Energy Release Rate Based Mechanism for the wear of Punches in Precision Blanking of High Strength Steel

THESIS

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By

Siddarth Singh

Graduate Program in Industrial and Systems Engineering

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Master's Examination Committee:

Dr. Rajiv Shivpuri, Advisor

Dr. Jerald Brevick
Abstract

Blanking and punching are amongst the most widely used manufacturing operations in the industries. There are hundreds of products, which are manufactured by applying these shearing mechanisms. Used through past multiple decades these processes are still characterized using classical and empirical models. Numerical finite element studies have been performed in literature to understand the mechanism of these operations but no predictive study has yet been done to characterize the punch tool life using multiple process parameters to reduce the need of extensive experimentation. Various wear models are available in literature, which predict the life of the punch. However, the punch life characterization and prediction models remain far from accurate; as it is very difficult to measure punch wear during the process without disassembling the setup.

Punches in the precision blanking of high strength steels wear excessively due to the tool and sheet metal properties, high shear stresses, and process parameters namely: clearance, punch edge radius and friction. This study reports a detailed investigation into the process of punching through experimental work, analytical modeling and finite element simulations. To study wear physics using experimental analysis, a 22000 runs blanking test with 0.005 mm single side clearance was implemented. Fracture analysis was done
using SEM and optical microscope to study the punch wear post blanking and the results were used to develop a numerical simulation using Rice & Tracey damage criteria with appropriately calibrated critical fracture value. This simulation model was then used to analyze and investigate crack mechanics, burnish height, burr formation and load-displacement curves. These results were used to propose an energy release rate based model to predict the burr formation and future state of the punch. Multiple types of advanced high strength steel (AHSS) sheet materials were modeled to confirm and validate the proposed model.
Dedication

This thesis is dedicated to my parents and sister for all their support and encouragement.
Acknowledgments

First and foremost, I want to thank my parents and my sister for their gifts of motivation, love and support. They’ve always promoted education as a portal to bigger and better things in life.

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Vita

May 2003 .................................................. Delhi Public School, New Delhi, India
June 2008 .................................................. B.S. Industrial and Systems Engineering,
                                           The Ohio State University, Columbus, Ohio
September 2008 to present ...................... Graduate Teaching Associate, College of
                                           Engineering, The Ohio State University

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CHAPTER 1: INTRODUCTION

1.1 Punching

Sheet metal working by shearing is one of the most applied and used operations in the manufacturing industry. There are hundreds of products that are manufactured by applying shearing mechanisms. The location of the sheet metal with respect to the punch and die coordinates determines if the operation is stamping, blanking, punching, folding, piercing or cutting off. In stamping and folding the objective is to obtain a plastically deformed sheet that is put into various applications. Whereas in blanking and punching the aim is to cut through the sheet metal. In order to cut through the metal, the material is first subjected to plastic strain that leads to dislocation and crack propagation under which the sheet metal eventually ruptures.

Punching and blanking are two of the most widely used operations to cut sheet or plates by a shearing process between punch and die. It involves numerous process parameters such as the blanking clearance, punches and dies corner radius, the sheet material, the sheet thickness, the punching speed, lubrication, and the wear state of the tool. Other parameters such as material hardening, damage evolution, crack initiation and propagation also need to be included in describing the behavior of the sheet during the operation.
1.2 Problem Statement

Punch wear, deformation and breakage have also been major areas of concern when punching and forging. The characteristics of punch while in operation determine the quality of the parts being produced. These punches undergo extreme thermal, chemical and mechanical conditions that impact and determine the tool wear. Tool costs can increase tremendously if the phenomenon of wear is not studied properly leading to an increase in the overall cost of the parts being produced. Different parameters that can potentially impact the wear on the punch are the punch material properties, workpiece properties, involved friction, top die surface speed, feed rate etc. A lot of empirical research has been carried out on punching processes in manufacturing.

Despite this intensive research, the numerical simulation work in this field has not been able to replace the necessity of extensive experimentation. Work is still being done in the field of numerical simulations to build predictive models. A successful numerical model that can predict and optimize the life of the punch can help reduce the downtime for die replacement while increasing the number of ‘good’ parts by predicting the punch wear based on burr formation. However, modeling of blanking and punching processes is complicated by the punch-part geometry, mechanical and chemical characteristics and process parameters. This has been a leading cause of why conclusive punch life characterization has not yet been performed in numerical methods. Various wear models
are available in literatures that predict the life of the punch. However, such models have not yet been developed and validated in simulation tools.

Figure 1: Schematic of a Punching Process

During the past few decades in mechanized and automated industries, the diversity of products on offer has increased drastically. Due to the increase in the competitiveness of companies it has become essential to carry lowest inventories of raw materials along with minimal work in progress and reduced stock of finished products. These constraints for saving money in the company leads to an added pressure on the companies in terms of flexibility, process quality and cost minimization. Punching and blanking despite being as old as probably any other metal forming operations do not have numerical models that
can adequately predict the process circumstances. Hence, work is now being done to search for potential methods to control and monitor the punching process in real time based on which the quality of the parts can be predicted. If successful the method should be able to provide a process control methodology to predict the part quality and hence making it possible to prevent producing non-desirable products.
1.3 Research Objective and Approach

Computer assisted simulations have become an important and expanding field in the recent decade. Industrial innovation and academic research have both adopted simulation softwares to understand a wide category of manufacturing operations. Operation specific simulations can be created and parameters can be varied to study results and obtain particular desired features from the process. Finite element analysis softwares provide the opportunity for researchers to apply desired properties to the punch, workpiece, die container, press etc and analyze the results. Initiative has increased in recent times to do finite element analysis for predicting tool wear in punching operations. The ambition of this study was to figure out a methodology to predict part quality based on the load-stroke curve that can be obtained by placing load cells on the punching equipment. Work has been done to provide insight into the information that can be obtained from these curves to predict tool life based on the change of burr formation with increasing number of punches.

FORGE, a Transvalor S.A. product, was used to develop and run a finite element simulation model that ideally replicates the outputs obtained from the punching experiments performed on mechanical press ROBINSON A3 in Baker Systems lab at The Ohio State University. Once simulation parameters were matched to the experimental
parameters, emphasis was laid on finding an approximate material damage criterion (Cockroft-Latham or Rice-Tracey) that accurately represented the experimental values.
1.4 Potential Research Contribution

As discussed, the main motive of this study is to calibrate the numerical simulation and use this calibrated model to investigate crack mechanics, punch wear, burr height formation, stress state at the punch edge using the load-stroke curve.

This objective can be achieved by developing a predictive model using a finite element analysis tool to build a model that can predict the wear on the punch while considering multiple process parameters and sheet metal and tool characteristics. This thesis provides insights into the process of punching and the possibility of developing a controlling mechanism for timely punch replacement to reduce downtime and bad quality part production.
1.5 Outline of Thesis

Chapter 1 provided the introduction to the punching process and the problem statement. Chapter 2 supplies pre existing information from literature regarding punch-wear. Chapter 3 includes all the experiments conducted for punching HSLA-350 sheet metal and the analysis done to obtain the required results using SEM and optical micrographs. Chapter 4 dwells into the finite element modeling setup using FORGE, a Transvalor Inc. product. It provides information about the methodology used for calibration of the model and punch-wear angle. Chapters 5 and 6 discuss the states of the punch and the sheet before, during and post process. Chapter 8 explains the impact of wear on formation of burr and burnish height. Chapter 9 contains the detailed outputs and their analysis for the formation of the proposed approach using energy release rate from the load-stroke curve to predict the wear in punches and burr height. In this chapter the proposed theory is validated by applying the model to 3 other advanced high strength steels (AHSS) namely: DP-600, DP-780 and TRIP-780. This is followed by the conclusions and the academic contributions.
CHAPTER 2: LITERATURE REVIEW

Tool materials usually lose their usefulness by breakage, obsolescence or wear. Updates in technology and processes cause many machines to go obsolete. Breakage is when the material undergoes an accident and is no longer in a working condition. Wear is slightly different and usually makes the material lose its usefulness over a given duration of time due to constant use. Generally, wear is a harmful phenomenon. There are however certain situations when wear contributes to practical utilities. Certain processes like writing with a pencil, production of new work surfaces and sharpening of blunt tool edges like blades, scissor edges, knives etc benefit from wear.
2.1 Ductile Wear: Literature Review

Buchmann (1963) published the effect of wear on steel sheet blanking process. His work comprised of studying the edge wear and punch and die face flank. Faura and Lopez (1997) used similar approach in understanding the process of tool wear. Extensive research was later done in Japan by Matsuno et al. (1984) to study crater wear, crater-slope wear in blanking and effects of work material restriction, clearance and finish of cutting edge were recapitulated.

Rabinowicz defines wear as the removal of material from solid surfaces as a consequence of mechanical action. Burwell (1958) categorized wear into four major categories: abrasive, adhesive, corrosive and surface fatigue wear. In abrasive wear, a soft surface containing hard particles or a rough hard surface slides over a softer surface that causes the formation of grooves over the softer material. Depending on how many hard particles are entrapped on the surface of soft material the amount of abrasive wear can vary. These hollowed out groove particles can form debris and get stuck between other surfaces causing further wear. Abrasive wear can be reduced and even eliminated by decreasing the probability of hard particles getting stuck between rubbing surfaces by surface cleaning and use of pure metals. Corrosive wear is caused by the sliding of surfaces leading to the top layer being removed that can lead to the corrosion of either surface. When these surfaces slide over each other, the layer is removed and the mechanism
continues till the material is rendered useless. The effect of corrosive wear can be substantially reduced by making sure the materials in contact do not react chemically with each other or with the lubricant being used for friction reduction or temperature control.

Surface fatigue wear occurs due to the continuous loading and unloading action (sliding or rolling) of the materials. This type of motion induces cracks in the surface that leads to eventual falling out of fragments leaving pits in the material. Surface fatigue wear can occur when brittle materials are strained beyond their elastic strength. Fatigue wear is reduced by other three wear mechanisms as those wear mechanisms keep removing the surface material before it has a chance to become fatigued by the constant stressing and unstressing multiple times.

Adhesive wear is a unique form of wear. It occurs when one of the bodies’ particles comes off and adheres to the other materials surface during sliding. This particle can stay adhered to the new material or get dislodged as abrasion causing debris. Theory states that this particle can also be transferred back to the original surface. Unlike the earlier discussed wear mechanisms reduction of adhesive wear in tools is a relatively tough and tricky problem. Since adhesion occurs during sliding between the atoms of the two surfaces, sometimes the atoms of one surface stay adhered to the foreign surface even after the bodies have parted. These atoms on the surface of the materials cause scratching and itching. This is one of the reasons why on the first glance these scratches are
mistaken for abrasive wear without understanding that the actual cause is adhesive wear. Adhesive wear occurs at a slow rate and it is almost impossible to eliminate it completely.
2.1.1 Archard's Wear Model

Adhesive wear has been observed in extremely soft material surfaces as well, this leads to the conclusion that that in certain cases, the adhesive wear rate can be independent of the surface roughness of the interacting materials. Archard's wear model is currently the most widely accepted plausible model of sliding process. According to Archard, the probability of an adhesive wear particle being formed every time two asperities form a contact junction is constant, k. His fundamental law of adhesive wear states that the volume of transferred fragments formed in sliding through a given distance, $x$, is given by:

$$V = \frac{kLx}{3p} \quad (1)$$

Where, $V =$ volume of transferred fragments,

$k =$ coefficient of wear,

$x =$ sliding distance,

$L =$ total load,

$p =$ hardness of the surface being worn away.
Lots of researchers during the 1950s tried to determine the type of wear associated with the failed sliding material. It is a complex process to determine the cause of failure by method of inspection. This is because most failures are caused by more than just one type of wear. Sprague and Dundy (1959), Kaufman and Walp (1953) and Bugbee (1958) have also observed cases of adhesive and abrasive wear, abrasive and corrosive wear acting together.
2.1.2 Crack Mechanics Theory

Crack nucleation occurs when substantial amount of dislocations pile up in a particular location to cause the crystal planes to separate causing propagation of cracks. Crack nucleation methods can vary depending on the type of material being studied. Three categories for separating materials are: brittle, semi-brittle, or ductile. The behavior of dislocations in crack nucleation is governed by their brittleness. In highly brittle materials, the dislocations are practically immobile, whereas, in ductile materials dislocations have a higher degree of freedom to move around. Nucleation of a crack in metals usually involves the rupture of interatomic bonds. Crack propagation can also start from any cavities, foreign particles and inclusions.

Plastic deformation plays an important role in ductile materials. The term ductility signifies a material’s capacity and ability to undergo plastic deformation without fracturing. The important feature which impacts the plastic deformability of materials is the flexibility of slip planes. Dislocation assemblies can function between multiple slip planes and even cross from one plane to another. When these dislocation assemblies pile against a barrier, the material cracks. These cracks are called Zener–Stroh cracks (1948). Upon multiple stressing and un-stressing, the dislocations are relaxed by the method of crack nucleation. If the dislocations move away from the barrier then the crack will not nucleate.
Cracks also propagate at interacting metal boundaries representing that those areas were highly stressed. The nucleation and growth of voids is of great importance in determining the fracture characteristics of ductile materials. Metals are characterized by movable dislocation assemblies and generally show a ductile fracture. Various models have been proposed for void growth.

During blanking and punching when the punch shears against the workpiece the temperature and the strain rate have contrary effects on ductility. A high temperature or a low strain rate leads to high ductility, whereas a low temperature or a high strain rate leads to low ductility. Rankine, Tresca, and von Mises have given their own flow yield and fracture criteria equations.
2.1.3 Burr Formation and Process Parameters

The process parameters in punching have been widely studied by Hambli et al. (2003). Hambli applied neural network and design of experiments in investigation of the effects of clearance and tool geometry and proposed mathematical relationship describing the fracture zone depth, the fracture angle and the blanking force. In addition to the above mentioned, the effect of optimum clearance has also been discussed by Hambli et al. (2003) on AISI 304 sheet, and Fang et al. (2002) on aluminum alloy 2024. Farzin et al. (2006) considered a new parameter “Die to Punch corner ratio” with various damage models.

Maiti et al. (2000) studied the blanking load by numerical method. It has been proved that the reduction in the tool clearance, increase of friction coefficient will result in the increase of blanking load. Fracture and burr formation is numerically analyzed in Hambli et al. (2002) and Taupin et al. (1996). Klaasen et al. (2006) focused on the surface damage process of hard metal tools in blanking of sheet metals. They found that metals resistance to adhesive wear and origin-propagation of fatigue cracks could control surface damage resistance.

Thipprakmas et al. (2005) compared both the FEM and experimental results and predicted the formation of defects on blanked surface, such as shear surface, a tearing shear surface, and cracks in fine blanking process.
Hatanaka et al. (2003) proposed a simulation method to investigate the formation of rollover and the burnished surface, and crack initiation and propagation. It is reported that the burnish length slowly increases at the beginning of punch penetration and then increases approximately in proportion to the punch penetration depth when punch displacement beyond 0.2. Taupin et al. (1996) and Farzin et al. (2006) also performed the process of matching fracture formation.

Although study of punch roughness has not been reported in literature roughness and friction at interface has been investigated in sheet drawing and stamping. The study of surface finish has been conducted in sheet metal forming. Wilson et al. (1983) idealize the surface roughness as being composed of asperities with a uniform height and spacing, and consider the effect of plastic deformation in the bulk material on the asperity flattening process.

Matuszak (2004) found that in the absence of lubricant, the sheet surface roughness produced a dispersion effect on the average friction coefficient, but in the presence of oil, the surface roughness is a quite insensitive variable. Harr (1966) studied the friction model in sheet metal forming in his thesis. The effect of roughness on friction in the boundary lubrication regime is confirmed with experiments that the friction increases with surface roughness. Lee (2002) has measured friction coefficients under a wide range of tribological conditions by on various steel sheets. The effect of die roughness on friction coefficient has been investigated. It shows Friction coefficient could be as low as
0.02 between 0.5 and 1 µm in surface. The friction coefficient increases and it could be up to 0.2 to 0.3 for ultra-smooth surface.
CHAPTER 3: EXPERIMENTAL DETAILS

3.1 Punching Experiment setup

The piecing test setup is schematically shown below in Figure 2 with the four-featured zones that are found at sheared edge of strip as shown in Figure 3. The sheared edge can be divided into rollover, burnish edge, and fracture zones. The burr is formed along fracture in the piecing direction.

Figure 2: Schematic Representation of the Piercing Test

In Figure 2, $R_p$ is the punch corner radius, $R_b$ the blank holder corner radius, $R_d$ the die corner radius, $L_d$ the hole diameter, $F_p$ the punch force, $F_b$ the blank holder force, $T$ the
sheet thickness, S₁ the guiding clearance and S the hole clearance. Generally, the burr height and the hole size define the hole quality. In geometry the most important factors T, S, and R (R₁, R₂, R₃) have been shown in Figure 2 with values in Table 1. The HSLA-350/450 has the stress-strain curve shown in Figure 4.

Figure 3: Schematic representation of the topology of sheared edge
Figure 4: HSLA-350/450 Stress-Strain Curve

An expedited test was designed with various surface finishes (no polish, 8-12 RMS, and 4 RMS), and coatings (Lumena, Alcrona, and Futura Nano) to study their influences on tool wear and hole quality as shown in Figure 5.

In the current phase the piecing test was performed with various surface finish (Ra polished 0.1, 0.25, and grounded 0.5 µm which corresponding to 8-12 RMS, 4 RMS, and No Polish) to study their influences on tool wear and hole quality. Figure 5 shows the hole configuration on a strip. Six un-coated punches installed in plate with heads ground flush and marked. Two punches at Ra 0.5 µm are positioned at 1 and 6. Two punches at Ra 0.25 µm are positioned on 2 and 5. Rest two punches polished at Ra 0.1 µm are
positioned in middle two. The piecing test is done on mechanical press ROBINSON A3 as shown in Figure 6. 620 strips are punched with 35-40 strokes per stripe for a total of 22,000 strokes. The stroke curve is also shown below in Figure 6.

![Figure 5: Hole configuration on strips and the surface finish for corresponding punches](image)

<table>
<thead>
<tr>
<th>Punch Description</th>
<th>Retainer Position</th>
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<td>Polish/No Polish</td>
<td>Coating</td>
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<tr>
<td>No Polish</td>
<td>No Coating</td>
</tr>
<tr>
<td>8-12 RMS</td>
<td>No Coating</td>
</tr>
<tr>
<td>4 RMS</td>
<td>No Coating</td>
</tr>
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Figure 6: Robinson inclinable punch press A3 and its punch-stroke time curve

The three views of piecing tools set have been shown in Figures 7-9. Table 1 below lists the geometry and material information for strips and tools set.
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<table>
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<td>Punch Diameter [mm]</td>
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</tr>
<tr>
<td>Punch Hole Diameter [mm]</td>
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<td>Progression [mm]</td>
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<td>HSLA-350</td>
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<tr>
<td>Matrix / Punch material</td>
<td>M2 HRC 62</td>
</tr>
<tr>
<td>Pressure Plate / Matrix plate Material</td>
<td>A2 HRC 56-58</td>
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</table>

Table 1: Geometrical features and material parameters for the test configuration

Figure 7: Tool set drawing side view 1
Figure 8: Tool set drawing side view 2

Figure 9: Tool set drawing top view
Figure 10: Picture of the strip blank (top) and punched (bottom): left top view, right bottom view
3.2 Experimental Data Analysis

3.2.1 Surface Roughness Analysis and Optical Examination

Roughness measurements for the punch surfaces were done with surface analyzer. These are included in this section. The displacement end at the 2.5mm mark corresponds to the punch edge and the origin corresponds to Zone C. Roughness is measured for the total 2.5 mm length in each case. Three discrete surface roughness are measured for A (2.2, 2.5), B (1.6, 2.2), and C (0, 1.6) and noted as Ra1, Ra2, Ra3 respectively.
Figure 11: Surface roughness measurements for punches 1, 2 and three after 20,000 runs
Figure 11 shows the surface roughness measurements of punch 1, 2, and 3 after run 20,000 with Ra1 corresponding to the cutting edge profile roughness (2.5 mm displacement). It is seen that the punches with the best surface finish (punches 3 and 4) have the greatest roughness near the cutting edge (Ra1) followed by the pins with the intermediate roughness (punches 2 and 5). This increased roughness may be due to the increased pickup (adhesion) in smoother finish.

Leco OLYMPUS PME3 optical metallograph was used to analyze the shear edge of round nugget, strip holes, and the punch surface. Rollover, burnish, and fracture zones at run 100 and run 22,000 were analyzed using the PME3 microscope. Samples of hole-2 and hole-6 were prepared to study under the microscope. Figure 12 shows the top and bottom views of selected holes and Figure 13 shows the three views of one pierced nugget.

Microscopic view of fracture edge of selected holes is shown in Figure 14. The burnish length has been recorded for selected holes. Based on analysis done, it is observed that as the punch wears out the burnish zone increases meaning the fracture is occurring at a later stage in the punching process. This characteristic can be attributed to the fact that total energy required by the punch to blank the sheet increases as the wear increases. This phenomenon is also confirmed by the numerical simulations performed for various Rice-Tracey constants at various levels of wear.
Figure 12: Top and bottom view of holes (Magnification 7.5x)

Figure 13: Three views of nugget (Magnification 7.5x)
Figure 14: Microscopic view of Burnish- Fracture edge of selected holes
The microscopic views of punches are shown in Figure 16. Three zones (A shearing zone, B pulling zone, and C original finish zone) can also be identified in Figure 16. Figure 16 also shows some defects on punches. In figure 17, optical micrographs of the punch surface are included at low magnification (7.5X). Considerable deformation and wear can be seen near the punch surface. On punches 1 and 6, with high surface roughness, the wear zone is larger and rather diffused. On punches 2 and 5, with intermediate surface finish, the wear zone near the cutting edge is clearly identified. Finally on punches 3 and 4 with fine surface finish, the wear at the cutting edge is rather low but chipping at the edge is observed and considerable adhesive wear is present at on the side flank. The circumferential marks observed are probably due to the finishing/polishing operations.
Figure 16 above shows the three zones at higher magnification. It is seen that Zone a (near the cutting edge) has considerable adhesive wear and abrasive ploughing with carbides in the M2 steels being pulled out leaving pits on the surface. Zone B (sheet contact during punch travel) has grooves attesting to the rubbing action of the sheet during the blanking operation. While Zone C shows telltale polishing marks.

Figure 16: Different zones observed on the punch surface: Zone A near the cutting edge, Zone B in the area of sheet-punch interactions, and Zone C the area of original surface (400X)
Figure 17 shows the typical defects observed on punches. Of special relevance is the chipping defects shown in the photos included in the left top and center-top of this figure. The rest of the photos show grooves and edge deformation.
3.2.2 SEM Examination

In this section are included the scanning electron microscope micrographs of the punches. The SEM pictures are at great magnification and provide a unique insight to the wear mechanisms. The observed wear location and patterns for the different punches are summarized below:

- Punch 1: Has edge wear and abrasion near the edges. The abraded area shows 1A-1 shows abrasion coupled with some plastic deformation at the edge.
- Punch 6: Shows considerable amount of abrasion and plastic deformation all around the cutting edge. Expanded view of the areas 6A-1 to 6A-4 show significant plowing of the surface and abrasive rounding of the edge.
- Punch 2: Does not show as much abrasive wear as punch 6. However, there is some rounding of the cutting edge.
- Punch 5: Has the least wear among all punches. There is pitting and wear near the cutting edge. Otherwise the punch surface is hardly deteriorated.
- Punch 3: Is also in relatively good shape except the abrasive wear and grooving at the cutting edge. This punch also has a chipped edge.
- Punch 4: Has localized punch wear and some chipping near a material defect otherwise the punch is relatively in good shape.
Figure 18: SEM examination of Punch 1

Figure 18 shows the location of abrasion areas on the flank near the cutting edge (top), select locations on the pin flank 1A, 2A, 3A and 1B (bottom), and the close up of these locations (right).
Figure 19: SEM examination of Punch 2

Figure 19 shows the location of abrasion areas on the flank near the cutting edge (top left), select locations on the pin flank 2A, 2B (top right), and close up of three locations on the flank 2-1, 2-2 and 2-3 (bottom).
Figure 20: SEM examination of Punch 3

Figure 20 shows the location of abrasion areas on the flank near the cutting edge (top left), select locations on the pin flank 3A, 3B, 3C (top and bottom right), and the close up of these locations 3A-1, 3A-2, 3A-3, 3A-4 and 3B-1 (bottom).
Figure 21 shows the location of abrasion areas on the flank near the cutting edge (top left), select locations on the pin flank 4A and 4B, 3C (top right), and the close up of these locations 4A-1, 4A-2, 4A-3, 4A-4 and 4B1 (bottom).
Figure 22: SEM examination of Punch 5

Figure 22 shows the location of abrasion areas on the flank near the cutting edge (top), select locations on the pin flank 5A, 5B, 5C and 5D (right), and the close up of these locations 5C-1, 5C-2, 5B-1 and 5B-2 (bottom)
Figure 21 shows the location of abrasion and adhesion areas on the flank near the cutting edge (top-left), select locations on the pin flank 6 A, 6B, 6C and 6D (top right), and close up of the locations on A shown in 6A-1, 6A-2, 6A-3 and 6A-4 (bottom).
Figure 24: Condition of the punch flanks: effect of surface finish
Figure 25: Cutting Edge of the 6 Punches after run-22,000
Figure 26: Wear mechanisms for the different punches: as ground (1,6), 8-12 RMS (2,5) and 4 RMS (3,4)
CHAPTER 4: FINITE ELEMENT MODELING

4.1 FEM Setup

The piecing test setup was schematically shown in Figure 2 in chapter 3. The four-featured zones found at sheared chip edge were also discussed. The wear-expedition piecing test was designed and performed with various surface finishes (Ra polished 0.1, 0.25, and grounded 0.5 µm) to study their influences on tool wear and hole quality. Figure 25 shows the punch set design by drawing of punch retainer back. Three rounds experiments were scheduled with 3 punches in one round. Six un-coated punches installed in plate with heads ground flush and marked. Two punches at Ra 0.5 µm are positioned at 1 and 6. Two punches at Ra 0.25 µm are positioned at 2 and 5. Rest two punches polished at Ra 0.1 µm are positioned in middle two.

The piecing tests were done on mechanical press ROBINSON A3. The details of the materials used and the specifications of the experiments have also been discussed in earlier section under experimental setup.
Figure 27: Punch retainer back surface and holes configuration on strip
4.2 Model Calibration

4.2.1 Punch and Sheet Selection

A Hansel-Spittel rheology law was used to model the blank sheet material HSLA-350/450 in Forge 3, which is shown in Equation 2. The meshing model is shown in Figure 28.

\[
\sigma_f = A e^{T m_1 T m_9 \varepsilon m_2 e^{m_4 / \varepsilon}} (1 + \varepsilon)^{T m_5 e^{\varepsilon m_7 \varepsilon m_3 e^{T m_8}}}
\]  

(2)

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<th>Thermo-mechanical conditions</th>
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</thead>
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<td>Hansel-Spittel rheology law</td>
</tr>
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<td>A1 =</td>
<td>Consistency</td>
</tr>
<tr>
<td>m1 =</td>
<td>Temperature term</td>
</tr>
<tr>
<td>m2 =</td>
<td>Sensitivity to Strain-hardening</td>
</tr>
<tr>
<td>m3 =</td>
<td>Sensitivity to strain rate</td>
</tr>
<tr>
<td>m4 =</td>
<td>Strain softening coefficient</td>
</tr>
<tr>
<td>m5=, m6=, m7=, m8=, m9=,</td>
<td>Unused coefficients</td>
</tr>
</tbody>
</table>

Table 2: Hansel Spittel Rheology Law Constants
The meshing of the material affects the computational time of the simulation. If the meshes are excessively fine then the number of nodes will increase in the simulation leading to a higher computational time. Askari et al (2001) made material meshes where the mesh was finer closer to the burnish fracture zone and got coarse as we move away from the area of interest. This is the main action zone and the severe strains and temperature changes take place in this zone. Also, since we’re analyzing the fracture characteristics of the sheet metal, it is important to have finer mesh in this region to get better results. Other researches in the past have taken the same approach. Some of them are Bendzsak et al (2000), North et al (2000), and Oliphant (2004), etc. Forge3 is capable of using the Langrangian technique and applying it to a high deformation and shearing problem.

Figure 28 shows that the mesh size in the vicinity of the punch is extremely small to allow for a higher resolution of billet motion. As the distance from the billet center increases, the mesh size also increases. Since there is no motion in this zone and we’re not collecting any data from this region we can afford to have a coarse mesh size.

The simulation model focuses on the flow of material and takes into account the heat transfer with air and the tooling on the machine. Both the billet and the punch were defined as deformable die to allow for a thermo-mechanical computation. The reason for considering a deformable punch is to be able to analyze the wear on the punch due to the punching operation.
Figure 28: Blank Sheet Meshing in FEM

Figure 29: Punch Meshing in FEM
4.2.2 Ductile Fracture Criterion Selection

Generally, two types of fracture can be observed: brittle and ductile fracture. Brittle fracture is distinguished from ductile fracture by the relatively small energy dissipation during crack growth.

A number of fracture criteria based on different assumptions and different mechanical models postulate that fracture occurs at a point in a solid when the accumulated plastic strain reaches a critical value. They can be written in a general form as an integral over equivalent plastic strain up to fracture of a certain function of the actual stress state reaching a threshold value C per unit of volume:

\[
\int_0^{\tau_f} f(\sigma) d\varepsilon_f = C. \tag{3}
\]

Bao (2004) observed that it is impossible to capture all features of ductile crack formation in different stress states with a single criterion. It is shown that different functions are necessary to predict crack formation for different ranges of stress triaxiality.
In view of the importance of the largest tensile stress, Cockcroft and Latham have suggested a fracture criterion as:

$$r_f \int_0^{\sigma_{\text{max}}} d\bar{\varepsilon} = C.$$  \hspace{1cm} (4)

The criterion is not based on a micro-mechanical model to fracture, but simply recognizes the dependence of the critical value at fracture upon the level of the largest principal stress. As experiments show that materials with very limited formability can be deformed successfully under high hydrostatic pressures this criterion has been adopted by several authors for blanking studies. Oh et al (1979) modified the Cockcroft-Latham criterion by normalizing the maximum principal tensile stress by the equivalent stress, which is shown in Equation 5.

$$\bar{r}_f \int_0^{\sigma_{\text{max}}} \frac{d\bar{\varepsilon}}{d\bar{\sigma}} = C.$$  \hspace{1cm} (5)
From observations at a microscopic level the separating fracture is generally a ductile one in the metal blanking process. Ductile fracture in metals is caused by microscopic defects in the material, inducing voids, which grow under large straining conditions. These voids are holes in the material caused by dislocation pile-ups, second phase particles or other imperfections. Under the influence of plastic deformation, the voids can grow until a number of voids coalesce to initiate a crack. Prediction of this type of fracture is usually based on a description of void formation and coalescence, applied in the form of a ductile fracture criterion. Based on this hypothesis, Rice and Tracey (1969) suggested a stress triaxiality function as shown in Equation 6 to describe the growth of a spherical void in an infinite rigid, perfect plastic matrix. It should be noted that the growth rate is strongly related to the hydrostatic stress. Different values of critical damage at fracture are to be found for each criterion for each material.

\[
\tau_i \exp \left( C_2 \frac{\sigma_{ii}}{\sigma} \right) d \bar{\epsilon} = C. \\
\text{where } c_1 = 0.283, c_2 = 1.5
\]
4.2.3 Critical Value of Rice-Tracey Selection

Cockroft-Latham-Oh criterion, used for the blanking process, does not predict the trend correctly for HSLA. The punch displacement at fracture for a small clearance is larger than for experimental results. The Rice-Tracey criterion gives comparable results. The hydrostatic stress criterion and general Rice-Tracey model work very well for the operation of high stress triaxiality. Goijaerts et al. (2000) have proved the validity of Rice-Tracey criterion over a wide range of clearances. It is shown, for this specific example, Cockroft-Latham-Oh criterion predicts brittle fracture.

Regarding Equation 6, Huang (1991) corrected the value of C1 and found a better approximation for 0.427. Chae et al. (2004) suggest C2 as 2.5 with increasing dependence on stress triaxiality when characterizing HSLA-100. Thipprakmas (2005) provides another format with C1=C2=1. Actually C1 is not critical because it appears as a proportional parameter that can be fitted experimentally. In current simulations C1=0.283 and C2=1.5 are chosen.

The definition of the critical value in fracture criterion is crucial. It has been defined as a workpiece material constant that does not depend on the working operation. The fracture damage is evaluated for each element of the workpiece. Element deletion occurs when
the critical value is satisfied. The critical value at fracture of the workability criteria was
not determined by conventional upset test or tensile test, but through matching the ratio
of sheared zone and fracture zone with experimental results. Numerical predictions when
compared with experiments revealed the amount of deformation necessary for crack
initiation.
4.2.4 Angle Modeling

The experimental punch wear was studied to observe the wear angle. Observations of all the punches after about 22,000 strokes, show that the wear (material loss) is primarily at the outer cutting edge, that the wear produces a small angle ($\Theta$) at the cutting edge, and that the wear always starts at the same location (height “h”) on the flank (similar to flank wear in cutting tools) for all punches, similar observations have also been reported by Hambli (2001), Olsson (2002) and Slomp (2004). This suggests that the wear can be assumed to follow an angle along the edge of the punch as shown in Figure 32. This assumption differs from that of other researchers who have assumed increase in the punch radius as the measure of wear as shown in Figure 30.

The wear-angle assumption used in this thesis is more reasonable as it incorporates two wear modes: increase in edge radius and wear of the flank. This assumption permits punch wear progression to be modeled as a series of simulations with increasing wear angle $\Theta$. The initial punch was taken as straight (0 degrees) with a small corner radius. The worn punches were modeled with $\Theta = 2$, 4 and 6 degrees wear angles.
Based on the experimental punch SEM analysis post punching, approximately 6 degree of wear was the final observation in punch 6. Even though the punch was not completely worn out, the experiments had to be stopped due to the propagation of an unacceptable burr along the inner circumference. The properties of this punch were then used to set up the simulations and the burr height matching, load-stroke curve studies were all done based on the parameters of punch 6. An optical image of the burr formed on HSLA-350 sheets at 6 degrees of punch wear is shown in Figure 31.
To study the progression of the wear on punch 6, a Design of Experiments matrix was created using a full factorial method to obtain the required Rice-Tracey Constant for the simulations of HSLA-350 sheets as shown in Table 3. Angles from 0 to 6 degrees with continuous progression of 2 degrees were added into the matrix to understand the progression of the wear as the number of punches increased. The reason behind selecting an increment of 2 degrees was purely based on reducing the number of simulations to be run as a single axisymmetric simulation took approximately 15-20 hours due to the extremely fine meshing around the cracking region of the sheet metal.
Figure 32: SEM micrograph of the punch 6 surface after 22,000 strokes showing the abraded edge and its geometric approximation

<table>
<thead>
<tr>
<th>Rice-Tracey Constant</th>
<th>Wear Angle (Degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>1.50</td>
<td>x</td>
</tr>
<tr>
<td>2.00</td>
<td>x</td>
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<td>3.00</td>
<td>x</td>
</tr>
<tr>
<td>3.53</td>
<td>x</td>
</tr>
</tbody>
</table>

Table 3: Design of Experiments Matrix for Punching Simulations varying Rice-Tracey Constants and the Wear Angle (Degree)
After the above-mentioned 20 simulations were run, the corresponding burnishing ratios of simulations were matched with the simulation outputs. Based on the burnish ratio progression as wear on the punch increases, 3.53 R-T constant with 6-degree wear simulation was found to be a perfect replication of the experimental results as shown in Figure 33.

<table>
<thead>
<tr>
<th>Wear Angle</th>
<th>Rice-Tracey Constant</th>
<th>Burnish Height (mm)</th>
<th>Fracture Height (mm)</th>
<th>Ratio of Burnish/Fracture</th>
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</thead>
<tbody>
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<tr>
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</table>

Figure 33: Rice-Tracey criterion selection matrix for the 5 selected RT constants with varying punch wear angles
This finding as stated above was also confirmed with the experimental results. Burnish and fracture height analysis was done for both simulation and experimental data to validate the fracture criterion as shown in Figure 34.

Figure 34: Experimental Data for burnishing ratios for varying surface finishes
CHAPTER 5: SIMULATION: PUNCH ANALYSIS

It is of great interest to understand the mechanical, thermal and chemical conditions being endured by the punch during the process. This information if captured accurately can help provide an insight into the causation of the wear that takes place. After model calibration for Rice-Tracey criterion value and the punch wear angles, the punch properties were studied from FEM simulation file outputs to observe the stresses in the punch during the punching process.

It is to be noted that any form of wear cannot be studied during the actual process itself. Also it is extremely hard to capture the stresses being endured by the punch. Depending on the parameters of the punching process and the material properties of the interacting punch and sheet we can deduce these stresses from the numerical simulations.

Also of interest was plotting the stresses with the increasing penetration height to obtain the behavior of these stresses depending on different phases of punching namely: crack initiation and completion. This chapter includes the analysis done on the punch from simulation results and the comparisons with the experimental data. The main component stresses in XX direction ($\sigma_{xx}$) have been plotted and studied along with the Von Mises
stresses ($\sigma_v$) on the punch for HSLA-350 sheet. Once analyzed, curves are also obtained for the 3 remaining steels namely: DP-600, DP-780 and TRIP-780.

Figure 35: VonMises Stresses on Punch during the Punching Process in FEM for 0 degree punch wear

In an elastic body that is subject to a system of loads in 3 dimensions, a complex 3-dimensional system of stresses is developed. That is, at any point within the body there are stresses acting in different directions, and the direction and magnitude of stresses
changes from point to point. The Von Mises criterion is used for calculating whether the stress combination at a given point will cause failure. There are three "Principal Stresses" that can be calculated at any point, acting in the x, y, and z directions. Figure 34 shows Mohrs circle representation of the stresses that can be used to calculate the principal stresses acting in the 3 coordinates and hence the Von Mises stresses.

Von Mises criterion states that, even though none of the principal stresses exceeds the yield stress of the material, it is possible for yielding to result from the combination of stresses. The Von Mises criterion is a formula for combining these 3 stresses into an equivalent stress, which is then compared to the yield stress of the material. The equation for Von Mises stress ($\sigma_v$) is given by:

$$\sigma_v = \sqrt{\frac{(\sigma_{xx}-\sigma_{yy})^2(\sigma_{yy}-\sigma_{zz})^2+(\sigma_{xx}-\sigma_{zz})^2}{2}}$$

(7)

Where $\sigma_{xx}, \sigma_{yy}, \sigma_{zz}$ are the stress tensor values in the principal stress coordinates namely x, y and z direction respectively.
Figure 36: Mohrs Circle Representation of Stress distribution in Principal coordinates

http://upload.wikimedia.org/wikipedia/commons/0/01/Mohr_Circle_plane_stress_%28angle%29.svg

In Figure 36, $\sigma_1$ and $\sigma_2$ are the principal stresses in x and y direction respectively.
Figure 35 shows the von Mises stresses ($\sigma_v$) on a fresh 0 degree wear punch during punching on a HSLA-350 sheet metal. It can be observed that as the punch goes deeper into the sheet the stress value increases. The maximum value is observed at the punch flank. The SEM study of the punch showed this to be the region of maximum wear. Once the crack is completed the value decreases to approximately 200-250MPa. The reason for the sudden decrease in the stress value can be attributed to the release of the stress on the punch once the punching process is complete.

Figure 37: VonMises Stresses on Punch during the Punching Process in FEM for 6 degrees punch wear
Figure 37 show the von Mises stresses ($\sigma_v$) in the punch during the punching process for 6 degree wear. It is evident that the maximum stresses (~700-800 MPa) are incurred at the edge of the punch towards the lower part where the wear occurs. It can be seen that as the punch wears the stress required for initiating fracture increases from 750 MPa to almost 900MPa. Also the location of the maximum stress value keeps moving upwards along the flank of the punch as the wear angle progresses. A similar movement of the stress along the punch flank was also observed in 2 and 4-degree wear of the punch. This explains the increase in the wear of the punch edge as the number of punching operations increases.

Figure 38: XX-Stresstensor for calibrated R-T constant (3.53 RT) versus Stroke Length for HSLA-350

67
Figure 38 shows the XX-Stresstensor ($\sigma_{xx}$) graph for the stroke length (total steps=61). The data was plotted for the punches with HSLA-350 sheets with varying punch wears. It is worth noting that the maximum compressive stress when there is no wear on the punch is 510 MPa (negative value indicates the direction, since its along the direction of the motion of the punch its compressive in nature). This value increases to 700MPa when the wear in the punch is up to 6 degrees. Once these compressive values reach their maximum value, the cracking begins and the stress value starts decreasing again. Towards the end of the process, we can see that the values of the XX-stresstensor ($\sigma_{xx}$) start decreasing again. This phenomenon can be attributed to the entrapment of the burr and residual material between the punch and the sheet. However, further analysis would be required to validate this concept. A similar pattern can be observed for the other sheet metals as observed in Figures 39-41.
Figure 39: XX-Stress tensor ($\sigma_{xx}$) for calibrated R-T constant (3.53 RT) versus Stroke Length for TRIP-780

Figure 40: XX-Stress tensor ($\sigma_{xx}$) for calibrated R-T constant (3.53 RT) versus Stroke Length for DP-780
Figure 41: XX-Stress tensor ($\sigma_{xx}$) for calibrated R-T constant (3.53 RT) versus Stroke Length for HSLA-350

Overall, between 0, 2, 4 and 6 degrees of wear it can be seen that the reversal in the values of negatively increasing stress occurs at the region where the fracture is initiated. In other words, the radial stress on the punch changes from compressive to tensile as the crack in the sheet initiates and propagates. This observation will be used in forming of the theory later when we discuss the load-stroke curve in proceeding chapters.
As discussed in Figure 38, a similar observation can be made for the 1\textsuperscript{st} principal stress in Figure 42. At Point 2 (formation of crack) the 1\textsuperscript{st} principal stresses start moving from an increasing negative value towards positive. Once again it was observed that the negative value of the stress increases with the increasing wear at the point of crack initiation. This provides the evidence that the initial stress on the sheet is compressive and once the cracking starts the sheet starts getting stretched and the stresses become tensile in nature.
Figure 43: 1\textsuperscript{st} Principal Stress for calibrated R-T constant (3.53 RT) versus Stroke Length for (top) DP-600 (middle) DP-780 and (bottom) trip-780
As shown in Figure 42, a similar analysis has also been done for other steels (DP-600, DP-780, and TRIP-780) with 0 and 6 degree wear in Figure 43. They show a similar pattern as observed in HSLA-350. However, an interesting observation can be made for DP-780 and TRIP-780 sheet metals, despite having the same yield strength, the two materials start cracking at different stress values. The stress value for DP-780 is 560MPa whereas it is 630MPa for TRIP-780. This can be reasoned based on the different flow stresses that these 2 materials have as they have different stress strain curves as shown in Figure 44.

Figure 44: Stress-Strain Curve from FEM
Figure 45: Archards wear model for calibrated R-T constant (3.53 RT) versus Stroke Length in FEM (top) for HSLA-350 sheet metal with 0 degree and (bottom) 6 degrees of punch wear
To observe the wear, Archard’s model was used in the simulation. As discussed in chapter-2 section 2.1.1, Archard’s wear model is the most widely accepted in literature.

According to Archard, the probability of an adhesive wear particle being formed every time two asperities form a contact junction is constant, k. His fundamental law of adhesive wear states that the volume of transferred fragments formed in sliding through a given distance, x, is given by:

\[
V = \frac{kLx}{3p}
\]  

(8)

Where, 

\[V\] = volume of transferred fragments,

\[k\] = Coefficient of wear,

\[x\] = Sliding distance,

\[L\] = Total load,

\[p\] = Hardness of the surface being worn away.

This wear model in FEM, showed the increase in the wear as punch depth increased. Similar to the experimental observations of punch flank wear we can observe that the maximum wear based on Archard’s model occurs in the lower punch region in contact with the sheet. Figure 45 shows when the punch wears (at 6 degrees), the wear starts
moving upwards in the vertical direction. This can explain the increase in the wear angle as the punching continues.

Figure 46: Generic Picture of Burr from FEM

Also of interest is figure 46. This is the cross-section of the sheet after punching. It should be noted that the fracture region is extremely rough and capable of catching debris being produced due to the constant rubbing of punch against the sheet. This debris also enhances and hastens the wear of the punch as the quantity of debris increases with every single stroke of the process. If the burnishing region can somehow be increased then the possibility of reducing punch wear can be obtained.
Combining the SEM and optical study of the experimental punch with the simulation results obtained in Figure 45, an important observation can be made that minimal wear takes place on the lower bottom flank of the punch as typically considered by researchers like Hambli et al (2003). This observation further validates the reason behind assuming punch wear to follow an angle along the edge of the punch rather than an increase in the edge radius as discussed in section 4.2.4.
CHAPTER 6: SIMULATION: SHEET ANALYSIS

It is known in the field of manufacturing that surface interaction properties are not fundamental. One important aim of research in the wear field has been to determine the nature of dependence of the fundamental properties at a complex level in order to predict the interaction behavior. The mechanical property parameters that govern the surface interaction behavior can be classified into two categories: namely volume properties that relate to the contacting bodies as a whole and the surface properties that determine the contacting interaction of the two bodies. In previous chapter, the punch and impact of different interacting properties with sheet in terms of mainly stresses was discussed. Due to the limitation of software and time restraints the volume properties and the impact of grain orientation, subgrain size etc was not considered in the model and hence the utilization of an axisymmetric two-dimensional model for analysis. Further studies will be done with three-dimensional simulations at a later stage. In this chapter the aim is to observe the superficial surface properties interaction impact on the sheet and its effect on the quality of the parts produced.
6.1 Stresses in Sheet

XX-stresstensor ($\sigma_{xx}$) values in Figure 47 show the negative increase in the stress that reverses when the fracture starts. It was observed that the stress values reach as high as ~500MPa in the region where the fracture is initiated. This region coincides with the region of maximum wear in the punch as discussed in Chapter-5 above.

Figure 47: XX-Stresstensor on HSLA-350 Sheet during the Punching Process in FEM (top) for 0 degree punch wear
The increase in the XX stress tensor during the punching of the HSLA-350 sheet metal using M2 tool punch can be observed in Figure 47 and 48. It is seen that for 0 degree punch wear the stress starts from approximately -400MPa and reverses at the initiation of the crack. Once the crack starts the value become positive going up to 500MPa. This is when tensile load is being applied on the sheet leading it to getting sheared and cracked eventually.

Figure 48: XX-Stress tensor on HSLA-350 Sheet during the Punching Process in FEM for 6 degrees of punch wear
When the punch gets worn out to 6 degrees, the maximum stress is delayed and so is the crack initiation. Also the value increases from 500MPa to almost 750MPa. This is because the surface area of the punch has increased leading to an increase in the crack initiation depth, hence more work has to be done before the cracking of the HSLA-350 sheet can begin.

Figure 49: VonMises Stresses on HSLA-350 Sheet during the Punching Process in FEM (top) for 0 degree and (bottom) 6 degrees of punch wear
As discussed earlier, Von Mises criterion is used for calculating whether the stress combination at a given point will cause failure. In Figure 48 and 49, we can see a constant increase in the von Mises stress value. The maximum accumulation of stress is occurring at the region where cracking is expected. An additional 250MPa is required when performing the same process with a 6 degree worn punch instead of a new 0 degree worn punch. Also of note are the residual stresses after the completion of the crack, collection of debris, increased friction, increased surface roughness due to fracture.
region. These all factors increase as the punch wears out leading to an increase in the stressing required to achieve the crack.
In the blanking industry, the punch wear has a significant impact on production. In particular, important wear causes a wrong geometry of the cut pieces, which can lead to a rejection of products. Among other defects, the apparition of burr is the most
incapacitating in the use of the blanking piece. So, in order to overcome this problem, industrials regrind their tools after a number of press storks. But this operation has a negative consequence on costs. In fact, the production stopping for regrinding or replacing punches creates substantial losses for the industry. Thus, it is important to control aspects of the blanking operation leading to the appearance of burr. To do this, it is necessary to have in advance a reliable way to measure the quantity of burr.

As stated above, burr plays an important part in determining the quality of the part being produced. As the burr height increases, a height is obtained beyond that the quality of the part become unacceptaible. The results from simulations were plotted along with the two data points from the experimental results for HSLA-350 in Figure 51. It is worth noting that the increase in the burr height is almost linear. This can be attributed to the limited data points that can be obtained from the 4 simulations. Once the number of angled simulations increases, a potentially curvy trend can be obtained. However, we are more concerned with the maximum value of burr height (and hence the wear angle) beyond which the part quality deteriorates beyond acceptable.
Figure 52: Burnish Ratio with changing wear angle

A similar pattern can be observed in the burnishing ratio graph in Figure 52. An increase in the ratio suggests the fracture is occurring later in the process as the punch wears. In other words, the punch has to progress further into the sheet before the rupture takes place.
A solution of an elasto-plastic fracture problem involves two parts: the determination of fracture resistance of the sheared material and the crack driving force. For a given sheet material and thickness, the shear resistance (Rice-Tracey critical value) remains constant for all numerical experiments. The crack driving force is often represented, in fracture mechanics, by the energy release rate. In a typical punching experiment, the energy required for fracture initiation and progression largely consists of the area under the force-displacement curve. Consequently, the energy release rate is the change of area under the force-displacement curve. Computed force-displacement curves for HSLA-350 material for different wear angles are included in Figure 54.

Figure 53 shows a typical force versus time or distance curve for punching. It is distinctively divided into 4 phases. During phase-1, the punch contacts the material subjecting it to elastic elongation. During phase-2 the plastic deformation begins and the punching force reaches its maximum value. It is at the end of this phase that the crack in the sheet metal starts propagating. Phase-3 end marks the competing of the crack. Phase-4 referred to as the oscillation phase shows the residual energy in the punch. An increase
in this residual energy leads to an increase in the burr height and wear on the punch as shown in the proceeding sections.

Figure 53: Load-Stroke Curve for Punching
In a typical punching experiment, the energy required for fracture initiation and progression consists of the area under the force-displacement curve. Consequently, the energy release rate is the change of area under the force-displacement curve phase-3. Computed force-displacement curves for HSLA-350 material for different wear angles are included in Figure 54.

Figure 54: Load-Stroke Curves for Multiple Wear Angles for HSLA-350
As stated above, to estimate the development of the wear angle, simulations were carried out with different wear angles using the abrasive wear model available in FORGE that is based on Archard’s criterion given below. In this criterion, material wear per unit sliding \( W \) is a function of a material constant \( k \), force normal to the surface \( F_N \) and hardness \( H \) of the surface being abraded.

\[
W_{\text{adhesive}} = \frac{V}{S} = \frac{kF_N}{3H} \quad \text{or} \quad V = K_W \cdot F_N \cdot S \quad (9)
\]

Where \( V \) is the volume of the material removed and \( S \) is the sliding distance. The wear constant \( K_W \) depends on the contact conditions and varies over the range \( 10^{-2} \) to \( 10^{-7} \) mm\(^2\)/N. Equation 9 is often discretized and used for wear calculations in FEM formulations. In these simulations, it is seen that maximum wear is initially at the edge radius and as the radius wear out, it moves towards the flank, finally reaching the flank corner. This suggests that the angle gradually develops as the abrasion wears out the outer edge. The existence of the edge wear and its fixed length has been reported by Olsson et al. and Slomb et al. Olsson reported that this length depends on the tribological conditions during punching. Assuming the wear angle represents the cutting edge wear, the wear volume is then defined as:
\[ V = \pi d_c (\frac{1}{2} h^2 \tan \theta) \]  \hspace{2cm} (10)

Where \( d_c \) is the diameter of the centroid of the triangular area. With the location of centroid and height being almost constant in punching, the wear volume is directly proportional to the angle \( \Theta \). Comparing equations 9 and 10 the number of punch strokes (N) needed to generate a wear angle is given as,

\[ N = \frac{S}{S_i} = \pi d_c (\frac{1}{2} h^2 \tan \theta) / (K_w F_N S_i) \]  \hspace{2cm} (11)

Where, \( S_i \) is the sliding length per stroke. In this equation 11, the denominator \( F_N S_i \) represents energy consumed during shearing during one stroke. In this equation, if the burr height can be related to the wear angle, the number of strokes to an unacceptable burr height can be predicted. The goal of this simulation then becomes an investigation of the work done during shearing and the relationship between the burr height and wear angle.

Further sections in this thesis analyze the load-stroke curves for calibrating the punching process of HSLA-350 to obtain the desired part quality. Analysis is done based on punch wear and burr height outputs obtained from experimental and simulation data. The proof
of concept is obtained by validating the procedure for DP-600, TRIP-780 and DP-780 steels.
8.2 Wear Angle-Load Stroke Analysis

One of the main objectives of the numerical investigation was to examine the energy consumed during the cracking process, represented by the $F_N S_t$ product in equation 10. For this propose, force stroke curves were generated for different wear angles of punch for HSLA-350 punching. It is seen that as the wear angle increases the total load (work done) during the period between crack initiation and fracture. This is proved from the fact that the crack initiation starts at approximately the same stroke length but the force slope steepness keeps decreasing, thus increasing the area under the curve: thus increasing the total energy consumed in the process.
Figure 55, shows the work done Slomp et al (2004). The graph above shows an increase in the maximum punching force as a result of an increased punch radius. It also shows a consistently increasing delay in the start of shear cutting, represented by the peak force. It is revealed that the final rupture of the blank, indicated by the sudden drop of the punching force, is suppressed by the introduction of a radius. This observation is consistent with an increasing radius. Also the tool radius affects the reduction of the punching force during shearing, indicated by the downward slope.
Figure 56: Load-Stroke Curve obtained from FEM Simulation for the 4 sheet metals
In Figure 56, we can see that for different materials the maximum load required to start the crack is different. HSLA-350 has a maximum value of 0.35 Kilo-Newton whereas DP-780 and TRIP-780 have the maximum blanking load of approximately 0.7 Kilo-Newton. As established earlier, the initiation of the crack very much depends on the state of the punch and the ductility of the sheet material we can see that the completion of crack is achieved at different times for all four materials. For 0 degree wear of punch it is worth noticing that despite having the same yield strength, DP-780 and TRIP-780 show difference in the crack completion. TRIP steel being more ductile than DP finally cracks at a later stage in the process.

Also for 6-degree punch wear we can see stagnation in the value of the load even after crack completion. This phenomenon is not observed when the punch is not worn out. This additional energy can be attributed to the increase in the friction. This friction in turn causes the increase in the adhesive and abrasive wear. Hence, as the punch life increases, it is easy to see ploughing, groove formation along with the abrasive and adhesive wear. The debris produced due to lose particles coming off from the punch and/or sheet material cause the grinding. When the friction increases and high stresses are induced these materials stick to either the punch or the sheet and rub against the surface hence wearing it in the process.
8.3 Shearing Energy Consumed

The cumulative energy curve for the processes was obtained by summation of the product of the total load with the distance the punch had travelled. This gave us the total work done by the punch and hence the energy consumed in doing that amount of work.

Figure 57 below shows an increase in the energy required for different sheet metals. This data was obtained from the load-stroke curves from FEM. Depending on the type of material the total required energy changes. HSLA-350 has the lowest energy required whereas TRIP-780 required the maximum energy to complete the operation. This makes sense as the yield strength of TRIP-780 was the highest.
Figure 57: Energy increase in Punching Operation for the 4 steels obtained from FEM simulations
In Figure 58, it is seen that the slope of the curve is almost constant, however the intercept shifts. The independence of the energy release rate (area under the curve) with respect to the edge geometry implies that it is a fundamental measure of the elasto-plastic shearing process in punching and does not change significantly with the number of strokes. This approach that the burr height can be measured using the load-stroke curve is further confirmed by examining the energy release rate curves for different materials that show the energy curves for different wear angles to be material dependent but almost independent of wear angle, except for TRIP-780 where the slope is slightly larger.
8.4 Clearance Effect Analysis

The effect of the burr can be easily observed by experimental analysis during the process by taking sheet metal samples. Clearance however could not be changed during the experiments. In this section further simulations were carried out for HSLA-350. The objective was to understand how the energy consumed during the punching process changed as a function of clearance. Figures 59 and 60 show the load-stroke curves at varying clearances.

![Load-Stroke Curve_0 degree wear](image)

Figure 59: Load-Stroke Curve for HSLA-350 Sheets with 0 degree punch wear for varying clearances obtained from FEM Simulations
In figure 59 and 60, the effect of changing clearance for HSLA-350 sheet metal has been shown. Keeping all other parameters in the simulation the same, the clearance was increased at intervals of 0.01mm from 0.01 to 0.03mm. The punch angle was also changed between 0 and 6 degrees to account for the punch wear effect. The load-stroke curve data was obtained and plotted in the same graph for visual inference. When the punch is not worn out it can be seen that the slope from the maximum load value is steeper for higher clearances. Also, the point where the crack begins is same and does not seem to be depending on the clearance value. However, the total energy consumed in the shearing process decreases as the clearance increases.
When the punch wear increases to 6 degrees a similar trend is observed where the crack starts at the same time but towards the end of the process an additional bump in the curve can be observed. This additional residual energy is required, as the punch edge sliding against the sheet has not moved up along the flank due to being worn out. This additional energy also explains the increase in the burr size, as the punch now has to travel additional distance before rupturing the sheet completely. Important thing to notice however is that despite the changing clearance the maximum force required to initiate crack remains the same.

Extensive work has been done in determining the clearance of the punch and sheet to obtain high quality parts in punching. Hambli et al. (2001) and Lee et al. (2002) have discussed the impact of changing clearance in a punching process. Depending the on the part being produced, the sheet metal and punch being used, clearance can have one or more of the following effects on the part:

A. Too much clearance
   1. Extra rollover at the top of the hole
   2. Increased burr at the bottom of the hole

B. Too little clearance
   1. More punching force needed
   2. Can reduce tool life due to excessive unnecessary abrasion
C. Ideal clearance

1. Ideal burnish height
2. Minimum rollover at the top of the hole
3. Minimum burr at the bottom of the hole

Figure 61 shows the increase in the rollover height as the clearance increases. Depending on the desired geometry of the product, an ideal clearance can be selected to match the
rollover height. It should however be noted that this cannot be a secluded decision as the burr height formed from various clearances along with the angle of the shearing also play an important role in decision of clearance. Another important factor that impacts the clearance decision is its impact on the life of the punch as discussed earlier in this section. The change in the cracking angle is discussed below.

Figure 62: FEM snapshots of changing cracking angle with varying clearance for HSLA-350
Figures 62 and 63 show the impact of changing clearances for the different worn out punches. We can see that as the clearance increases, the angle at which the cracking starts increases as well hence affecting the quality of the desired part. This phenomenon of increased cracking angle can directly be related to the formation of the burr height. The farther the crack propagates towards the punch, higher the volume of sheet trapped underneath the punch and hence increased the burr height. This has already been proved using the load-stroke curve where the residual energy is higher with increased clearance as compared to lower clearance value. But also we have to be considerate in the formulation of the parameters as a highly reduced clearance can lead to a reduced burr but
it can also increases the total maximum load required to achieve cracking and abrade the punch faster due to extreme stress changes.
8.5 Conclusions

Based on the above analysis it has been shown that the initial crack propagation starts at roughly the same time/punch displacement but the slope varies depending on the material being used. This confirms the hypothesis that the wear angles are material depend and can be analyzed using the load-stroke curve. Also of interest is the residual energy in the punch (phase-4). It can be observed that this energy increases as the punch wear angle increases. This additional energy causes the increase in the height of the burr as the wear angle increases.

Clearance conclusions: We established that an increase in the required energy caused an increase in the burr height and as this energy increased further an unacceptable burr height could be established where the punch would need replacement. From figures 59 and 60 we can easily see that as the clearance decreases the required plastic deformation energy increases. This is seen in phase-3 of the figures as the slope becomes less steep as the clearance increases.
CHAPTER 9: SUMMARY AND POTENTIAL ACADEMIC CONTRIBUTIONS

An elasto-plastic numerical model was developed for the hole punching process and calibrated with low clearance punching experiments of high strength steel sheets. In this model, the wear of punch edge is represented by a wear angle. Using this assumption, relationship is derived that can forecast the number of strokes possible before the development of an unacceptable burr. Analysis of the load displacement curves show that the rate of unloading during crack initiation and propagation is sensitive to the geometry of the cutting edge but the energy release rate is not so sensitive, and can be taken as a material constant for computing wear rate. Since the energy release rate during shearing (cracking), for fixed processing conditions, is primarily determined by the flow behavior of the sheet material and it can be used to predict the burr height and the number of strokes to an unacceptable burr. The burr height and the energy release rate can be determined either numerically or experimentally for a new tool and given punch set up.
9.1 Summary

This thesis analyzed the operation of punching/blanking. Experimental data was validated with a simulation approach and a set of knowledge base was developed. The following conclusions can be made based on the work done so far:

1. Experimental model calibration was done in FORGE3 model to replicate the actual experiment in a finite element simulation tool. This calibration helped us identify the type of fracture taking place in the punching operation of HSLA-350. It also helped us accommodate the accurate Rice-Tracey criterion value at which the given sheet metal fractures.

2. The effects of Rice-Tracey constant and wear of the punch on the quality of the punched parts was analyzed. Burr height behavior under different worn out punches was established using experimental and simulation data.

3. This thesis reported the initial steps in developing a numerical method of test simulations, which can assist in calibrating punching/blanking experiments where operators can control and vary the technological parameters of the numerical method to obtain a finished product with the desired characteristics (physical and mechanical).
4. Based on FEM results and comparison with experiments, basis for developing a new energy release rate based wear model for the punches has been proposed. Relationship between the load-stroke curve and burr height was established to estimate the number of acceptable parts that can be produced under a given set of process parameters.

5. Load-stroke curve was used to understand the burr height changes, clearance effects, and wear of punches. The change of burr and hence the part quality was related to the load-stroke curve so observing the curve could provide an insight into the acceptability of the parts being produced.

6. The impact of clearance on the part quality was discussed and related to the load-stroke curve. Using the load-stroke curve, it can be predicted if the clearance being used can provide good quality parts.
9.2 Academic Contributions

A calibrated numerical simulation model was constructed to investigate the crack mechanics; burr formation and punch wear using a load-stroke curve. This predictive model can be used to obtain a load-stroke curve that can potentially provide the required information for part quality, number of punches before reject parts and wear on the punch.

A few assumptions, which were used in making the above-mentioned analysis, were:

1. With close to 35 simulations were run and each simulation taking approximately 15-20 hours, axisymmetric conditions were assumed and only half of the geometry was modeled. This helped in reducing the computational time.

2. 3-D simulations of the model were not done due to simulation time constraint.
9.3 Future Work

Future research will explore these important frontiers: (i) effect of micro structural evolution of both punch and part and its calibrated impact on the quality of the blanked parts (ii) 3-dimensional modeling of the process to obtain multidimensional accurate results which can also help understand offsetting of punch and its effect on the burr formation and part quality (iii) study of influence of void nucleation, growth and coalescence in ductility of metals in punching using finite element simulation.
CHAPTER 10: REFERENCES


