

TOOL GEOMETRY EFFECTS IN METAL SHEARING USING FEM

by

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ABSTRACT

In manufacturing industry cutting of sheet metals is an everyday occurrence. With this in mind hand tool design is limited by empirical conventions for tool clearance, in the range of 4.5% to 8%. Conventional cutting force calculations and tool clearance calculations exist in reference material and can easily be calculated. These conventions are based on shear theory for force and experimental data for tool clearance. By applying these conventions to an FEM model for common engineering alloys of thicknesses between .020" and .080", and analyzing it the resulting stress fields and tool displacements trends in the increase of tool displacement required for the same stress state for all tool clearances.

Cohesive zone placement based on first analysis leads to describing the failure of the material cutting process. Traction separation laws describing cohesive elements can accurately describe the cutting of sheet metals. For the 6061-T6 aluminum, 1020 steel, 4340 steel, and 302 stainless the optimum tool clearance discovered through the cohesive zone FEM model is shown to be 3.8% to 8.3%. This information can be used for extrapolating the optimum clearances for other thicknesses of the materials, and the model can be expanded to encompass a larger material set.

INTRODUCTION

Sheet metal cutting, blanking, and trimming are a requirement in most all forms of fabrication and in many industries, from the stamped hoods on cars to the cut shapes of metal bookshelf ends. The analysis of the shearing processes in various alloys requires knowledge of the stress reactions beyond the elastic zone of material response as well as crack initiation, and crack propagation. Considerable research has resulted in vast knowledge of this material response [1-19].

The cutting process in sheet metals is best described as a ductile fracture process containing four stages which result in full separation of bulk material. The first stage comes from the microstructure level where micro-voids and micro-cracks which are inherent in any material, begin to move through the material as a function of growing stresses. The second stage is the nucleation of these micro-voids which is caused by slippage on grain boundaries. The third stage happens as the stresses increase these voids and cracks grow, as these voids grow they begin to coalesce throughout the material and develop into larger cracks and voids resulting in yielding and plastic deformation of the material which is referred to as plasticity. The final step is the coalescence of these larger cracks and voids which propagate along with the growing stress field concluding with a void or crack which will reach a critical length resulting in separation of the material. This process occurs at different rates as a function of different loading conditions, and type of material being processed. There has been a number experimental studies done which describe the force displacement relationships between cutting tools for blanking, shearing, and trimming [10].

Most recent exploration in the shearing process uses the finite-element method combined with the processing power of modern computers to analyze the cutting process. Today, this method has been adapted in a number of ways to include the formulation of cutting from node separation method [10], cohesive zones, and extended finite element method. Each method utilizes specified criteria to describe the bulk material properties as well as the degradation of material properties in each element based on the growing stress field.

Optimization of tool cutting geometry and tool clearances benefits from these advances in FEM. Modeling of the tool offset using FEM allows for no physical waste from testing while minimizing the time, cost, and calculations for each simulation. Also, multiple simulations can be run simultaneously. From these analyses a large number of variables from displacements, stresses, strains, and reactive forces can be calculated.

Knowing the reactive forces from the cutting process on tool faces in all directions allows design of tools to be more material and job specific. This information relates not only to the cutting faces themselves, but also the apparatus supporting the cutting faces. Materials will deform and fail differently depending on their material response to loading. Brittle materials will deform significantly differently than ductile materials and fail in a different manner as well. The material response will have a large effect on the resulting forces and displacements during the cutting process. The knowledge of how each type of material responds is vital to creating a cutting tool tailored that specific response as well as the type of process to be used.

Motivation for Research

In modern manufacturing reference material it can be found that common metal cutting tools and analysis utilize a cutting tool clearance of 3 to 8 percent of the material thickness [1, 10, 11, 17] depending on the type of material. These values are chosen to create a primarily shear mode failure zone. It has been hypothesized by me that there is a transition as tool clearance is increased to a primarily bending type failure mode from the primarily shear failure mode. What is not known is how the material response effects the cutting tool geometry and the process.

BACKGROUND

Crystalline Structure

All metals form a crystalline structure of atoms in a unique arrangement during normal solidification conditions. This crystalline structure is composed of a three dimensional pattern of sets of atoms arranged in a particular way. This three dimensional pattern is part of a larger lattice which exhibits order and symmetry. Each three dimensional set of points which repeats itself within the lattice is referred to as a unit cell. The number and arrangement of atoms in this unit cell plays a role in determining many of the physical and mechanical properties exhibited by the material [20].

Steel

The largest percentage of material in steel is that of iron which has a unit cell crystalline microstructure of body centered cubic (BCC) which is shown in Figure 1. This crystalline structure consists of eight corner atoms which are shared between adjacent cubes with one atom centered within the cube.

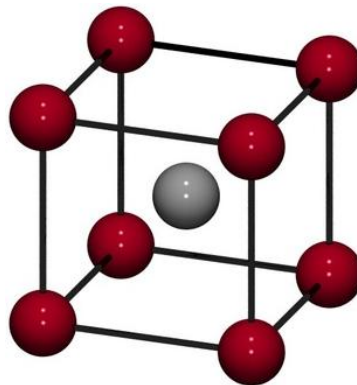


Figure 1: BCC microstructure

Depending on the volume of the material there is an increasing chance that other voids or dislocations will exist within the lattice of the material. These voids and dislocations lead to the plasticity of the material. Due to the smaller number of atoms and their orientation within the unit cell a material with this structure is less ductile than aluminum, copper, and gold which have a face centered cubic (FCC) structure[20]. The reason for this is due to slip planes and will be discussed.

Aluminum

Face centered cubic crystalline structure in the unit cell of aluminum is a similar cubic category structure to the BCC of steel, the difference being that each surface of the cube contains another atom that is shared with each adjacent cube. The increase in ductility over the BCC is due to the slip planes stated previously which will be discussed. Figure 2 shows a pictorial representation of FCC structure[20].

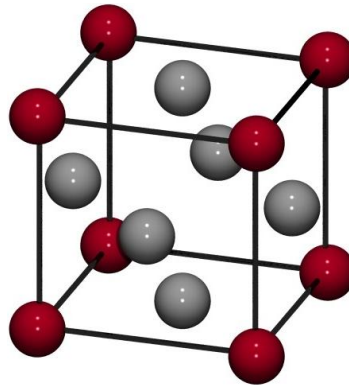


Figure 2: FCC microstructure

Slip Planes

Slip within the metallic crystalline structure is a plastic deformation process resulting from dislocation motion within the lattice. Slip occurs due to external body

forces acting on the material and is dependent upon the crystalline structures close packed planes. Close packed planes are the geometric planes created between the dense arrangements of atomic spheres.

An FCC crystalline structure has 12 slip systems in each unit cell. This number of slip planes results in the material having a more ductile strain response than that of the BCC structure. In a BCC unit cell there are no close packed planes requiring more energy for slip to occur. Figure 3 shows the slip plane configuration for both FCC and BCC unit cell microstructure.

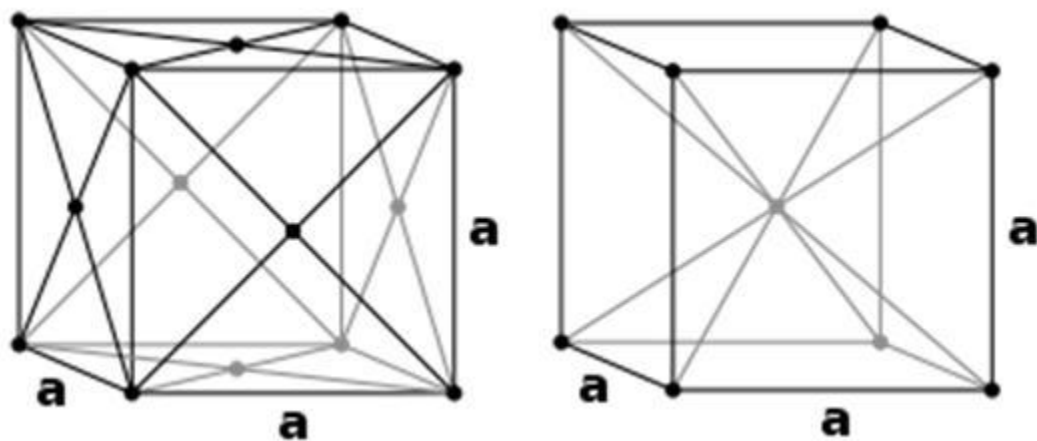


Figure 3: Left-FCC Slip plane diagram, Right-BCC Slip plane diagram

Vacancies and Dislocations

The earliest material studies developed a way to calculate the strength of materials of perfect crystalline structures. These calculated strengths were discovered to be significantly higher than those experimentally obtained values. This phenomenon is now known to be the result of the existence of flaws within the microstructure of the material. Flaws or missing atoms within the crystalline structure are inherent and are known as

dislocations. These dislocations in the microstructure are what move throughout a material as the local stress increases, which is known as slip. This movement gives yielding and plastic deformation in a material. As stated previously, micro-voids and dislocations move within the material and coalesce against opposing grain boundaries as well as other dislocations within the material as the localized stress field grows causing these voids to become macro-voids which eventually become cracks that lead to failure. Figure 4 shows what a dislocation in a polycrystalline lattice looks like.

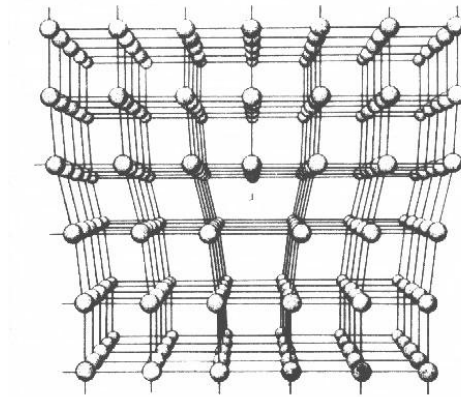


Figure 4: Polycrystalline dislocation

Grains and Structures

Within a material the unit cells are in ordered and repeated sections known as the lattice. Larger structures like sheet metal or round are not composed of completely ordered lattices. Within the structure there are individual sets of lattice or regions of lattice known as grains. Each grain has its own orientation within the material. Boundaries between grains inhibit dislocation movement during plastic deformation. Grain structure is shown in Figure 5.

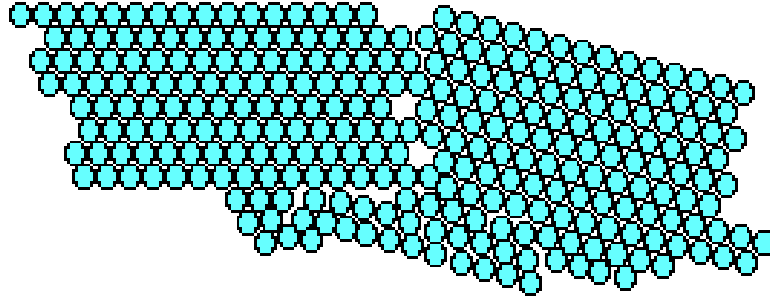


Figure 5: Grains within a material

During the process of manufacturing metals the rate at which the material is cooled results in a change in grain structure. The slower the material cools the larger the grains are resulting in fewer dislocations and a more ductile material response. Cold working and heat treating are two ways of increasing the number of dislocations within the material resulting in a material that resists plastic deformation.

Shear Failure

The failure in the cutting of a metal consists mainly of shear. It hypothesized that as the offset between shear forces is increased during the process there is a point at which pure shear no longer exists as the primary mode of failure. There must be a point at which the transition from pure shear becomes dominated by bending therefore increasing the work energy required for completion. Exploration of the shear zone and possible transition zone was the focus of the analysis and results that follow.

Pure shear stress is at a maximum when there is offset between shear forces, and no bending moment acting on the area in question. The stress field for the case of a rectangular beam is shown in Figure 6. This theory and geometry was applied to the

model and analysis used due to the fact that the material plate represents a rectangular beam[21].

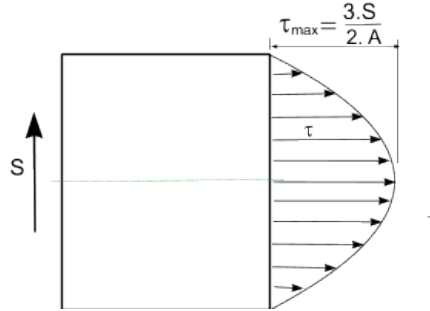


Figure 6: Max shear profile in a rectangular beam

As stated previously the cutting of sheet metal is primarily a shearing action. By increasing the tooling clearance in the operation the pure shear is hypothesized to transition to a bending.

Von Mises Stress

Von Mises stress is independent of the first stress invariant making it applicable yielding criteria for ductile materials. It states that the material in question will yield when the second deviatoric stress invariant reaches a critical value, k . This critical value is shown in Equation 1 and is a function of the yield stress of the material. By substituting in the second invariant J_2 into Equation 2 the von Mises stress can be calculated. The result is that the three dimensional stress state of a material can be represented by a singular value.

Equation 1: Critical value for von Mises stress

$$k = \frac{\sigma_y}{\sqrt{3}}$$

Equation 2: Von Mises relation to second stress invariant

$$\sigma_{vm} = \sqrt{3J_2}$$

Equation 3: Second stress invariant as a function of stress tensor components

$$J_2 = (\sigma_{xx} - \sigma_{yy})^2 + (\sigma_{yy} - \sigma_{zz})^2 + (\sigma_{zz} - \sigma_{xx})^2 + 6(\sigma_{xy}^2 + \sigma_{yz}^2 + \sigma_{zx}^2)$$

Equation 4: Von Mises stress equation

$$\sigma_{vm} = \frac{1}{\sqrt{2}} \sqrt{(\sigma_{xx} - \sigma_{yy})^2 + (\sigma_{yy} - \sigma_{zz})^2 + (\sigma_{zz} - \sigma_{xx})^2 + 6(\sigma_{xy}^2 + \sigma_{yz}^2 + \sigma_{zx}^2)}$$

Equation 4 describes the calculation of the von Mises effective stress from that of the stress tensor components. This effective stress was used in the FEM analysis to describe whether or not the material had reached a state of failure. Using the uni-axial criteria commonly known for alloys of steel and aluminum, a known stress state in the material can be related to the uni-axial yield stress by the von Mises effective stress.

Power Law Strain Hardening

Strain hardening, or work hardening of a material is the strengthening of the material through plastic deformation. This phenomenon is the result of dislocation movement. When a material is plastically deforming beyond the elastic limit, the dislocations within that material move and begin to stack upon one another as well as grain boundaries making it more difficult for further movement. The nucleation of the

dislocations at grain boundaries and other impurities restricts further movement thereby resulting in a higher material strength. There are many different ways to describe the hardening effect mathematically. Bi-linear material response describes a material as having a linear elastic section up to yield and a linear section after yield to failure. For the analysis that was completed the power law hardening approach was used. This mathematical description describes the material as consisting of both an elastic strain and a plastic strain. Equation 5 is the Ramberg-Osgood plasticity model which Abaqus utilizes to evaluate power law strain hardening material responses [22].

Equation 5: Power law strain hardening

$$E\varepsilon = \sigma + \alpha\sigma\left(\frac{|\sigma|}{\sigma^0}\right)^{n-1}$$

σ Stress

ε Strain

E Young's modulus

α Yield offset

σ Yield stress

n Hardening exponent

The exponent n is a material property evaluated from experimental data and is shown in Table 1 for several engineering alloys. Figure 7 shows the uni-axial stress-strain relationship of several engineering alloys by the power law strain hardening description.

Table 1: Material strain hardening exponents

Material	$n-1$
Low Carbon Steel (1020)	0.21
High Carbon Steel (4340)	0.12
Stainless Steel (304)	0.54
Aluminum	0.16

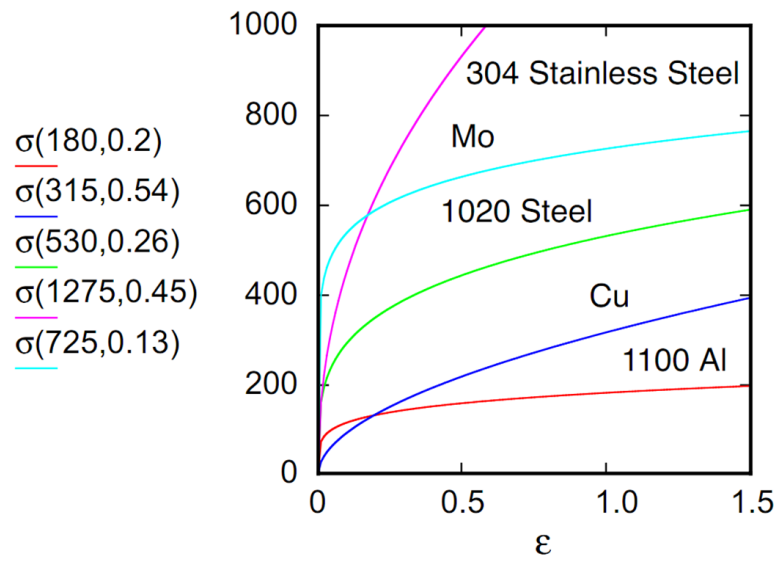


Figure 7: Power law strain hardening and bi-linear strain hardening

The standard power law used does not account for softening once the ultimate tensile strength of the material is reached. Due to this, it is assumed as stated previously that once the von Mises stress of the material reaches the ultimate tensile strength failure has occurred[23]. All other material properties required in the analysis are shown in Table 2[24].

Table 2: Material properties for materials used

Material	Young's Modulus (ksi)	Yield Stress (psi)	Ultimate Stress (psi)	Poisson's Ratio	Elongation at Break (%)	Density (lb/ci)
6061-T6 Aluminum	10000	40000	45000	.33	17	.0975
1020 Steel	29700	50800	60900	.29	15	.284
4340 Steel	29700	125000	185900	.29	12.2	.284
302 Stainless Steel	28000	37000	84800	.25	57	.284

ANALYTICAL CALCULATIONS

Tool Clearance

Metal shearing and blanking processes have a conventional clearance of between 4% and 8% of material thickness. This clearance is theorized to eliminate the tools contacting each other during the process while giving room for the material being cut to clear the tools. These conventional tool clearances do not describe the optimum tool clearance for a particular material type and thickness[25].

Equation 6 describes the conventional tool clearance calculation as it relates to the material thickness and allowance for that material. It is notable that this equation is strictly a geometrical relationship and is not described by material properties. Table 3 lists allowances for common engineering materials.

Equation 6: Tool clearance

$$C = at$$

Table 3: Tool offset allowance

Material	a
1100S and 5052S Aluminum	0.045
2024ST and 6061ST	0.06
Steels	0.075

Shear Cutting Force

The convention for describing the force needed for shearing or blanking of a material comes from the Jourawski formula and is acting on an infinitely thin section of a rectangular beam. Equation 7 describes the maximum shear force in a rectangular beam with only a shear force applied. There is assumed to be no moment applied.

Equation 7: Max shear in a rectangular beam

$$\tau = \frac{SQ}{tI}$$

This equation is a function of the first moment of area Q and the first moment of inertia I . S is the shearing force being applied to the material and t is the thickness of the material.

Equation 8: First moment of area above neutral axis

$$Q = \int_{y_1}^c y dA = b \int_{y_1}^c y dy = \frac{b}{2} (c^2 - y_1^2)$$

Equation 9: First moment of inertia for rectangular beam

$$I = \frac{bh^3}{12}$$

By applying equations Equation 8 and Equation 9 into Equation 7 the result is a simplified definition of shear stress based on geometry and the force applied. Equation 10 describes shows this simplified relationship.

Equation 10: Simplified max shear

$$\tau = \frac{3S}{2bh}$$

For the case in which fully plastic yielding has occurred within the plate failure is no longer governed by yielding, but rather the flow characteristics post yielding. This reduces the computation to a limit load requirement[26]. For this regime the max shear stress can be related to the uni-axial tension test ultimate stress by the von Mises effective stress from Equation 4. This is done by substituting in the ultimate tensile strength for the first principal stress, σ_{xx} , and setting all other values to zero. By applying this value to the max shear, Equation 10 can then be rearranged to obtain the shear force S required to fully plastically yield the material and in this case fail it.

Equation 11: Force required to shear a rectangular material

$$S = \frac{2}{3}Lt\sigma_u$$

Using Equation 11 and the specified material properties of the various steels and aluminums the forces required to cut the material can be calculated for varying thicknesses of material. These forces have been calculated for four general engineering metals and are shown in Table 4, assuming a unit length of cut. As the length of cut is increased this value will change.

Table 4: Analytical force calculations

Material	t (in)	0.02	0.025	0.03	0.035	0.04	0.045	0.05	0.055	0.06	0.065	0.07	0.075	0.08
6061-T6 Aluminum	S (lbf)	600	750	900	1050	1200	1350	1500	1650	1800	1950	2100	2250	2400
1020 Steel	S (lbf)	812	1015	1218	1421	1624	1827	2030	2233	2436	2639	2842	3045	3248
4340 Steel	S (lbf)	2479	3098	3718	4338	4957	5577	6197	6816	7436	8056	8675	9295	9915
302 Stainless Steel	S (lbf)	1131	1413	1696	1979	2261	2544	2827	3109	3392	3675	3957	4240	4523

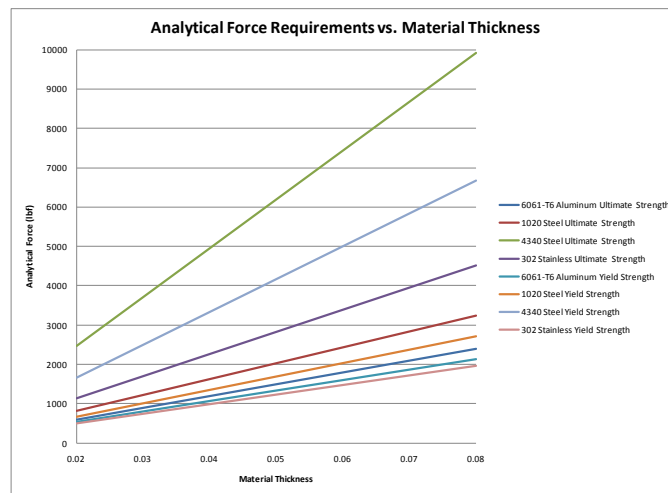


Figure 8: Analytical forces vs. thickness

FEM DOUBLE SHEAR MODELING

Double shear type cutters differ from a single shear such as scissors in that they have two cutting sections operating simultaneously. This results in a section of material being removed between the two cutting sections. Figure 9 shows a double shear type model with the axis of symmetry down the middle of the cutter.

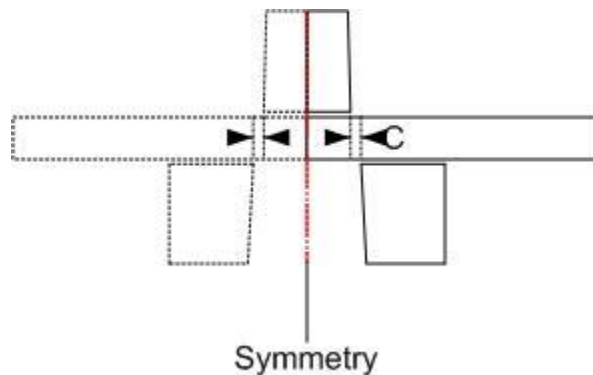


Figure 9: Double shear model

The modeling for this analysis was created using Abaqus/CAE version 6.9. Several assumptions have been made with regard to the system allowing it to be considered as a two dimensional plane strain model. This was chosen due to the fact that shearing process of sheet metal is primarily a scissoring action, or a straight blanking process. It was assumed that in a scissoring type process each infinitely thin layer of the bulk material must fail individually as the process continues throughout the material. For the straight edge blanking type process each infinitely thin layer is a direct representation of the material as a whole while the material is failing. These assumptions allowed for the use of two dimensional plane strain modeling and calculations.

Cutting Tool Model

Cutting tools are modeled as analytical rigid bodies for the reason that materials selected for cutting faces are considerably harder than the materials they are intended to cut. This also neglects the effects of tool wear. The leading edge of the cutting tools was modeled as having a radius of .0005" which was arbitrarily chosen due to physical cutters not having an infinitely sharp cutting edge. Relief angles on tool cutter inner faces were arbitrarily chosen of 5 degrees and modeled which allow for no contact between already separated material and cutting tools. Figure 10 shows the geometry of the final cutting tool geometry as it was modeled for the first FEM analysis. Both top and bottom cutting tools are modeled the same. A reference point was created at the corner opposite the radius tip for application of the constraints and loads.

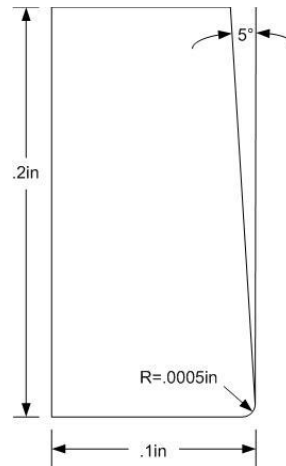


Figure 10: Cutting tool geometry

Material Plate Model

The raw material to be cut was modeled as a two dimensional deformable solid allowing for stress, strains, and reactive forces to be calculated by Abaqus. A length of .25" was selected to allow for far field stresses to have a negligible effect on the shear zone. The thickness, t , was varied from .020" to .080" for the four engineering materials chosen. A representation of the material plate geometry is shown in Figure 11.

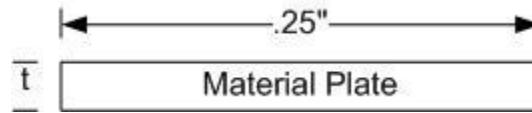


Figure 11: Material plate geometry

Four materials were chosen; 6061-T6, 1020, 4340, 302 and assigned their specified material response described previously[24]. The material properties given were; Young's modulus, yield stress, ultimate stress, poisons ratio, yield offset, hardening exponent, and density which are shown in Table 5. Each material was then applied to the section of the material plate.

Table 5: Material properties for materials chosen

Material	Young's Modulus (ksi)	Yield Stress (psi)	Ultimate Stress (psi)	Poisson's Ratio	Elongation at Break (%)	Density (lb/ci)	Exponent n-1
6061-T6 Aluminum	10000	40000	45000	.33	17	.0975	.16
1020 Steel	29700	50800	60900	.29	15	.284	.21
4340 Steel	29700	125000	185900	.29	12.2	.284	.12
302 Stainless Steel	28000	37000	84800	.25	57	.284	.5

Mesh

The mesh was specifically chosen with a density that allows for the tools to contact with the mesh in the same manner with every increment of tool clearance. This was obtained by seeding the top and bottom sides of the material plate with a value that creates a mesh size as a function of the tool clearance steps of .0005". The mesh density as a function of the tool clearance eliminates inconsistencies due to contact of the tool tip always contacting on a node and not varying between node and element face contact. For this analysis the element types are CPE4R, which are four node bilinear plane strain quadrilateral. For the plane strain a unit depth was chosen.

A test of the mesh density for convergence was completed before continuing with the modeling. The mesh density stated previously was doubled to find the difference in displacement between the two. By doubling the mesh there was a difference of .1355% between the two results. This was determined to be negligible so the mesh density stated above was used.

Assembly

The system was assembled in a way that allows the tool offset, λ , to be varied in steps of .0005" starting at .0005" up to material thickness. The offset was decided to not exceed the material thickness. Tool cutters were placed with a clearance to the material plate of .001" required for contact to later be initiated in the first step of the analysis described later. The assembled system to be analyzed by Abaqus is shown in Figure 12.

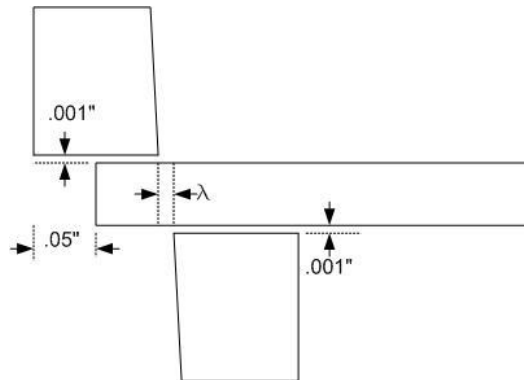


Figure 12: Assembly geometry

Analysis

Process

The shearing process in this case is considered to occur in the quasi-static regime, therefore dynamic effects were neglected. Abaqus CAE standard analysis was used to perform the analysis. For cost optimization macros were created due to the large number of analyses to be completed. Using the macro manager, a macro recorded the steps in adjusting the tool clearance which was then edited with an iterative loop to incrementally increase the tool clearance by .0005" up to material thickness and create input files for submission. A Python code was created to open, and run all of the input files created in

the working directory. Finally, the information of interest was pulled from the output databases created from each input file.

Boundary Conditions

Boundary conditions were applied in a manner that closely represents a real world scenario of a double shear cutting mode. In the case of the end opposite the cutting action, the plate was held in the x-direction only allowing the plate to move up and down. For the left end of the plate, under the top cutter, a symmetry condition was used to describe a double shear type cutting tool. The bottom cutter is held fixed in all directions and rotations at the reference point to represent a solid base on which the cutting process is taking place. All boundary conditions are shown pictorially in Figure 13.

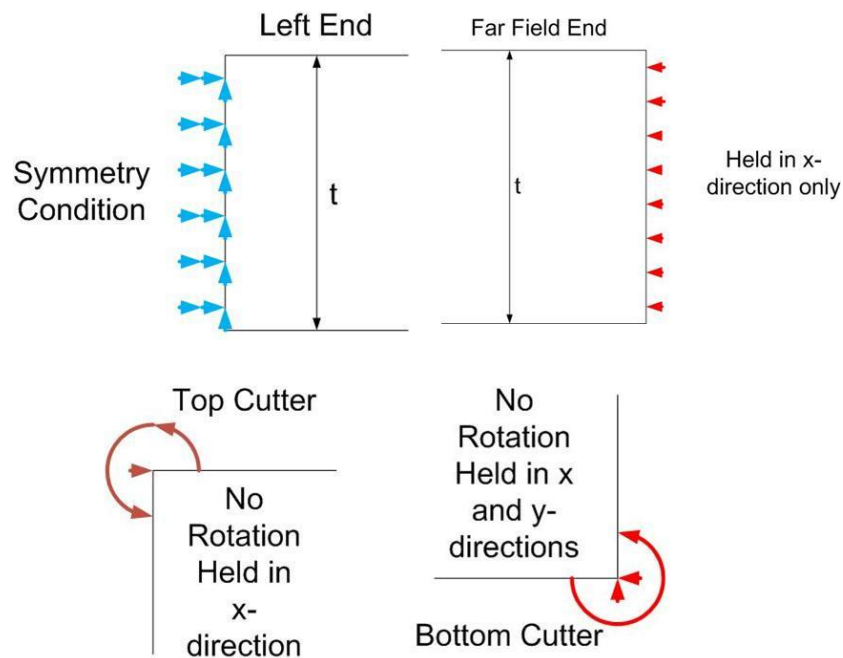


Figure 13: All boundary conditions

Loading Conditions

Applied load requirements for the FEM analysis come from the analytical data calculated in Table 4 for the specified material and thickness. These calculated forces were applied to the top cutter reference point with a ramping amplitude starting at zero and ending at calculated force. Shown in Figure 14.

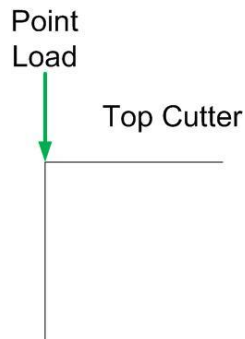


Figure 14: Load applied to top cutter

Abaqus Analysis

Abaqus analysis utilizes steps to analyze a given model. This stepped approach allows for modifications of conditions as the analysis progresses. Descriptions of the steps created for this analysis are as follows:

Initial Step: This step consists of the initial geometries in the model as they are described by the assembly position constraints prior to any modification or movement. In this step the all part instances, position constraints, and interaction properties are described. The cutting tools are positioned, as stated previously, at .001” from the material plate allowing for contact properties to be applied. The contact interaction properties between the cutters and the material plate are described as being hard contact

with no penetration and a tangential friction component with a coefficient of .2. The tool cutter faces are chosen to be the master surfaces and the material plate edges the slave surfaces for these interaction properties.

Make Contact Step: The initial offset between the cutters and the material plate must be removed in order to establish contact between the cutters and the material plate. This was achieved by applying a displacement condition equal to the offset specified in the initial step. If the force were to be applied in this step the tools would contact the material with a velocity resulting in chatter between the two resulting in convergence issues in the analysis.

Apply Load Step: Once the tool contact is made, the load is applied to the tool cutter forcing it through the material with a ramping amplitude. During this step the bottom cutter is fixed in its position allowing the tracking of tool displacement to be that of only the top cutter. A field output was created to track this tool displacement for creation of a plot from the Abaqus output database. A node set was created on the top cutter for the output database to be applied to. The results of this output field were pulled from the working directory using a macro to open each output database and creating x-y data plots and printing them to a report file.

FIRST FEM ANALYSIS RESULTS

A shear stress field in the part grew progressively through the material plate starting at the contact point of the cutting tool tips following through the material to each other. This stress field always grew in this manner independent of the material thickness and tool clearance. This phenomenon can be seen in Figure 15 which shows the stress field in the .020" thick aluminum plate with a clearance of .0005". Figure 16 also shows this for the .080" thick aluminum with a clearance of .080".

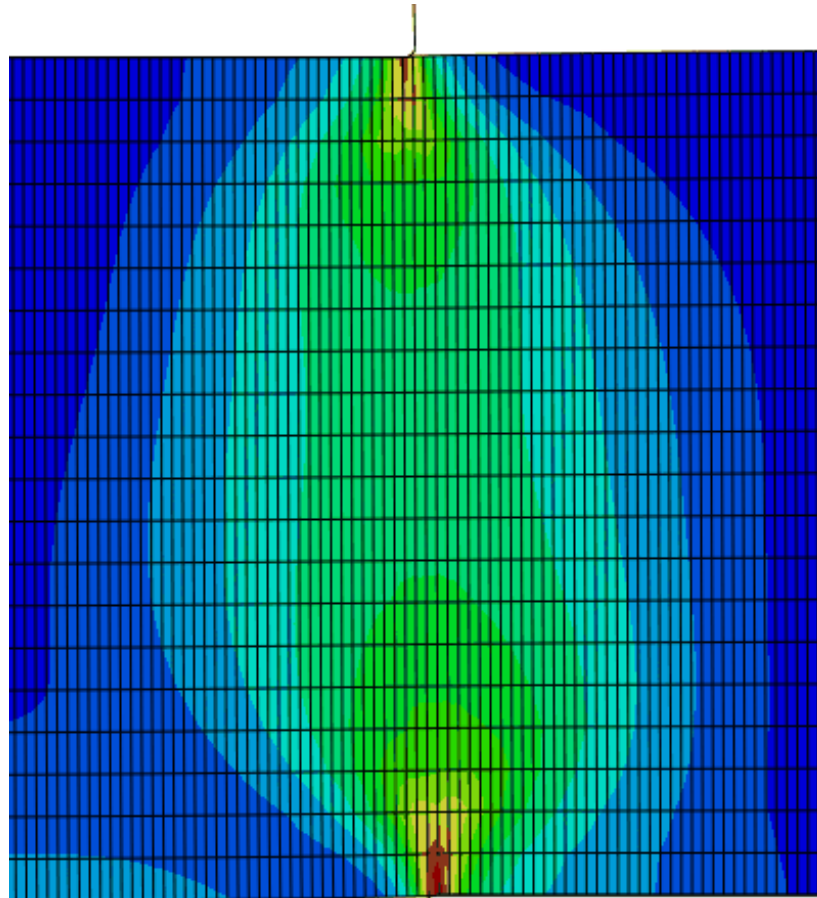


Figure 15: Stress field in .020" thick material with .0005" tool clearance

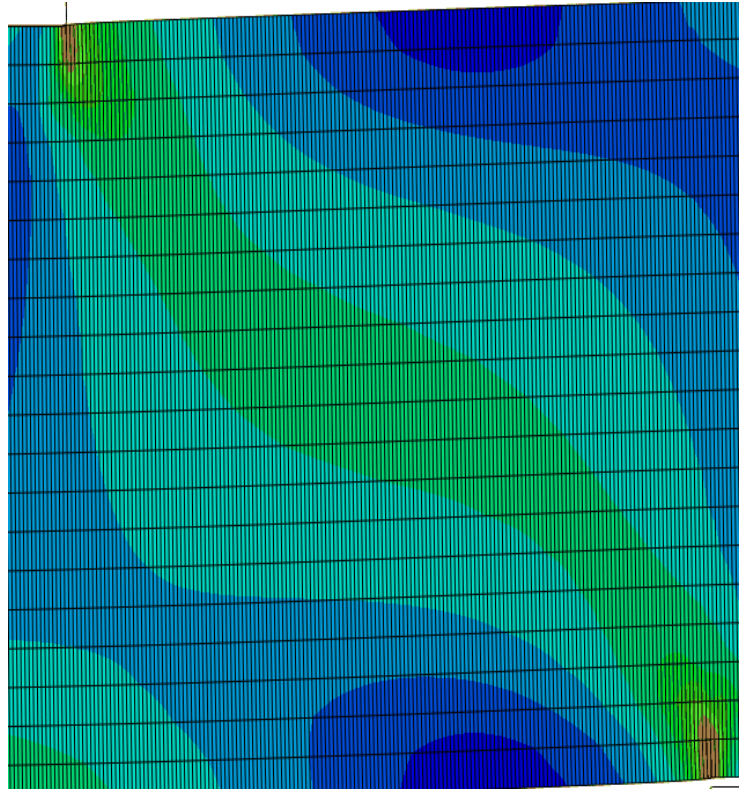


Figure 16: Stress field in .080" thick material with .080" tool clearance

A field output was created on the top cutter reference point to output only the displacements in the U2 direction. By tracking the displacement of the top cutter in the U2 direction the tool displacement at failure was recorded. Figure 17 shows the relationship of the tool displacement versus the tool offset of the 6061-T6 aluminum model. This data does not describe a definite point at which the primary cause of strain switches from shear to bending, however it does show that as the offset is increased there is more dependency on bending resulting in larger displacements.

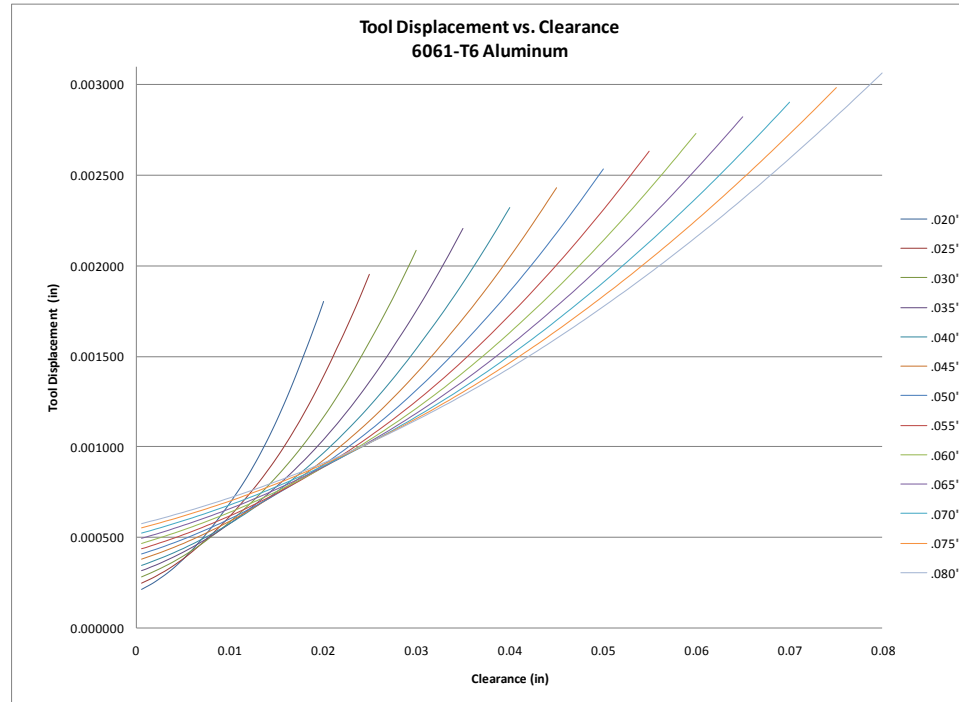


Figure 17: Tool displacement vs. tool offset for 6061-T6 aluminum

If the tool offset is normalized with respect to the thickness the result is a set of curves for each aspect ratio showing the difference in tool displacement required to reach the same stress and strain field in the material. This relationship is shown for the 6061-T6 aluminum in Figure 18 and it can be shown by the 4.5% and 8% clearance lines that there is a smaller difference in displacement of the tool cutter for each material thickness. This smaller difference shows that this tool clearance works for all thicknesses of this particular material. This same relationship is similar in the other three materials and can be seen in the figures of Appendix A.

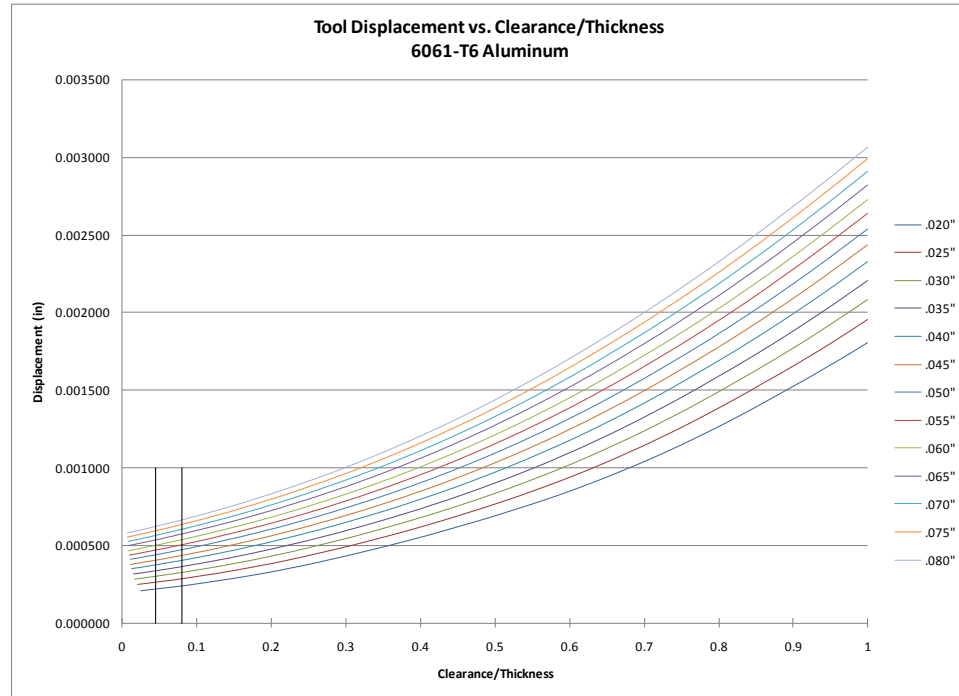


Figure 18: Tool displacement vs. normalized thickness for 6061-T6 aluminum

By calculating the shear strain in the shear zone using Equation 14 and normalizing the offset with thickness with the tool displacement there is a transition range between the 4.5% and 8% tool offset lines indicating that this is the area where there is higher strain for the loading condition for all thicknesses. This means that these offsets allow the failure strain to be reached with minimal tool displacement. This better describes the pure shear versus bending transition. While the offset is very small the strain is high making failure occur sooner. Figure 19 shows this relationship with the 4.5% and 8% lines. This relationship can be seen with the other materials modeled and can be seen in appendix A

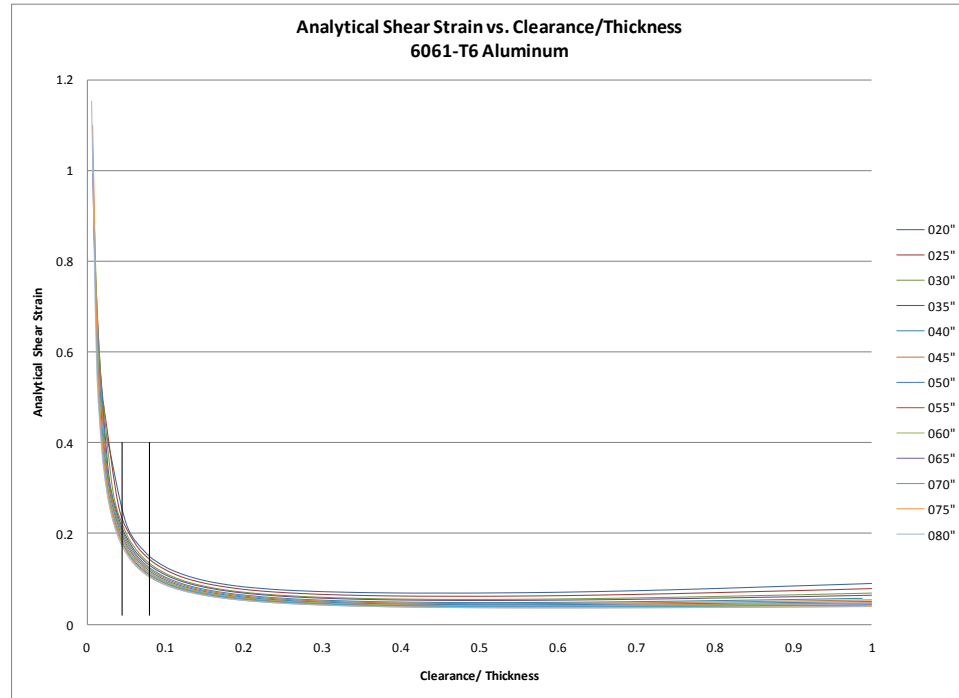


Figure 19: Analytical shear strain vs. normalized tool offset

From the fact that the stress zone grows in the same manner from tool tip to tool tip, and that the model does not simulate the separation of the material the model was adapted to better describe the process with failure. This was accomplished by applying a layer of cohesive elements at a specified position.

All of these shapes and trends are consistent for all materials and thicknesses. Figure 20 shows the similarity between normalized tool displacement and normalized clearance for all selected materials at a thickness of .020" with their respective applied loads. The variations in the shapes of the data series is due to the difference in material flow characteristics. For all thicknesses of a material the same maximum stress is reached during the cutting process.

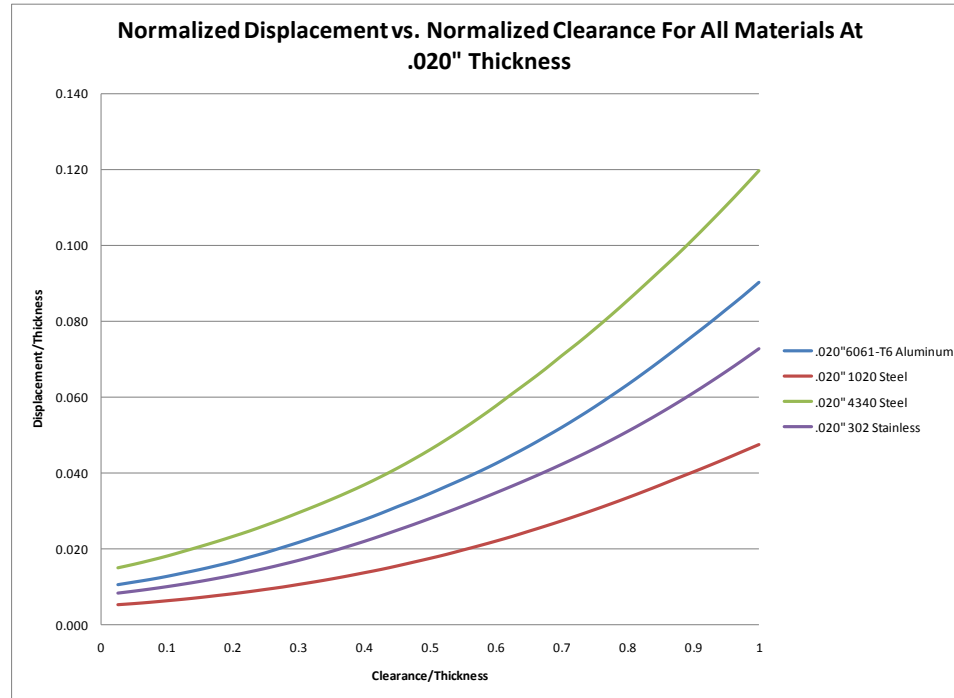


Figure 20: Same thickness for all materials

It should be noted that there is an x component of the reactive force in this model that should be addressed. Due to the boundary conditions of the cutting tools be held rigid in the x direction there must be a reactive force due to this lack of movement. This information is important to note because it relates to the stiffness of the cutting tool and the length of the cut. The tool cutter must consist of a material that resists this reactive force to maintain a constant tool clearance optimizing the process. As the length of cut is increased the net force on the cutter increases thereby increasing the deflection which in turn increases the tool clearance. This increase in tool clearance will result in a higher displacement required to reach a strain level of failure in the part as seen in Figure 19.

This same force causes a coupling moment on the cutting tool. This moment would need to be resisted in the cutting tool. This phenomenon is experienced when

using tin snips and having the handles rotate. The larger the distance between tools the higher the reactive moment.

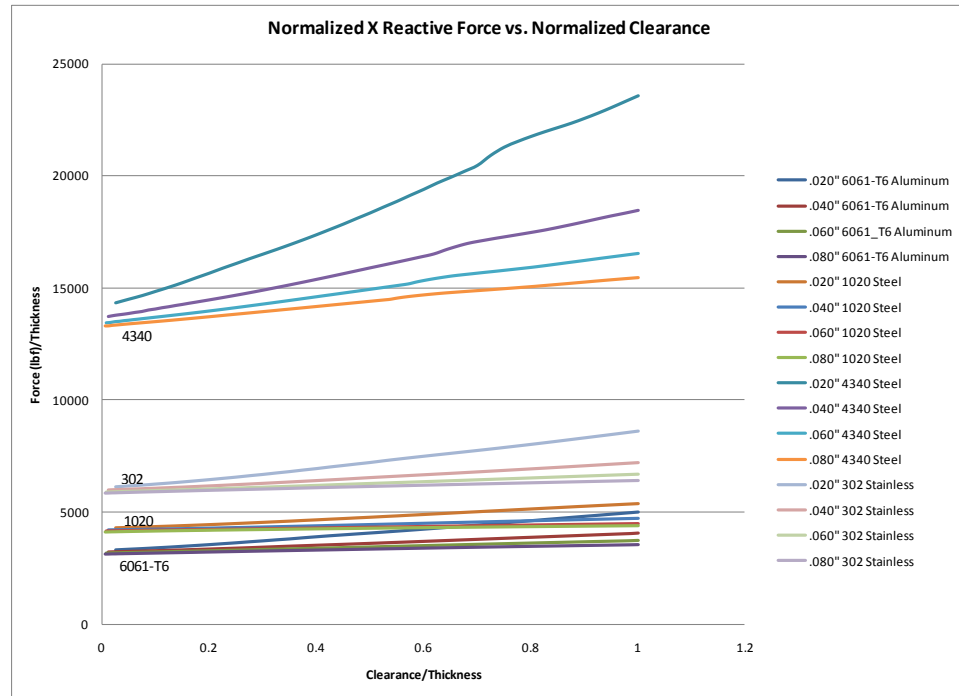


Figure 21: X-direction reactive force on top cutter

By also tracking the x-direction reactive forces on the top cutter it can be shown that the force increases as the tool clearance is increased as seen in Figure 21. This information was readily available and could be used for further analysis and in designing of the tools. Their rigidity and length would depend on the tool clearance and cut length.

MODELING ADVANCEMENT

Based upon the conclusions from the preliminary results and analysis it was decided to adapt the model using cohesive elements to show the separation due to the cutting process. A new section of the material plate was created with a thickness of .0005" and assigned cohesive elements for the mesh. This section was created to go from tool tip to tool tip which is known where the highest stress and strain field grows in the same manner independent of thickness and clearance, from the preliminary analysis shown in Figure 15 and Figure 16

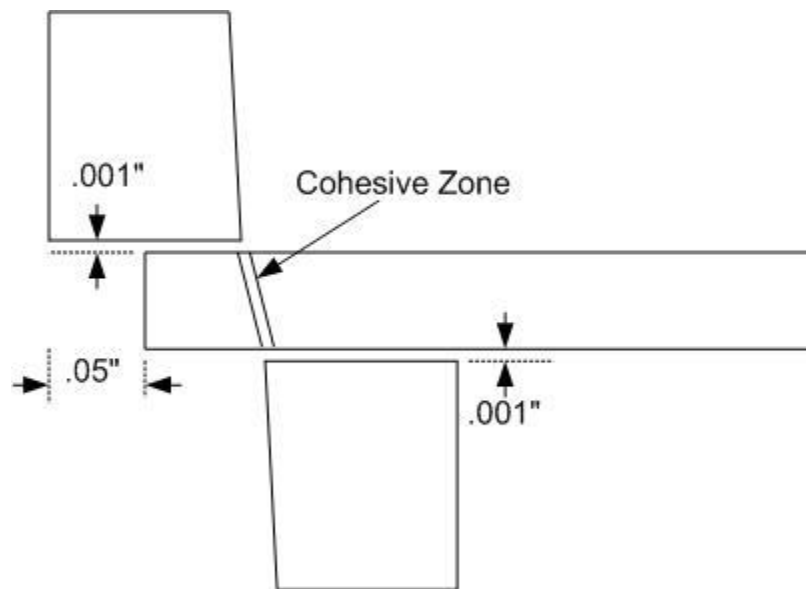


Figure 22: Full model geometry with cohesive element zone

Cohesive Elements

Cohesive elements are primarily used in analysis of bonded plates with adhesive properties, or in de-lamination analysis through the process of traction separation. They

were chosen in this case for the purpose of describing the separation of the two halves of the material plate at the shearing zone. The separation of the material can be described as that of tractions separation within the stress field from tool tip to tool tip.

In order to apply the cohesive elements the material plate model was adapted by creating two parallel partition faces from tip to tip locations. The section created between these two partition faces was designated to be meshed with the cohesive elements and assigned the material properties required for the cohesive zone. Field outputs were created from the set of cohesive elements to track the damage.

Cohesive Material Description

Material parameter values required for each of the engineering materials selected vary, however the parameters themselves are consistent throughout. The material must first be defined as elastic traction type with Young's modulus and shear modulus. It must then be defined with damage evolution. The element type is COH2D4, which is a four node two dimensional cohesive element for use with traction separation criteria [22].

Traction Separation: Figure 23 describes the calculations of traction separation utilized by Abaqus. The first section is the linear elastic material description. The peak in the graph describes the point in which damage initiation has occurred. From that point the linear damage evolution is described by the final displacement at failure, or separation of the material. It is at this point in the analysis that the element is deleted from the model due to the fact that it no longer supports any load. The values for the final displacement at failure are required to describe the damage evolution in the element.

These values have been tabulated from the material property values for strain. This will be discussed in the displacement softening criteria section.

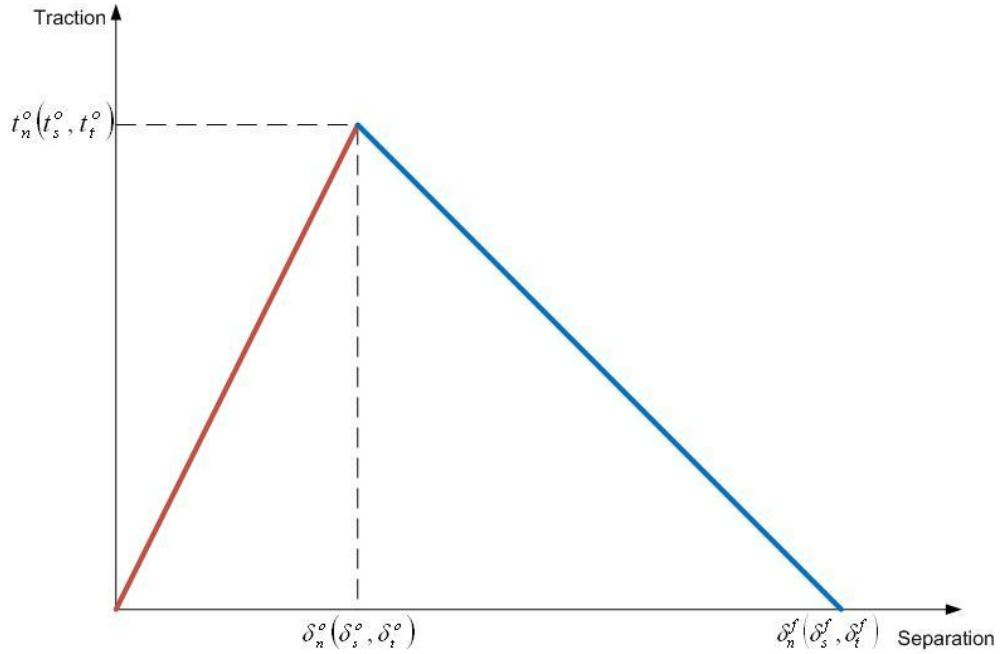


Figure 23: Traction separation with linear damage evolution

Max Nominal Stress Criterion: The criteria used in the cohesive element model to describe the traction response of the material was the MAXS, or max nominal stress criteria. This criterion is described in Equation 12 by stating that as the tractions in the part in relation to the specified maximum traction goes to the value of one, damage has initiated in the part. These traction forces are shown in Damage does not occur if there are only compressive loads in the element. This damage initiation is assumed to be the result of yielding and plastic deformation. From this point on, the material was described as having a linear softening effect as the displacement increased [22].

Equation 12: Max nominal stress criterion

$$MAX \left\{ \frac{\langle t_n \rangle}{t_n^0}, \frac{t_s}{t_s^0} \right\} = 1$$

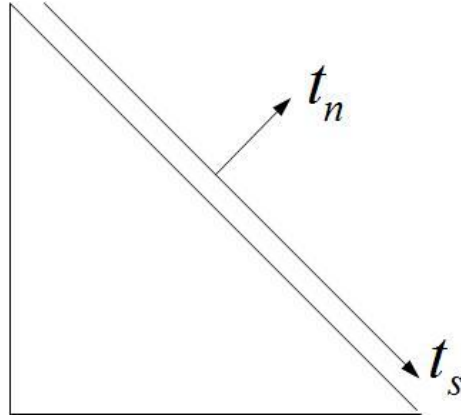


Figure 24: Traction components for cohesive elements

Displacement Softening Criterion: The displacement softening criterion describes the second zone of Figure 23 between damage initiation and failure. By defining an effective displacement at complete failure, δ_m^f , relative to the displacement at damage initiation, δ_m^0 the softening modulus is described by Equation 13.

Equation 13: Abaqus defined displacement failure criterion

$$\delta = \delta_m^f - \delta_m^0$$

These values were calculated using the shear strain calculations combined with element size and material properties. Figure 25 represents the shear strain, γ , in the material due to the applied load, F . This shear strain is calculated geometrically as the change in angle, α as described by Equation 14.

Equation 14: Shear strain

$$\gamma = \frac{d}{L}$$

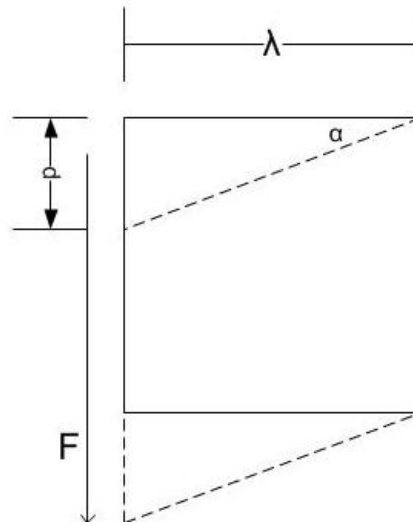


Figure 25: Shear Strain

From the strain at yield and the strain at failure material properties the displacement difference can be extrapolated using the shear strain Equation 14. A list of these calculated values are listed below in Table 6.

Table 6: Displacement values for damage evolution

Material	δ
6061-T6 aluminum	$1.66e^{-5}$
1020 Steel	$1.48e^{-5}$
4340 Steel	$1.18e^{-5}$
302 Stainless	$5.69e^{-5}$

Damage and Element Deletion: Damage in the elements is a function of the displacements in that element. From Equation 15 it is shown that the damage starts at a value of zero and increases based upon the specified traction separation criteria described previously. Once the material damage has reached a value of one it has completely failed and the stiffness has gone to zero. It is at this point that the element can be deleted from the model.

Equation 15: Damage evolution criterion

$$D = \frac{\delta_m^f(\delta_m^{max} - \delta_m^0)}{\delta_m^{max}(\delta_m^f - \delta_m^0)}$$

Cutting Tool Advancement

Several initial analyses were run using the cutting tool geometry from the preliminary analysis model. This tool geometry was shown to not have an aggressive enough relief angle resulting in tool relief face contact with the material plate. This effect resulted in higher reaction forces in both the x and y directions. Figure 26 shows the resulting contact on the relief face. In order to eliminate this, the cutting tool geometry was changed to have an arbitrarily large relief angle of 26.6 degrees. The new cutting tool geometry resulted in elimination of contact with the relieved face, however there is still contact at the radius surface of tool tip. This contact has a negligible effect on the resultant forces due to the maximum force occurring after the material has cleared the tool tip.

The new tool geometry is shown in Figure 27.

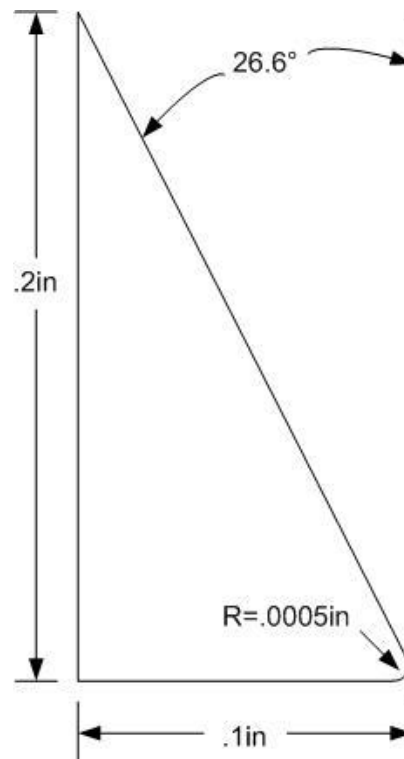


Figure 27: Adapted tool geometry for cohesive model

From the results previously, the cutting tool relief angle is a function of the flow characteristics of the material being cut. For a more ductile material being cut there will be a resulting higher relief angle required in order to alleviate contact with the cutter face. This is due to the higher strains exhibited by a ductile material meaning that it will curl over during the cutting process and contact with the cutter face. For a more brittle material which does not flow as far as a brittle material a smaller relief angle would be needed to eliminate the tool contact.

This relationship to the ductility of the material was found through the completion of the first set of completed analyses using the cohesive zone. It was found that the aluminum model and the stainless steel model were the two that contacted the cutting tool face requiring the adaptation to the larger relief. This was due to the fact that these two materials exhibit more ductile type behavior than the other two steel materials chosen. This increased ductility results in a higher displacement during the cutting process allowing the cut edge to displace far enough to make contact with the cutting tool. This was not seen in the materials that exhibit a more brittle type material response.

RESULTS AND DISCUSSION

The cohesive zone shows the separation of the material during the cutting process and is shown in Figure 28. It is shown that the stress field grows in the same manner as the first analysis and results in strength degradation leading to element deletion.

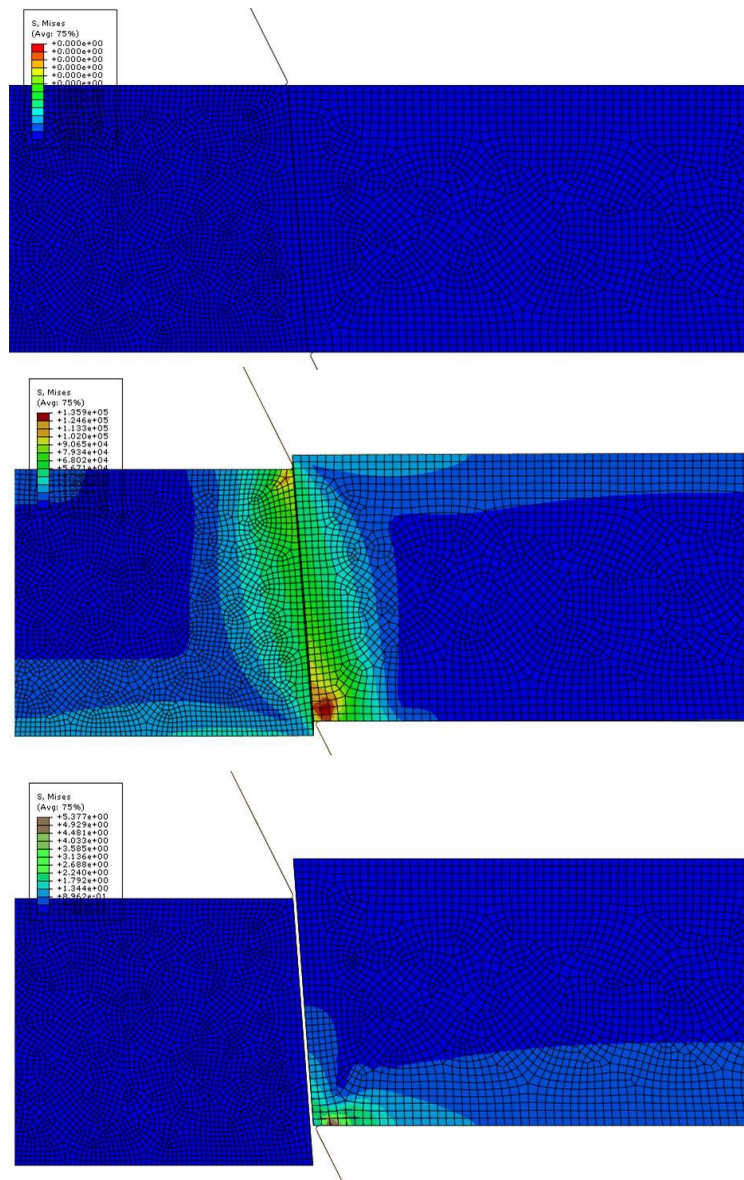


Figure 28: Steps showing cohesive model separation

From tracking of the reactive force in the y-direction and plotting it versus the normalized material thickness shown in Figure 29 for the case of .020" 1020 steel there is a trend of increasing force as the tool clearance is increased. Upon further inspection of other materials this is shown to be consistent for all materials and thicknesses.

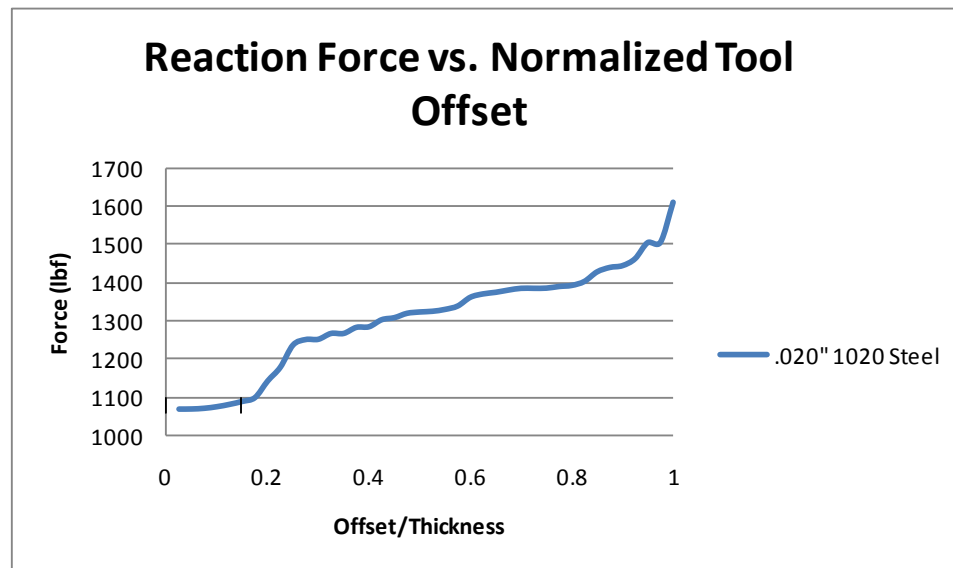


Figure 29: Reactive force in .020" 1020 cohesive model

Due to the consistency of the increasing trend of the reactive force it was decided to focus in on the first 15% of tool clearances. The first section of the .020" 1020 steel data is shown in Figure 30 which shows a minimum reactive force being in this regime. It was further decided to decrease the increments of tool clearance steps to .0001" in search of a local minimum of reactive force in the smaller tool clearance regime. The process was again optimized using Python codes for thicknesses of .020", .040", .060", and .080" in order to capture the entire set of material thicknesses.

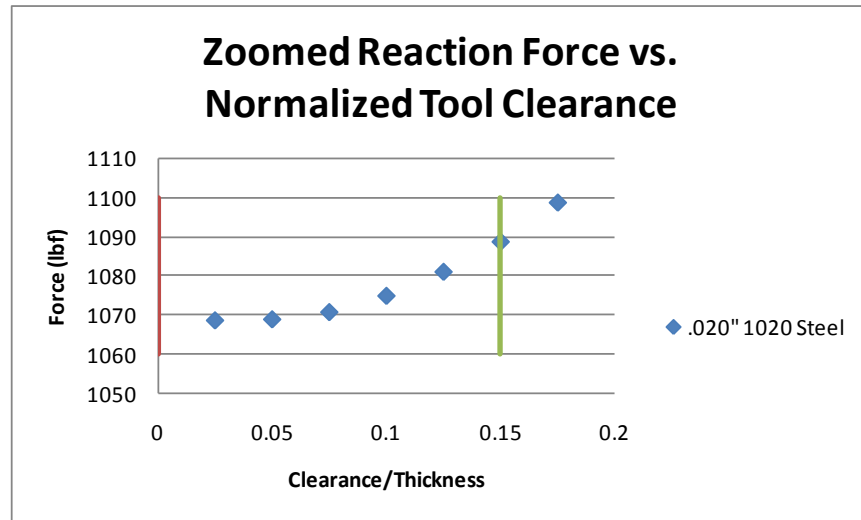


Figure 30: Zoomed lower end of .020" 1020 cohesive model

In the case of .020" 1020 steel shown in Figure 31 there is a definite local minima in reactive force. By curve fitting the data with a second order polynomial and differentiating, the value of the local minima is calculated. This value is the allowance from before in the analytical clearance calculations.

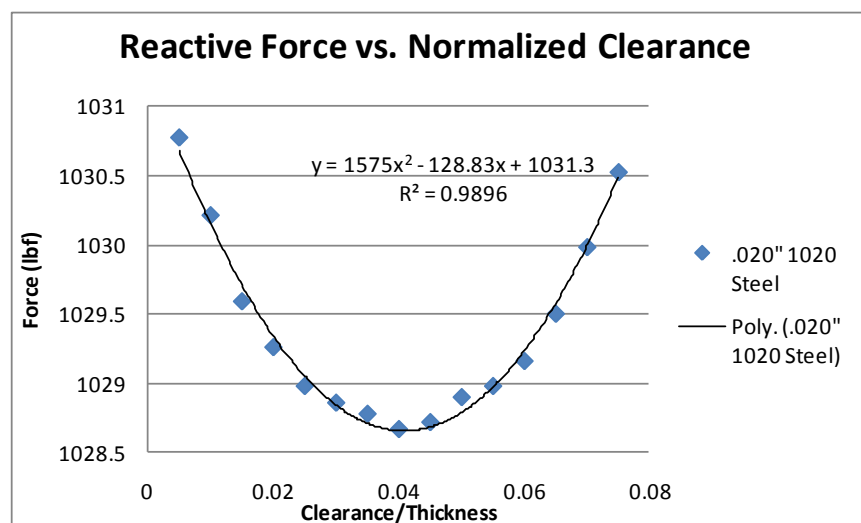


Figure 31: Zoomed cohesive reactive force for .020" 1020 steel

Optimum tool allowances for all the metals selected, at the .020", .040", .060", and .080" thicknesses, is shown in Figure 32. These data series can be trend fit for the calculation of all material thicknesses both between .020" and .080" as well as beyond these limits. Specific values of optimum tool allowance are shown in Table 7

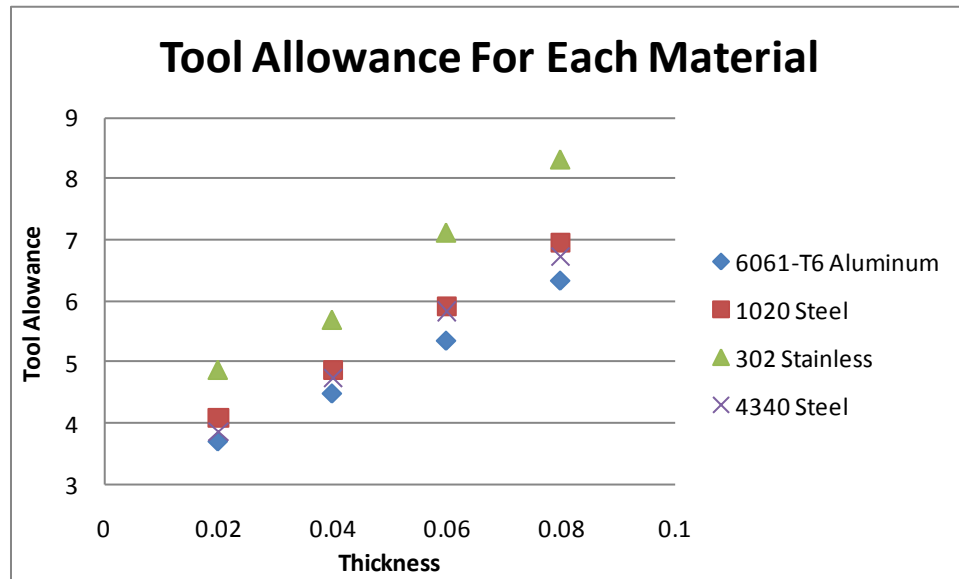


Figure 32: Optimum tool allowance

Table 7: Optimum tool allowance

<i>Material</i>	<i>0.02"</i>	<i>0.04"</i>	<i>0.06"</i>	<i>0.08"</i>
6061-T6	3.69	4.48	5.35	6.34
1020	4.09	4.87	5.92	6.95
4340	3.85	4.74	5.83	6.73
302	4.87	5.69	7.12	8.32

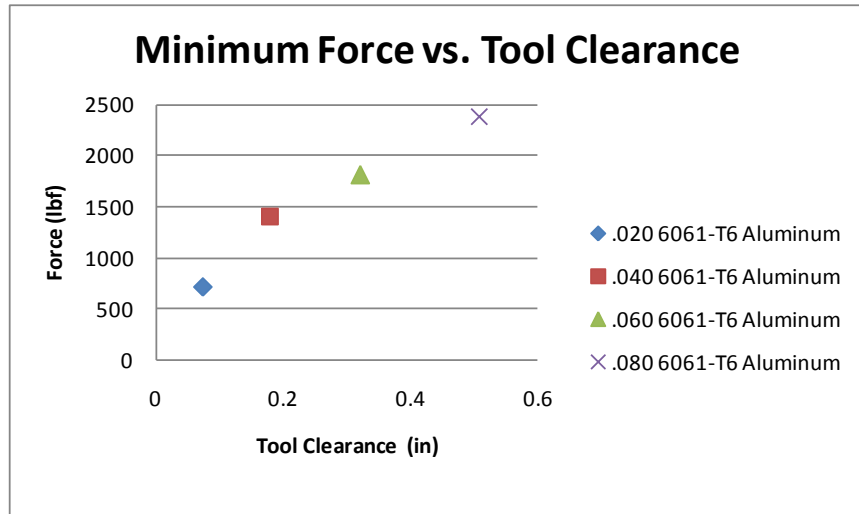


Figure 33: Minimum reactive force vs. tool clearance for 6061-T6 aluminum

Figure 33 shows the relationship between the minimum reactive force and the tool clearance for the thicknesses chosen for the 6061-T6 aluminum. This relationship shows an increase in tool clearance as well as an increase in force as the thickness is increased for a material. This increase in force is congruent with the analytical calculations performed previously. This also shows the increase in tool clearance which is a function of the allowance and the thickness which is a percentage base. For an increase in material thickness the clearance will increase for the same allowance from the analytical calculations.

The use of the cohesive zone and elements with traction separation definitions limits the tool clearance to being a function of only ultimate tensile strength of the material, Young's modulus, and the strain at failure. By increasing the ultimate tensile strength of the material the resulting reactive force will increase as well. By changing modulus of the material you change the displacement of the part at which the failure is

initiated. If you change the failure strain the reactive displacement will change as a result. These types of relationships are shown in Figure 34.

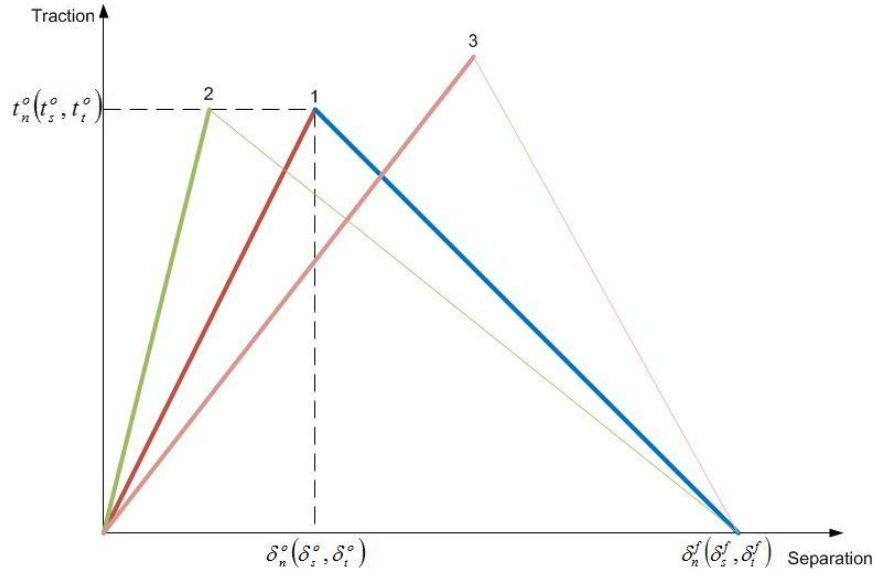


Figure 34: Changes in cohesive element description

A parametric study was effectively completed by simply running the analyses. Abaqus does not know the difference between the materials as they are named, but rather by the parameters given in order to describe the materials response. Due to this fact it is shown by the results for the cohesive model that the tool geometry becomes a function of the parameters chosen. In this set of materials the tool clearance decreases with ductility, while the relief angle increases as ductility increases.

CONCLUSIONS

There is a tool clearance in the tool geometry that results in a minimum force requirement for the cutting operation. This optimum tool clearance is largely within the 4.5-8% convention in references. Optimizing of the tool geometry will result in easier cutting of materials with less energy required, as well as operation specific tool design.

This analysis verifies the linear cohesive zone approximation between the two tool tips. Due to the fact that the optimum tool clearance is of such a small value the stress zone is a maximum across the line between the tool tips. This would not hold true if the minimal force were at a larger tool clearance and would result in erroneous information of the reactive force. The line between the tool tips is an accurate assumption in the smaller tool clearances where the reactive force has a local minimum.

Optimum geometries ranged from 3.8% to 8.3% for all of the selected materials within the thickness range specified. Materials with a more ductile material response were shown to require a smaller tool allowance while more brittle materials require a larger allowance. As the material thickness increases the tool allowance increases as well.

The tool clearance in this analysis is a function of the modulus of the material being cut and the ultimate strength of the material as well. These two values will change the result of the analysis by shifting the damage description of the cohesive elements.

Cohesive element zones were shown to be adequate in modeling the cutting of sheet metals in two dimensions. Traction separation grasps the material failure phenomenon in the material during the process.

FUTURE WORK

The research conducted only encompassed the tool clearance in the shearing process. There are many other factors that could be included in future research to develop a vast understanding of all aspects involved. The future research would allow for development of an optimized shear tool.

Cutting tool geometry specifics such as tool relief angle on the cutting face, serrations on cutting edge, and basic geometry could affect the material response during the process. These geometries could change the reactive forces in all directions on the tool face, and the required forces for the process.

Another aspect that could be explored would be that of tool wear and fatigue over life of use. Does the cutting edge geometry change the life of the tool and how does it change over time? What types of tool geometry minimize tool wear while optimizing the forces required? These are answers that could be addressed.

In terms of tool geometry the questions has been posed as to whether or not serrations on the cutting face affect the outcome of the process. What purpose do the serrations serve in the process, and how do they affect tool wear and tool response.

All of the previously stated aspects could be combined for the two most common types of shear tools out there, scissoring, and straight edge. What is the primary difference between the two types and what are their primary modes of failure? Which type provides the optimum strain field required for failure to occur? \

REFERENCES

- [1] Bolt, P. J., and Sillekens, W. H., 2000, "Prediction of shape aberrations due to punching, shearing and slitting," *Journal of Materials Processing Technology*, 103(1), pp. 87-94.
- [2] Bratus, V., Kosel, F., and Kovac, M., 2010, "Determination of optimal cutting edge geometry on a stamped orthotropic circular electrical steel sheet," *Journal of Materials Processing Technology*, 210(2), pp. 396-407.
- [3] Faura, F., Garcia, A., and Estrems, M., 1998, "Finite element analysis of optimum clearance in the blanking process," *Journal of Materials Processing Technology*, 80-1, pp. 121-125.
- [4] Ghosh, S., Li, M., and Khadke, A., 2005, "3D modeling of shear-slitting process for aluminum alloys," *Journal of Materials Processing Technology*, 167(1), pp. 91-102.
- [5] Haboussa, D., Gregoire, D., Elguedj, T., Maigre, H., and Combescure, A., 2011, "X-FEM analysis of the effects of holes or other cracks on dynamic crack propagations," *International Journal for Numerical Methods in Engineering*, 86(4-5), pp. 618-636.
- [6] Hansen, N., Huang, X., and Winther, G., 2011, "Effect of Grain Boundaries and Grain Orientation on Structure and Properties," *Metallurgical and Materials Transactions a-Physical Metallurgy and Materials Science*, 42A(3), pp. 613-625.
- [7] Hatanaka, N., Yamaguchi, K., and Takakura, N., 2003, "Finite element simulation of the shearing mechanism in the blanking of sheet metal," *Journal of Materials Processing Technology*, 139(1-3), pp. 64-70.
- [8] Hayajneh, M. T., Astakhov, V. P., and Osman, M. O. M., 1998, "An analytical evaluation of the cutting forces in orthogonal cutting using a dynamic model of the shear zone with parallel boundaries," *Journal of Materials Processing Technology*, 82(1-3), pp. 61-77.
- [9] Jagirdar, R., Jain, V. K., Batra, J. L., and Dhande, S. G., 1996, "Characterization of shearing features for sheet metal components in 2-D layout," *International Journal of Production Research*, 34(1), pp. 157-190.

- [10] Komori, K., 2001, "Simulation of shearing by node separation method," *Computers & Structures*, 79(2), pp. 197-207.
- [11] Li, Y. N., Luo, M., Gerlach, J., and Wierzbicki, T., 2010, "Prediction of shear-induced fracture in sheet metal forming," *Journal of Materials Processing Technology*, 210(14), pp. 1858-1869.
- [12] Loehnert, S., Mueller-Hoeppe, D. S., and Wriggers, P., 2011, "3D corrected XFEM approach and extension to finite deformation theory," *International Journal for Numerical Methods in Engineering*, 86(4-5), pp. 431-452.
- [13] Mackensen, A., Golle, M., Golle, R., and Hoffmann, H., 2010, "Experimental investigation of the cutting force reduction during the blanking operation of AHSS sheet materials," *Cirp Annals-Manufacturing Technology*, 59(1), pp. 283-286.
- [14] Marklin, R. W., Lazuardi, L., and Wilzbacher, J. R., 2004, "Measurement of handle forces for crimping connectors and cutting cable in the electric power industry," *International Journal of Industrial Ergonomics*, 34(6), pp. 497-506.
- [15] Merle, R., and Zhao, H., 2004, "Experimental study of sheet metals under dynamic double shear at large strains," *Advances in Engineering Plasticity and Its Applications*, Pts 1 and 2, W. P. Shen, and J. Q. Xu, eds., Trans Tech Publications Ltd, Zurich-Uetikon, pp. 787-792.
- [16] Qin, S. J., Li, H. B., Peng, J. G., and Li, S. B., 2003, "Numerical simulation and optimization of clearance in sheet shearing process," *Transactions of Nonferrous Metals Society of China*, 13(2), pp. 407-411.
- [17] Saanouni, K., Belamri, N., and Autesserre, P., 2010, "Finite element simulation of 3D sheet metal guillotining using advanced fully coupled elastoplastic-damage constitutive equations," *Finite Elements in Analysis and Design*, 46(7), pp. 535-550.
- [18] Steglich, D., Wafai, H., and Besson, J., 2010, "Interaction between anisotropic plastic deformation and damage evolution in Al 2198 sheet metal," *Engineering Fracture Mechanics*, 77(17), pp. 3501-3518.

- [19] Tugcu, P., Wu, P. D., and Neale, K. W., 2002, "On the predictive capabilities of anisotropic yield criteria for metals undergoing shearing deformations," *International Journal of Plasticity*, 18(9), pp. 1219-1236.
- [20] Callister, W. D., *Materials Science and Engineering an Introduction*.
- [21] Gere, J. M., *Mechanics of Materials*.
- [22] "Abaqus Analysis User's Manual (6.9)."
- [23] Shames, I. H., and Cozzarelli, F. A., *Elastic and Inelastic Stress Analysis*.
- [24] 2011, "Online Materials Information Resource - MatWeb."
- [25] Groover, M. P., *Fundamentals of Modern Manufacturing*.
- [26] Anderson, T. L., 1994, *Fracture Mechanics: Fundamentals and Applications*, Second Edition, CRC Press.

APPENDICES

APPENDIX A

FIRST FEM RESULTS

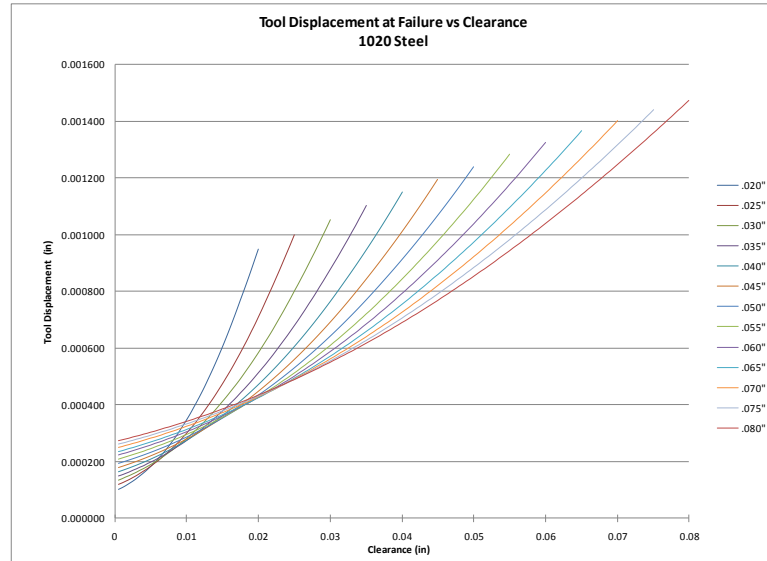


Figure 35: Tool displacement vs. clearance for 1020 steel

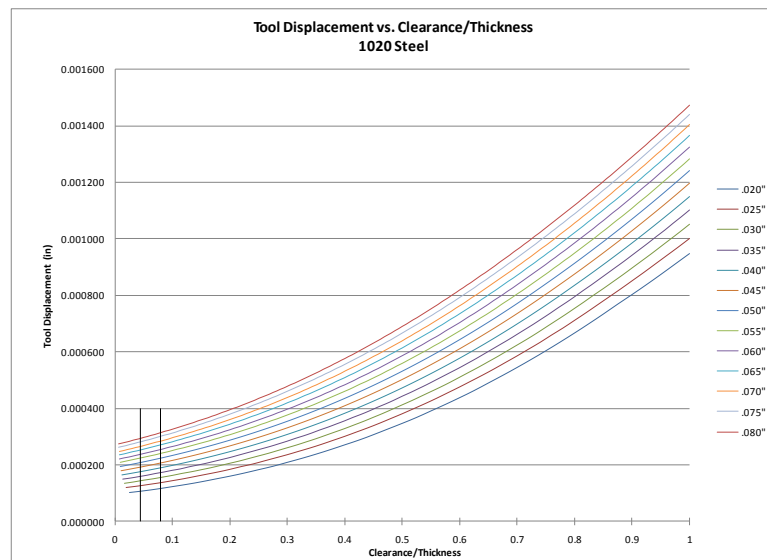


Figure 36: Tool displacement vs. normalized clearance for 1020 steel

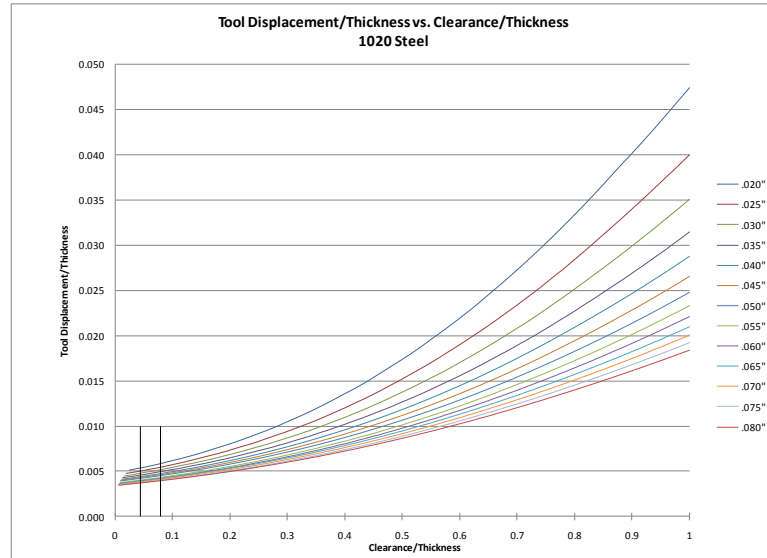


Figure 37: Normalized tool displacement vs. normalized clearance for 1020 steel

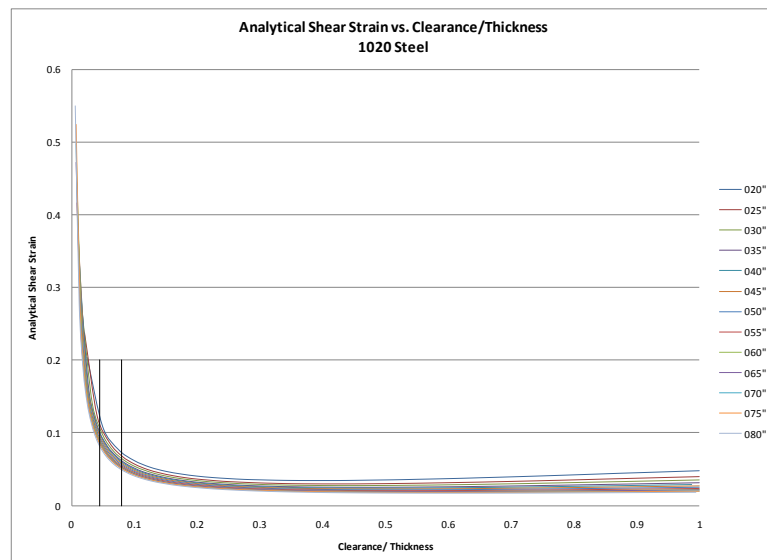


Figure 38: Analytical shear strain vs. normalized clearance for 1020 steel

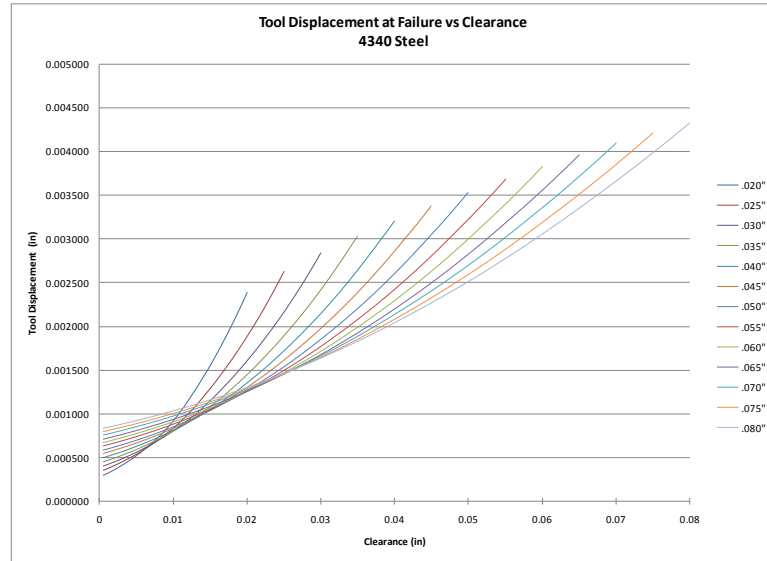


Figure 39: Tool displacement vs. clearance for 4340 steel

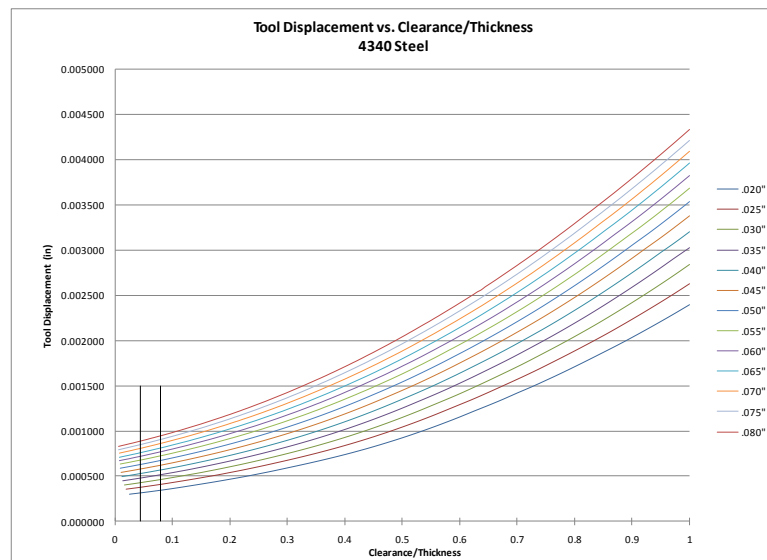


Figure 40: Tool displacement vs. normalized clearance for 4340 steel

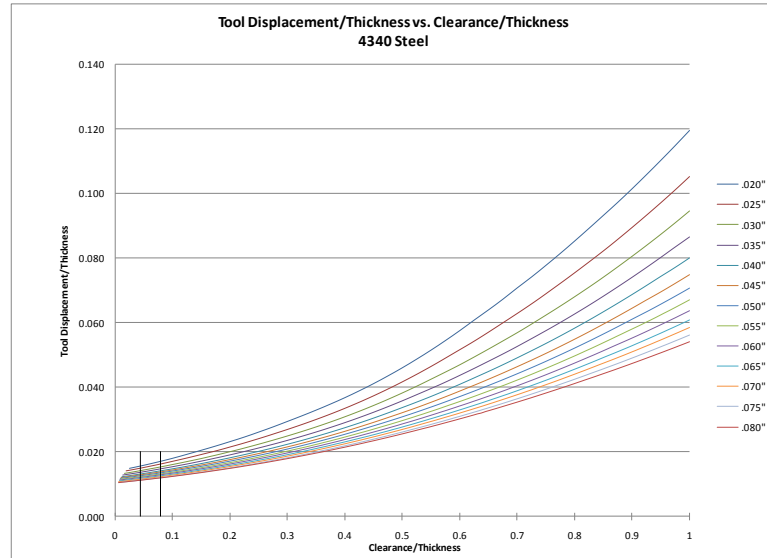


Figure 41: Normalized displacement vs. normalized clearance for 4340 steel

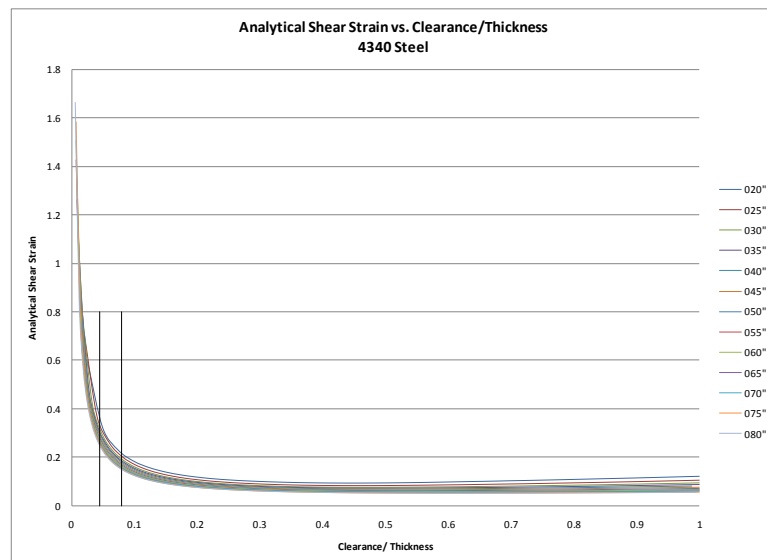


Figure 42: Analytical shear strain vs. normalized clearance for 4340 steel

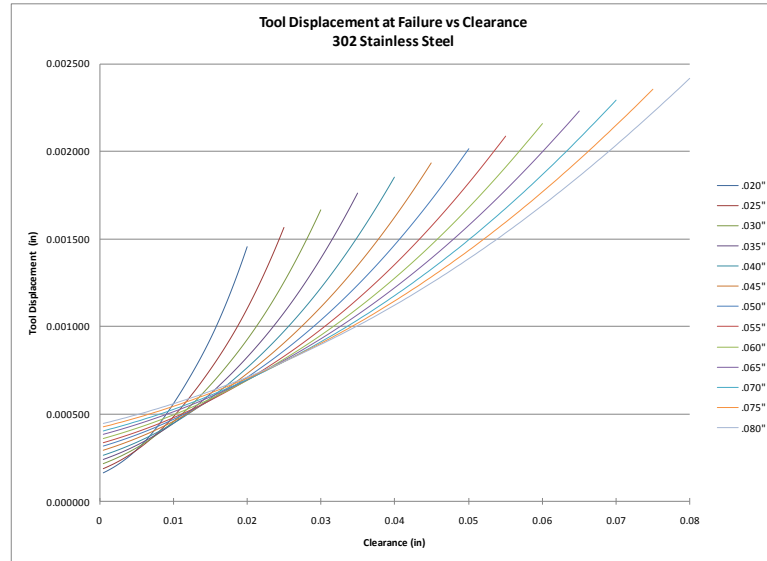


Figure 43: Tool displacement vs. clearance for 302 stainless steel

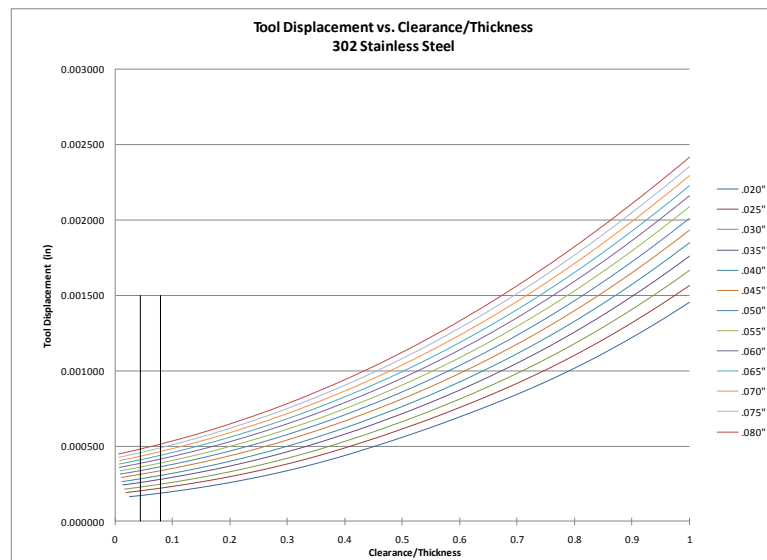


Figure 44: Tool displacement vs. normalized clearance for 302 stainless steel

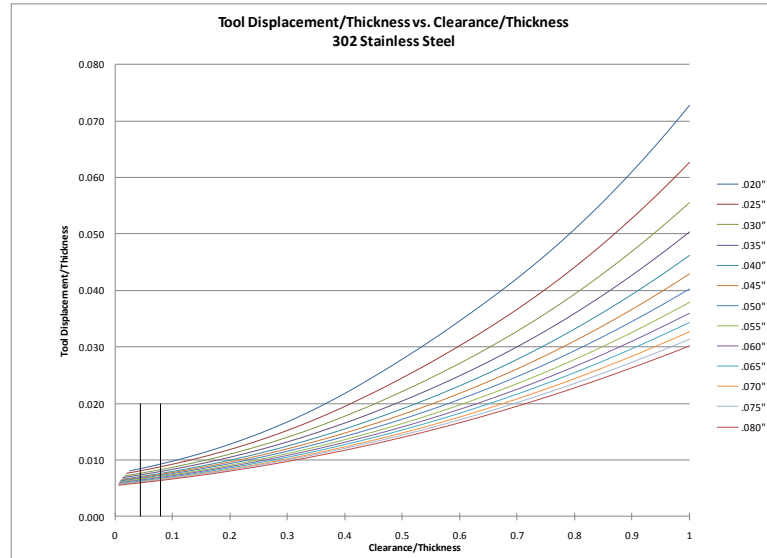


Figure 45: Normalized displacement vs. normalized clearance for 302 stainless steel

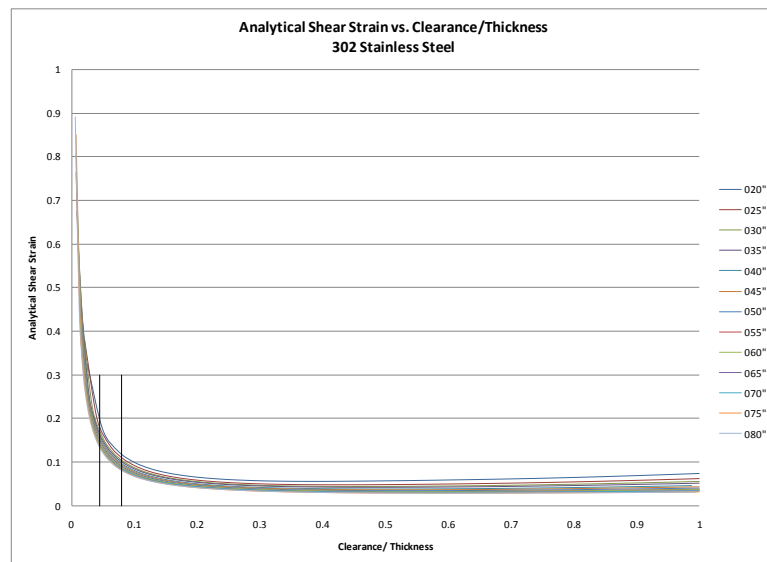
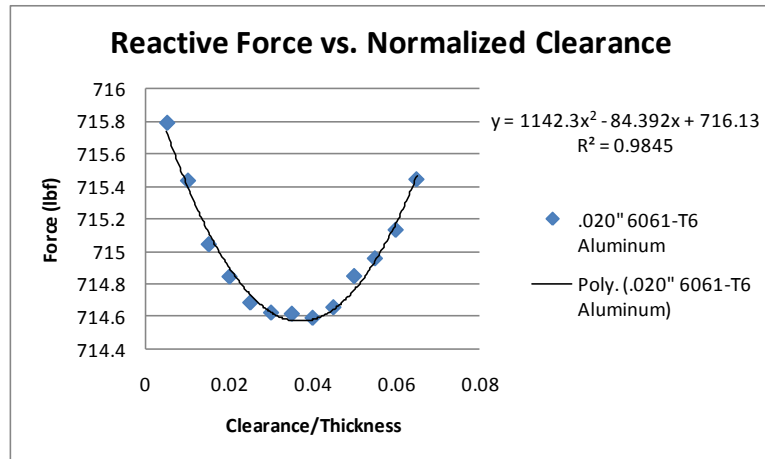
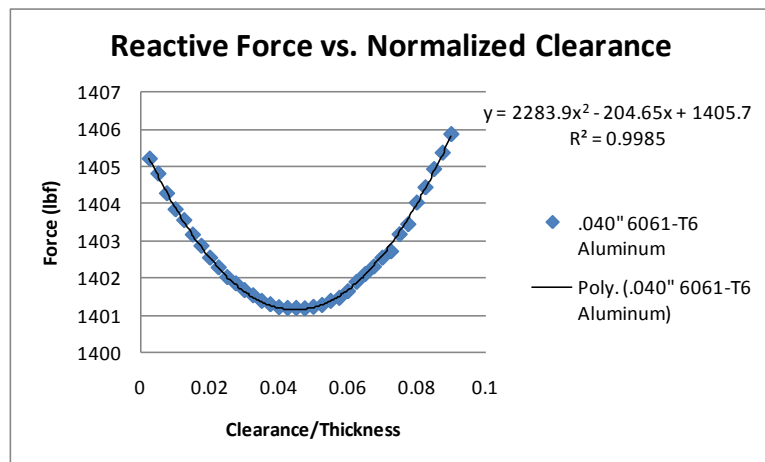
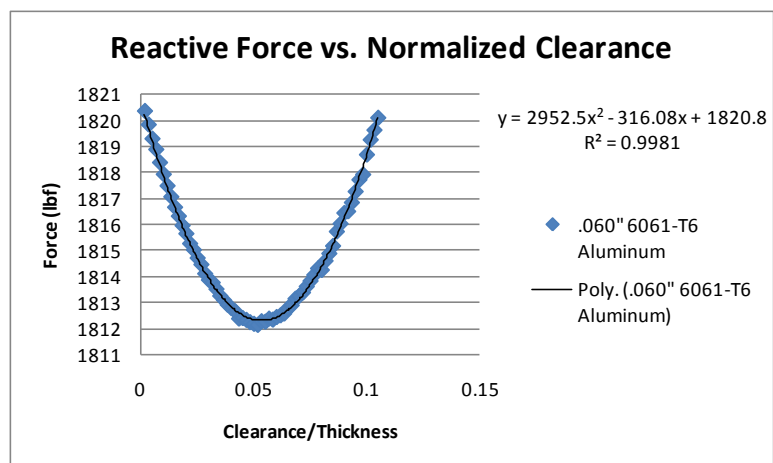
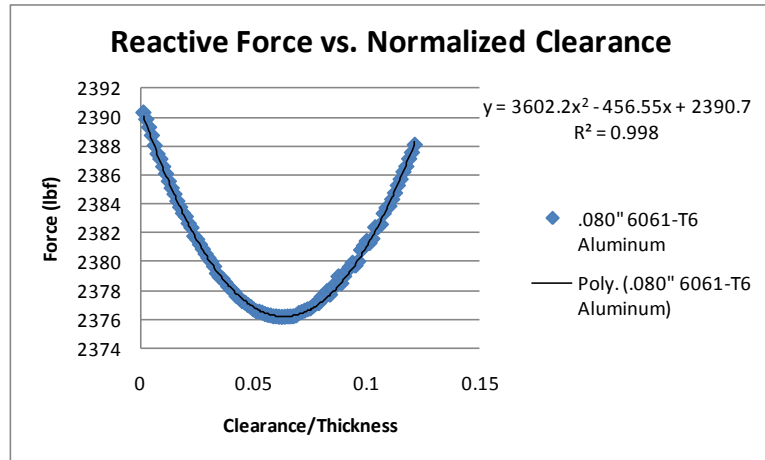
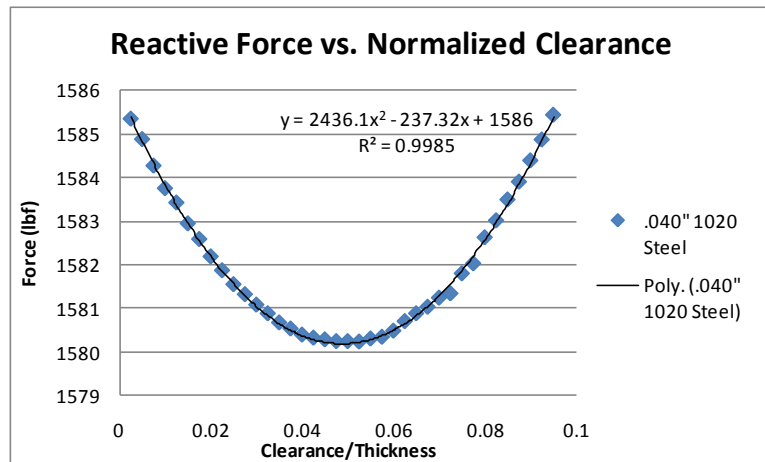
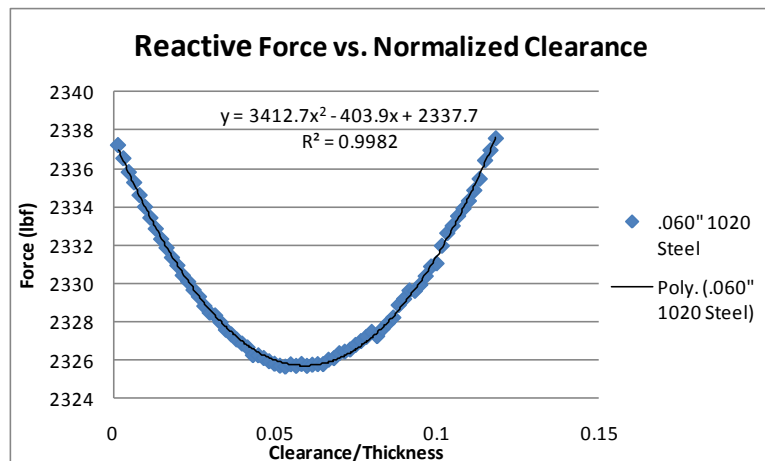


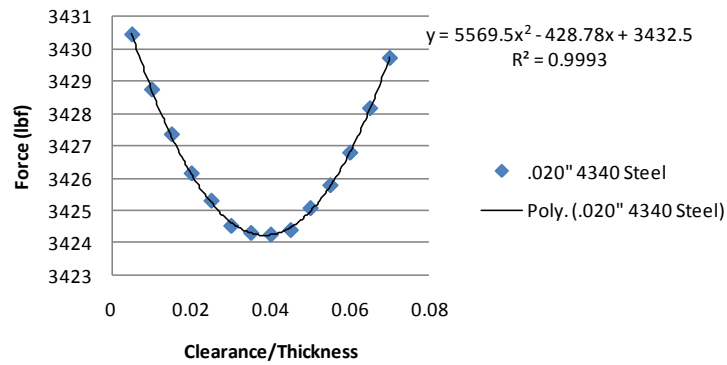
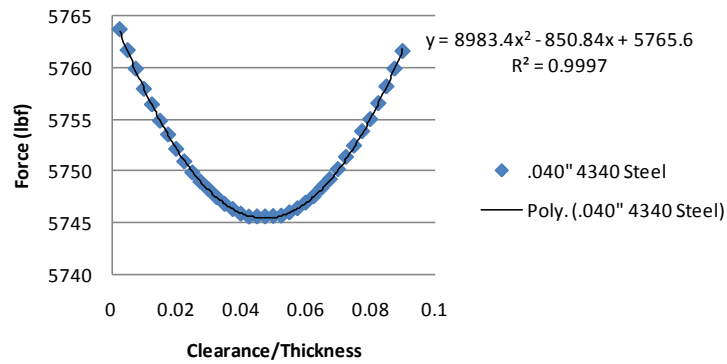
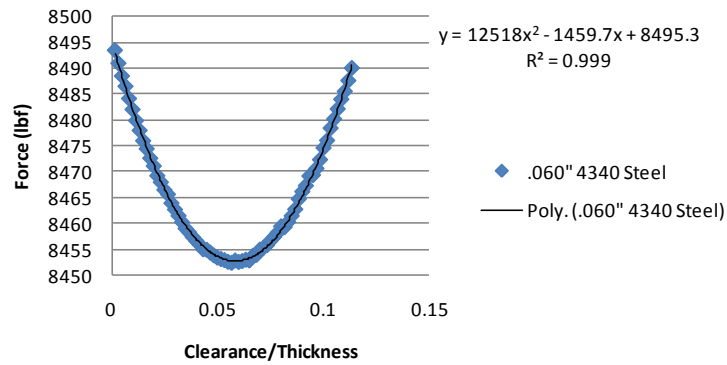
Figure 46: Analytical shear strain vs. normalized clearance for 302 stainless steel

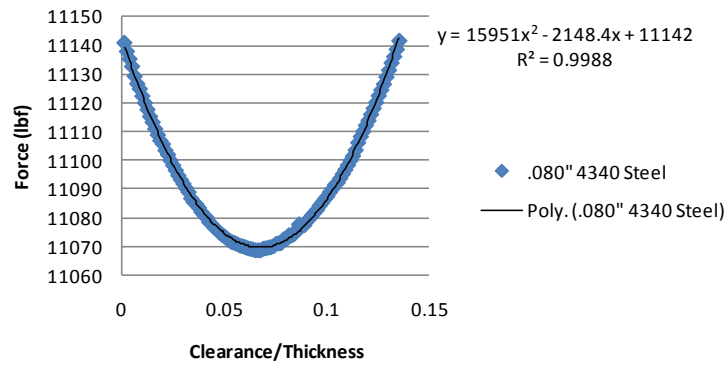
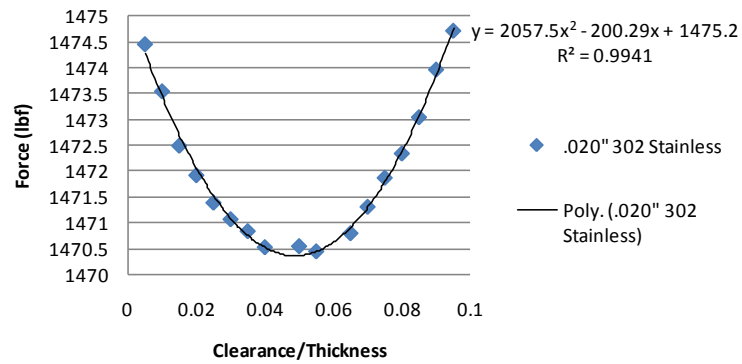
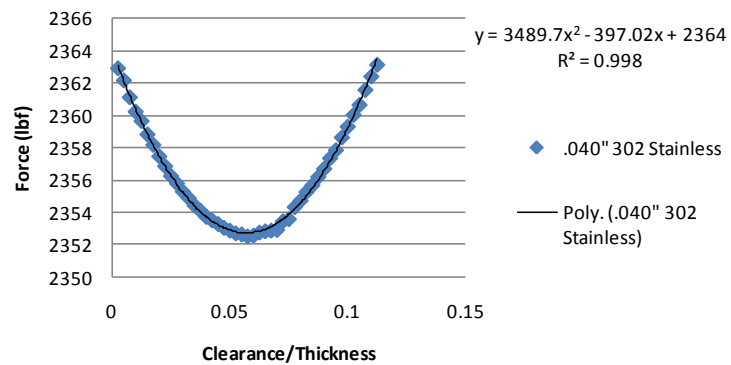
APPENDIX B

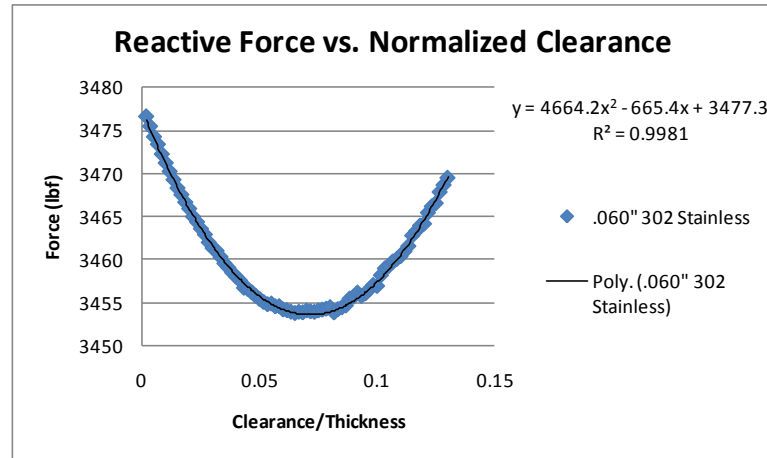
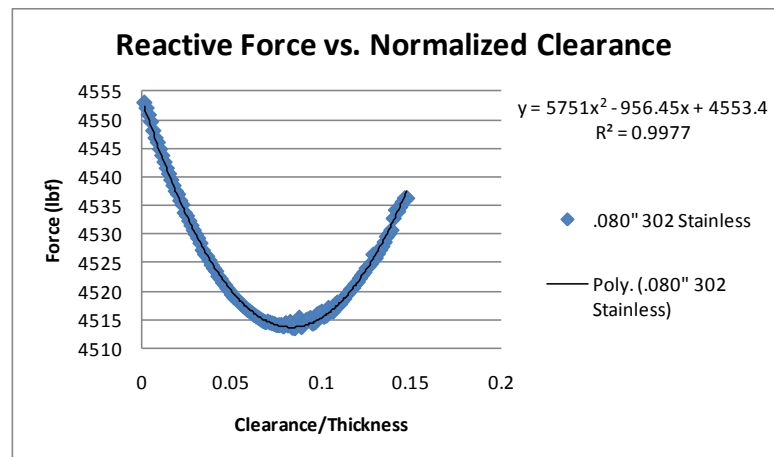
COHESIVE FEM RESULTS





Reactive Force vs. Normalized Clearance**Reactive Force vs. Normalized Clearance****Reactive Force vs. Normalized Clearance**

Reactive Force vs. Normalized Clearance**Reactive Force vs. Normalized Clearance****Reactive Force vs. Normalized Clearance**



APPENDIX C

SAMPLE CODING

Python code required to run all input files in a designated work directory:

```

Import os, glob
NewInputFiles=glob.glob(*.inp)
For file in NewInputFiles:
    Print „INPUT FILE =%s’ %file
    Str=’abaqus job=%s int ask=off’ %file
    Os.system(str)

```

Sample macro in Python required to incrementally increase tool offset for a .020” thickness and a material:

```

From abaqus import *
From abaqusConstants import *
Import __main__

```

```

Def Macro():
    import section
    import regionToolset
    import displayGroupMdbToolset as dgm
    import part
    import material
    import assembly
    import step
    import interaction
    import load
    import mesh
    import job
    import sketch
    import visualization
    import xyPlot
    import displayGroupOdbToolset as dgo
    import connectorBehavior
    for i in range (40):
        a = mdb.models[„Model-1’].rootAssembly
        a.features[„Edge to Edge-4’].setValues(clearance=-0.2005-i*.0005)
        a = mdb.models[„Model-1’].rootAssembly
        a.regenerate()
        session.viewports[„Viewport: 1’].assemblyDisplay.setValues(Loads=OFF,
        bcs=OFF, predefinedFields=OFF, connectors=OFF)
        mdb.Job(name=’Job-0’+str(i), model=’Model-1’, description=’ ‘,
        type=ANALYSIS, atTime=None, waitMinutes=0, waitHours=0,
        queue=None, memory=50, memoryUnits=PERCENTAGE,
        getMemeoryFromAnalysis=True, explicitPrecision=SINGLE,

```

```
nodalOutputPrecision=SINGLE, echoPRint=OFF, modelPrint=OFF,  
contactPRint=OFF, historyPrint=OFF, usersubroutine=' ', scratch=' ',  
parallelizationMethodExplicit=DOMAIN,  
multiprocessingMode=DEFAULT, numDomains=1, numCpus=1)  
mdb.jobs[:,Job-0'+str(i)].writeInput(consistencyChecking=OFF)
```