force. These fluctuations are seen in the wire die system as vibrations which can potentially be harmful. If these oscillations increase to a certain level then a uniform diameter in the wire can be lost or the wire could fracture. What parameters affect the magnitude of these oscillations is explained in more detail later in this section.

5.2.2 Effect of Drawing Speed

From a manufacturing standpoint the most important factor in drawing wire is how much can be produced in a given amount of time. Because of this reason there are constant attempts being made to increase the acceptable drawing speed for various materials. Currently for steel wire drawing the average speed is from 3-10 m/s depending on the type of steel and the desired properties of the drawn wire. By determining the approach angle which corresponds to the lowest drawing force for a given speed, the optimized geometry of the die can be obtained.

<table>
<thead>
<tr>
<th></th>
<th>1mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final Diameter</td>
<td></td>
</tr>
<tr>
<td>Reduction</td>
<td>12 %</td>
</tr>
<tr>
<td>Bearing Length</td>
<td>40% of Wire Diameter</td>
</tr>
<tr>
<td>Exit Angle</td>
<td>90°</td>
</tr>
<tr>
<td>Friction Coefficient (µ)</td>
<td>0.3</td>
</tr>
</tbody>
</table>
Figure 5-7: Required Drawing Force for Steel at 3 m/s

Figure 5-7 shows the variation in required drawing force and internal die stress as a function of the approach angle. It can be seen that at very small approach angles, under 7°, the required drawing force is almost twice that required at some optimized approach angle. Solely based on the drawing force, the optimal approach angle to minimize this factor would be between 25° and 30°. However, this shift comes at the price of a higher stress in the die at the entrance into the bearing channel. This increase in stress results in more die wear and a shorter usable lifetime. Both of these parameters need to be balanced in order to determine the optimal configuration. This predicted operating range is somewhere between 10° and 15°. Where the actual optimal approach angle falls will depend on the material being drawn and whether or not it can support these higher drawing stresses in order to increase the lifetime of the die.
Figure 5-8: Required Drawing Force for Steel at 10 m/s

Figure 5-9: Required Drawing Force for Steel at 20 m/s
As drawing speeds increase so does the optimum approach angle at which this tradeoff between drawing force and die stresses occurs. For a drawing speed of 10 m/s the predicted range of operation is now between 12° and 17°. Furthermore, at a drawing speed of 20 m/s the predicted operating range is at an approach angle between 15° and 20°. At some point as the speed were to increase further and further there will come a point where the deformation in the wire will be happening so rapidly that the strain rate will continue to grow until the wire cannot support the load. At this point the plastic zone will move from the area inside of the die to areas further down the wire and uncontrolled elongation will occur until fracture. From a production standpoint, a relationship must be made between the increase in production due to the higher drawing speed and the increased die wear due to the higher surface stresses. This will then determine what the optimal drawing configuration for a given material is.

5.2.3 Effect of Hardening Exponent

After a material has exceeded its yield strength the relationship between true stress and true strain is governed by the hardening exponent “n”, as shown in Eqn. 5-1, until the material fractures.

\[ \sigma_t = Ke_t^n \]

In most cases this exponent is determined through experimental tensile testing in which the engineering stress and strain are found and used to compute the true stress and strain using Eqn. 5-2 and 5-3.
This hardening coefficient is high for ductile materials and low for brittle materials as shown in Fig. 5-10. This coefficient was varied from 0.1 to 0.5 while keeping the geometric properties constant, shown in Table 5-3. An approach angle of 10° and a drawing speed of 10 m/s were chosen since this configuration is one of the most common in modern production for the drawing of steel wire.

\[
\sigma_t = \sigma_e (\varepsilon_e + 1) \quad 5-2
\]

\[
\varepsilon_t = \ln(\varepsilon_e + 1) \quad 5-3
\]

**Figure 5-10**: Influence of Hardening Exponent on Material Properties in Modeling
As the hardening exponent is increased there is a non-linear relationship between the required drawing force and this increase in hardening coefficient as well as between the hardening coefficient and the die stress. At low hardening coefficients in the range of 0.1 to 0.2 there is a drastic increase in the required drawing force and also in the die stresses. As the hardening coefficient continues to increase from 0.2 to 0.5 its effects begin to be less and less significant. At these low hardening coefficients only a stress slightly higher than the yielding stress is needed in order to permanently deform the material. As this coefficient increases, more and more stress is required to deform the material and therefore higher stresses are present at the face of the die in contact with the wire, especially in the transition between the approach angle and the bearing channel where the highest strain rates are present. This increase in die stresses will cause an increase in the wear rate of the die material and decrease the overall lifetime of the part. This becomes a production factor when determining the cost to produce a certain amount

<table>
<thead>
<tr>
<th>Table 5-3: Constant Model Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Drawing Speed</strong></td>
</tr>
<tr>
<td><strong>Approach Angle</strong></td>
</tr>
<tr>
<td><strong>Final Diameter</strong></td>
</tr>
<tr>
<td><strong>Reduction</strong></td>
</tr>
<tr>
<td><strong>Bearing Length</strong></td>
</tr>
<tr>
<td><strong>Exit Angle</strong></td>
</tr>
<tr>
<td><strong>Friction Coefficient (µ)</strong></td>
</tr>
</tbody>
</table>
of wire, not only due to the cost of the die but also the downtime required to replace them after a failure due to wear or fracture.

Table 5-4: Hardening Exponents of Commonly Drawn Materials, [ASM]

<table>
<thead>
<tr>
<th>Material</th>
<th>Hardening Exponent (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon and Alloy Steels</td>
<td>0.1-0.48</td>
</tr>
<tr>
<td>Copper Alloys</td>
<td>0.49-0.56</td>
</tr>
</tbody>
</table>

Figure 5-11: Influence of Hardening Exponent on Drawing Force and Die Stress
The hardening coefficient does not only have an effect on the wire during drawing it also has a significant effect on the material properties of the wire after it has been drawn. Figure 5-12 shows the permanent strain in a wire with a hardening coefficient of 0.1. The outer edge of the wire in direct contact with the die contains a permanent strain of 15.8% while the center of the wire has only 8.7%. This variation in strain throughout the thickness of the wire leads to internal stresses and can also lead to non-homogenous properties within the wire. If this process continued to happen through a series of dies, the outer edges of the wire could have an increased hardness and brittleness while the center is more ductile with a lower hardness. Figure 5-13 shows the permanent strain in a wire with a 0.4 hardening exponent. This increase in hardening exponent increases the strain uniformity of the wire after it exits the die.
Figure 5-13: Von Mises Plastic Strain With 0.4 Hardening Exponent

Figure 5-14: Elastic and Plastic Deformation in Wire Drawing
Instead of having a strain gradient from the outside of the wire to the inside as with the 0.1 hardening coefficient, there is a much larger high strain region at the exit of the die leading into a uniform strain at a distance further from the exit. Although the wire with the increased hardening exponent contains a more uniform strain throughout the wire a larger percentage of this strain is not permanent. As Fig. 5-15 shows, an increase in hardening exponent results in a decrease in permanently dominated strain during drawing and an increase in elastically dominated strain. This will result in a radial expansion of the wire as it exits die, as seen in Fig. 5-13, which reduces the amount of permanent reduction in each drawing pass. This increase in hardening exponent also increases the amount of stress acting radially on the die face causing it to deform inward. This deformation inward further decreases the amount of area reduction which the wire is undergoing during each pass.

When materials with a low hardening exponent are drawn, they contain high tensile stresses on the outer edges of the wire and high internal compressive stresses due to non-uniform strain gradients during drawing. These materials contain lower amounts of elastically dominated strain and produce less stress on the die face, leading to less die wear. Materials with a high hardening exponent contain less tensile and compressive stress variations throughout the wire thickness, contain more elastically dominated strain during drawing and produce more stress on the die face, leading to more die wear.
5.2.4 Effects of Friction During Drawing

As seen in the previous section, at low approach angles there is a dramatic increase in the required drawing force. This increase is due to the friction between the die and the wire being drawn. At low approach angles (< 10°) the surface to surface contact area is much greater than at higher approach angles and this frictional force plays a large role in the overall stress state of the die-wire system. As approach angles increase the resultant stresses become more influenced by the strain rate of the wire material than on the frictional effects. It can be seen in Fig. 5-16 that an increase in the friction coefficient between the wire and the die leads to a linear increase in both the drawing force and the die stress.

Figure 5-15: Strain Variations as a Result of Hardening Exponent
By changing the friction coefficient from 0.1 to 0.2 there is an increase in over 50% in the required drawing force and 30% in the die stress. For this reason much research has been done in determining ways to minimize the friction during drawing by means of dry powdered lubricants, liquid lubricants and even fully submerging the drawing die and steel casing in a lubricant bath during drawing. Besides increasing the stress state of the system, the friction causes increases in temperature which can be problematic to the performance of the die as well as the microstructural features of the wire.

**Figure 5-16: Influence of Friction Coefficient on Drawing Force and Die Stress**

![Influence of Friction Coefficient on Drawing Force and Die Stress](image)
5.2.5 Effects of Reduction Ratio During Drawing

The reduction ratio at each pass of the wire drawing process is critical in tailoring the final material properties of the wire. A small reduction ratio will only slightly harden the material however a large reduction ratio may brittle the material too much. Also, a large reduction ratio will cause higher stresses in the die and lead to increased wear and a shorter usable lifetime. A tradeoff between these can be made at each die pass throughout the entire setup to tailor specific material properties. This section does not attempt to quantify which drawing setup may produce the best material properties, it is simply showing the relationship this reduction ratio has with the stresses in the die and the wire.

![Influence of Reduction Percentage on Drawing Force and Die Stress](image)

**Figure 5-17:** Influence of Reduction Percentage on Drawing Force and Die Stress
Figure 5-17 shows that an increase in reduction percentage produces an exponential increase in both the required drawing force and the die stress. At lower reduction ratios, like those commonly used in steel wire drawing, the increase in drawing force is about 100N for every 1% increase in reduction. The increase in die stress at these lower reduction ratios is roughly 40MPa for every 1% increase in reduction. The ideal reduction ratio will vary for different materials but will most likely be dependent on the optimization of the die stresses and final material properties. The amount of reduction per pass as well as the total reduction in wire diameter will determine whether the material will require a heat treatment after drawing to relieve some of the internal stresses caused during drawing.

5.2.6 Effects of Bearing Length During Drawing

The length of the bearing channel is a function of the diameter of the wire being drawn. As shown in Fig. 5-18, there is an exponential response in the drawing force and die stress as the bearing length is increased. The increased bearing length causes an increase in surface area of the die and wire in contact and increases the friction forces during drawing. For steel wire drawing a bearing length of 40% of the wire diameter is used. This value falls on the lower end of the curve where the increase of bearing length is not as influential on the drawing force and die stresses. Also, as the bearing length is increased the amount of plastically dominated strain in the wire is also increased while the amount of elastically dominated strain is decreased, shown in Fig. 5-19. Therefore, a longer bearing length can produce a higher tolerance on the final diameter of the wire.
Figure 5-18: Influence of Bearing Length on Drawing Force and Die Stress

Figure 5-19: Strain Variations as a Result of Bearing Length
6.1 Micro-Scale Particle Modeling

Comparison between 2D and 3D analyzes show that the slight decrease in accuracy of the 2D model is negligible when compared to the time saved in computation. Analysis of TCHP under tensile loading shows stress concentrations surrounding core particles, however further analysis is needed in order to determine the amount of their influence. Due to the composite nature of TCHP it is able to withstand shear loading better than that of a homogeneous structure. This is due to the influence of the Co material throughout the WC matrix.

6.2 Wire Drawing Modeling

Wire drawing is a complex process and is extremely subjective to the material parameters, production method, and desired final material properties. In order to determine an optimal drawing scenario it is necessary to analyze the material and geometric properties of both the wire and die. The speed at which wire can be drawn is of most interest in production and was found to influence the optimal die approach angle. As the drawing speed increases there must be an increase in the approach angle in order to maintain a minimal drawing force and internal die stress. If the approach angle is low
then frictional effects become predominant and if the angle becomes too high then the high strain rate produces increased stresses.

The hardening exponent and also plays an important part in the stress state during drawing and the final material properties of the wire. Materials with low hardening exponents will contain strain gradients through their thickness which produces tensile stresses on the outer edges of the wire and compressive stresses near the center. Materials with higher hardening exponents contain less strain variations and therefore less of a presence of tensile and compressive stresses. A tradeoff between these two extremes is also found in the amount of elastic and plastically dominated strain in the wire after it exits the die. When materials with a low hardening exponent are drawn they contain more plastically dominated strain and produce less die stress, while materials with high hardening exponent contain less plastically dominated strain and produce more die stress. As the diameter of the wire being drawn decreases the effects of strain variations are of less importance. These two properties effect the overall lifetime of the drawing die as well as the achievable tolerances during drawing.

The reduction ratio and the bearing length can be used hand in hand to optimize the drawing scenario for a given material. A larger reduction ratio is possible for materials with a high hardening exponent as opposed lower ones, because these materials distribute the deformation more uniformly throughout their thickness therefore producing less internal stresses. However, these materials with high hardening exponents require a longer bearing in order to reduce the amount of elastically dominant strain and increase the amount of plastically dominated strain.
When these relationships are combined several generalizations can be made about wire drawing. As the hardness of the material being drawn increases, the bearing length required to maintain plastic deformation decreases. Also, as drawing speed increases there must also be an increase in the die approach angle.

Optimized die geometries are specific to a desired application and understanding the relationship between the die geometry and the resultant stress states allows improvements on existing drawing techniques as well as the possibility for drawing new materials.

Future work on this topic could include analysis of drawn wire to determine the levels of compressive and tensile stresses found while drawing various materials. Implementation of temperature dependence during wire drawing would be beneficial and would allow for the analysis of a broader range of materials such as tungsten filament. Lastly, creating a small region of TCHP particles, as shown in the micro-scale modeling, surrounding the entrance to the bearing channel would allow for analysis of stress distributions through the particle matrix during drawing.
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Appendix A

Additional Wire Drawing Graphs

A.1 Variations in Approach Angle

Influence of Approach Angle on Drawing Force as Several Drawing Speeds

Influence of Approach Angle on Drawing Force at Several Approach Angles
A.2 Variation in Hardening Exponent

**Determinination of Hardening Exponent**

![Graph showing determination of hardening exponent with equations for different values of the exponent.]

**Deformation of Wire and Die During Drawing**

![Graph showing deformation of wire and die with time.]

- Wire Deformation
- Die Deformation
Appendix B

Ansys Input Codes

B.1 2D Particle Modeling

/PREP7

ET,1,PLANE183,1

BLC4,0,0,5.7e-3,5.3e-3,0

CYL4,1.5e-3,1.5e-3,1.25e-3
CYL4,4.25e-3,1.5e-3,1.25e-3
CYL4,2.85e-3,3.8e-3,1.25e-3
WPOF,5.7e-3,3.8e-3,
PCIRC,1.25e-3,0,90,270,
WPOF,-5.7e-3,,
PCIRC,1.25e-3,0,-90,90,

ASBA,1,2
ASBA,7,3
ASBA,1,4
ASBA,2,5
ASBA,1,6

WPOF,-3.8e-3,
CYL4,1.5e-3,1.5e-3,1e-3
CYL4,1.5e-3,1.5e-3,1.1e-3,1e-3
CYL4,1.5e-3,1.5e-3,1.25e-3,1.1e-3

CYL4,4.25e-3,1.5e-3,1e-3
CYL4,4.25e-3,1.5e-3,1.1e-3,1e-3
CYL4,4.25e-3,1.5e-3,1.25e-3,1.1e-3

CYL4,2.85e-3,3.8e-3,1e-3
CYL4,2.85e-3,3.8e-3,1.1e-3,1e-3
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WPOF,5.7e-3,3.8e-3,
PCIRC,1e-3,0,90,270,
PCIRC,1.1e-3,1e-3,90,270,
PCIRC,1.25e-3,1.1e-3,90,270,

WPOF,-5.7e-3,.
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PCIRC,1.25e-3,1.1e-3,-90,90,

AGLUE,1,3,4
AGLUE,5,6,7
AGLUE,8,9,10
AGLUE,11,12,13
AGLUE,14,15,16
AGLUE,2,4,7,10,13,18

!* Material 1: WC
MP, EX, 1, 580E6
MP, NUXY, 1, 0.30

!* Material 2: WC-Co (50% Mix)
MP, EX, 2, 450E6
MP, NUXY, 2, 0.30

!* Material 3: Co
MP, EX, 3, 200E6
MP, NUXY, 3, 0.30

!* Material 4: Alumina
MP, EX, 4, 380E6
MP, NUXY, 4, 0.30

MAT, 3
ESIZE, 0.2e-3 $ AMESH, 3
ESIZE, 0.2e-3 $ AMESH, 6
ESIZE, 0.2e-3 $ AMESH, 9
ESIZE, 0.2e-3 $ AMESH, 12
ESIZE, 0.2e-3 $ AMESH, 17

MAT, 2
ESIZE, 0.3e-3 $ AMESH, 15
ESIZE, 0.3e-3 $ AMESH, 16
ESIZE, 0.3e-3 $ AMESH, 19
ESIZE, 0.3e-3 $ AMESH, 20
ESIZE, 0.3e-3 $ AMESH, 21
MAT, 4
ESIZE, 0.4e-3 $ AMESH, 1
ESIZE, 0.4e-3 $ AMESH, 5
ESIZE, 0.4e-3 $ AMESH, 8
ESIZE, 0.4e-3 $ AMESH, 11
ESIZE, 0.4e-3 $ AMESH, 14

MAT, 1
ESIZE, 0.5e-3 $ AMESH, 2

DL,1,,UY,0
DL,3,,UY,0
DL,18,,UX,0
DL,52,,UX,0
DL,38,,UX,0
DL,93,,UX,0
DL,94,,UX,0
DL,37,,UX,0
DL,51,,UX,0
DL,2,, UX,0

SFL,23,PRES,-10000000
SFL,50,PRES,-10000000
SFL,30,PRES,-10000000
SFL,82,PRES,-10000000
SFL,83,PRES,-10000000
SFL,29,PRES,-10000000
SFL,49,PRES,-10000000
SFL,24,PRES,-10000000

/SOL
SOLVE

B.2 3D Particle Modeling

/PREP7
ET,1,SOLID187
BLC4,0,0,0.0057,0.00175,0.0053

WPOF,0.0015,,0.00275,,
SPHERE, 0.00125, , 0, 180

WPOF,0.0015,0.0015
SPHERE, 0.00125, , 0, 180

WPOF,0.00145,0.0023
SPHERE, 0.00125, , 90, 180

WPOF,-0.00285,,
SPHERE, 0.00125, , 0, 180

WPOF,-0.00285,,
SPHERE, 0.00125, , 0, 90

VSBV,1,2
VSBV,7,3
VSBV,1,4
VSBV,2,5
VSBV,1,6

WPOF,0.0015,-0.0023
SPHERE, 0.001, , 0, 180
SPHERE, 0.0011, 0.001, 0, 180
SPHERE, 0.00125, 0.0011, 0, 180

WPOF,0.00275,,
SPHERE, 0.001, , 0, 180
SPHERE, 0.0011, 0.001, 0, 180
SPHERE, 0.00125, 0.0011, 0, 180

WPOF,0.00145,0.0023
SPHERE, 0.001, , 90, 180
SPHERE, 0.0011, 0.001, 90, 180
SPHERE, 0.00125, 0.0011, 90, 180

WPOF,-0.00285,,
SPHERE, 0.001, , 0, 180
SPHERE, 0.0011, 0.001, 0, 180
SPHERE, 0.00125, 0.0011, 0, 180

WPOF,-0.00285,
SPHERE, 0.001, , 0, 90
SPHERE, 0.0011, 0.001, 0, 90
SPHERE, 0.00125, 0.0011, 0, 90

VGLUE,1,3,4
VGLUE,5,6,7
VGLUE,8,9,10
VGLUE,11,12,13
VGLUE,14,15,16
VGLUE,2,4,7,10,18,13

!* Material 1: WC
MP, EX, 1, 580E6
MP, NUXY, 1, 0.30

!* Material 2: WC-Co (50% Mix)
MP, EX, 2, 450E6
MP, NUXY, 2, 0.30

!* Material 3: Co
MP, EX, 3, 200E6
MP, NUXY, 3, 0.30

!* Material 4: Alumina
MP, EX, 4, 380E6
MP, NUXY, 4, 0.30

MAT, 3
ESIZE, 0.0002 $ VMESH, 3
MAT, 3
ESIZE, 0.0002 $ VMESH, 6
MAT, 3
ESIZE, 0.0002 $ VMESH, 9
MAT, 3
ESIZE, 0.0002 $ VMESH, 12
MAT, 3
ESIZE, 0.0002 $ VMESH, 17
MAT, 3

MAT, 2
ESIZE, 0.0003 $ VMESH, 15
MAT, 2
ESIZE, 0.0003 $ VMESH, 16
MAT, 2
ESIZE, 0.0003 $ VMESH, 19
MAT, 2
ESIZE, 0.0003 $ VMESH, 20
MAT, 2
ESIZE, 0.0003 $ VMESH, 21
MAT, 2

MAT, 4
ESIZE, 0.0004 $ VMESH, 1
MAT, 4
ESIZE, 0.0004 $ VMESH, 5
MAT, 4
ESIZE, 0.0004 $ VMESH, 8
MAT, 4
ESIZE, 0.0004 $ VMESH, 11
MAT, 4
ESIZE, 0.0004 $ VMESH, 14
MAT, 4

MAT, 1
ESIZE, 0.0005 $ VMESH, 2

DA,1,ALL,0
DA,2,UX,0.0001

/SOL

SOLVE

B.3 Wire Drawing

/PREP7
ET,1,PLANE183,1
ET,2,PLANE183
MP,EX,1,193E9,-100E3 ! C0 and C1 terms for Young's modulus
MP,NUXY,1,0.3
MP,DENS,1,7850 !*kg/m2
TB,BKIN,1,1 ! Activate a data table
TBDATA,1,285E6, 41E8 ! Yield = 285E6; Tangent modulus = 41e8

*afun,deg
diam = 0.001
theta=5
phi = 45
red  = 0.12
blength = 0.4

k,,0,0,0
k,,0,0.017
k,,0.00153,0.017
k,,0.008-(0.0095-(0.00124 + (diam*blength)))*tan(theta) ,0.0095
k,,0.008-(0.00325-(0.00124 + (diam*blength)))*tan(theta) ,0.00325
k,,0.008-(((0.00124+(diam*blength))+(diam/40))-(0.00124 + (diam*blength)))*tan(theta)

k,,0.008,(0.00124+(diam*blength))-(diam/40)

k,,0.008-(0.00325-(0.00124 + (diam*blength)))*tan(theta),0.00124-(0.00325-(0.00124 + (diam*blength)))*tan(theta)

k,,0.00676,0
k,,0.009,0.004
k,,0.007827,(0.00124+(diam*blength*0.95))

k,,0.008 + (diam/2), 0.00124
k,,0.008,0.00124
k,,0.008,(0.00124+(diam*blength))

k,,0.008-((diam/2)*red), 0.00124 + (diam*blength) + (((diam/2)*red)/(tan(theta)))

k,,0.008-((diam/2)*red), 0.02
k,,0.008 + (diam/2), 0.02

k,,0.00153,0

LARC,6,7,12,0.0003
LARC,3,4,10,0.015,
LSTR,  1,   2
LSTR,  2,   3
LSTR,  4,   5
LSTR,  5,   6
LSTR,  7,   8
LSTR,  8,   9
LSTR,  9,  10
LSTR, 10,   1
LSTR, 13,  14
LSTR, 14,  15
LSTR, 15,  16
LSTR, 16,  17
LSTR, 17, 18
LSTR, 18, 13

kdele, 11
kdele, 12

AL, 3, 4, 5, 6, 1, 7, 8, 9, 10
AL, 11, 12, 13, 14, 15, 16

!* Material 2: WC-Co
MP, EX, 2, 500E+9!* Pascal (N/m2)
MP, NUXY, 2, 0.23
MP, DENS, 2, 9600!* kg/ccm

TYPE, 1
MAT, 2
ESIZE, 0.00075 $ AMESH, 1

TYPE, 2
MAT, 1
ESIZE, 0.0001 $ AMESH, 2

KREFINE, 5, 6,, 2, 5
KREFINE, 8, 9,, 1, 5

FLST, 5, 4, 4, ORDE, 3
FITEM, 5, 1
FITEM, 5, 6
FITEM, 5, -, 8
LSEL, S,, , P51X
NSLL, S, 1
NSLL, S, 1
CM, DIE, NODE
ALLSEL, ALL
FLST, 5, 3, 4, ORDE, 2
FITEM, 5, 12
FITEM, 5, -, 14
LSEL, S,, , P51X
NSLL, S, 1
CM, WIRE, NODE
ALLSEL, ALL
/COM, CONTACT PAIR CREATION - START
CM, _NODECM, NODE
CM, _ELEMCΜ, ELEM
CM, _KPCM, KP
CM_LINECM,LINE
CM_AREACM_AREA
CM_VOLU_CM_VOLU
/GSAV,cwz,gsav,,temp
MP,MU,1,0.3
MAT,1
MP,EMIS,1,7.88860905221e-031
R,3
REAL,3
ET,3,169
ET,4,172
R,3,,1.0,0.1,0.
RMORE,,,1.0E20,0.0,1.0,
RMORE,0.0,0.1,0.,1.0,0.5
RMORE,0.1,0,1.0,0.0,,1.0
RMORE,10.0
KEYOPT,4,3,0
KEYOPT,4,4,2
KEYOPT,4,5,3
NROPT,UNSYM
KEYOPT,4,7,0
KEYOPT,4,8,0
KEYOPT,4,9,0
KEYOPT,4,10,2
KEYOPT,4,11,0
KEYOPT,4,12,0
KEYOPT,4,2,0
! Generate the target surface
NSEL,S,,,DIE
CM_TARGET,NODE
TYPE,3
ESLN,S,0
ESURF
CMSEL,S,_ELEMCM
! Generate the contact surface
NSEL,S,,,WIRE
CM_CONTACT,NODE
TYPE,4
ESLN,S,0
ESURF
ALLSEL
ESEL,ALL
ESEL,S,TYPE,,3
ESEL,A,TYPE,,4
ESEL,R,REAL,,3
/PSYMB,ESYS,1
/PNUM,TYPE,1
/NUM,1
EPLOT
ESEL,ALL
ESEL,S,TYPE,,3
ESEL,A,TYPE,,4
ESEL,R,REAL,,3
CMSEL,A,_,NODECM
CMDEL,_,NODECM
CMSEL,A,_,ELEMCM
CMDEL,_,ELEMCM
CMSEL,S,_,KPCM
CMDEL,_,KPCM
CMSEL,S,_,LINECM
CMDEL,_,LINECM
CMSEL,S,_,AREACM
CMDEL,_,AREACM
CMSEL,S,_,VOLUCM
CMDEL,_,VOLUCM
/GRES,cwz,gsav
CMDEL,_,TARGET
CMDEL,_,CONTACT
/COM, CONTACT PAIR CREATION - END
ALLSEL,ALL

DL,10,,UY,0
DL,3,,UX,0
DL,16,,UX,0
DL,11,,UY,-0.005

/SOL
ANTYPE,4     !*Transient Analysis
NLGEOM,ON     !*Large Deformations
NROP,UNSYM    !*Unsymmetric Stiffness Matrix
NSUBST,100,500,10 !*Number of Substeps
OUTRES,ERASE  !*Controls solution written to database
OUTRES,ALL,ALL
AUTOTS,1     !*Automatic time-stepping
TIME,0.0005   !*Time to Solve
KBC,0         !*Ramped Loading
CUTCONTROL,PLSLIMIT,0.8 !*Maximum strain per substep
NCNV,0,0,0,0,0 !*Do not terminate analysis
STABILIZE,CONSTANT,ENERGY,0.1,NO   !*Stabilized Element
SOLVE