Numerical Simulations of Wear

MONA ÖQVIST

Department of Mechanical Engineering
Division of Machine Elements
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Mona Öqvist
Division of Machine Elements
Department of Mechanical Engineering
Luleå University of Technology
SE-971 87 Luleå, Sweden

Luleå and Älta 2000
Preface

This licentiate thesis deals with numerical methods to calculate wear, with a focus on tool wear in deep drawing. The work has been carried out at the Division of Machine Elements of the Department of Mechanical Engineering at Luleå University of Technology, Sweden.

First of all I would like to express my gratitude to my supervisors, Dr Elisabet Kassfeldt and Prof. Erik Höglund for their guidance and support. I am also grateful to Lars Karlsson LicEng for introducing me to the subject.

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Mona Öqvist
Abstract

Wear of engineering components is often a critical factor influencing product life. Prediction of wear is therefore an important matter in engineering. One method that can be used to obtain some level of control over the effects of wear is numerical simulation. The objective of this licentiate thesis is to study the effects of tool wear in sheet metal forming tools and how the wear process can be simulated in an efficient manner.

A wear model in accordance with Archard’s wear equation has been incorporated in a finite element program. Two different ways of implementing the geometrical changes, due to wear, in the finite element modelling have been used. None of the methods involves a complete remeshing, as this is time-consuming. The first approach was to move the nodes in the contact zones that had been subjected to wear. The second approach was to move the nodes on the outer rim of the cup to the same extent as the nodes on the worn surface. An adaptive method for the step size between the geometry updates was implemented in the simulations to minimise the simulation time.

The method of simulation used in this work is not limited with respect to the material model. The material model used is non-linear and is easy to replace if necessary. An implicit finite element code in combination with a driver was used to perform the simulations. The driver compensated for one of the drawbacks when using an implicit finite element formulation instead of an explicit one, namely the problem of attaining convergence in the solution process.

The mathematical model that describes the process has to be verified before it can be used in simulating the behaviour of the process; otherwise the conclusions drawn from the simulation cannot be relied on and the modelling and simulation have no value. In Paper A, the contact forces in a deep drawing die were investigated. In Paper B, a wear model was incorporated into the finite element model and the validity of the wear model was verified by experiments. The wear model verified in Paper B was then used in the deep drawing simulations of Paper C.

Paper A covers the influence of die geometry in deep drawing. It can be concluded that the claim that the tractrix curvature in a deep drawing die reduces die wear is only weakly confirmed in Paper A, as the contact forces are only reduced by approximately 10%. This result showed that a further investigation was needed.
In Paper B the wear of a steel cylinder oscillating against a steel plate was studied experimentally. The worn shape of the cylinder was then compared with a numerical simulation of the shape. The aim of the work was to show how wear simulations could be performed in a fast and accurate way by allowing the time step for the geometry update to vary in the simulations. The main conclusion from this paper is that using an adaptive method for the step size between the geometry updates can minimise the simulation time. The method of simulation is good, as it gives both fast and accurate results and therefore can be used for comparison of the wear of different parts.

Paper C shows how finite element analysis can be used to simulate the wear of deep drawing dies. The wear of two different deep drawing dies was investigated. The shape of the dies before and after the wear was compared, as well as the stresses and strains in the formed cups. It can be concluded that the tractrix transition gives a die with less total wear than a die with circular transition. The changes in the shape of the cups produced in the tractrix die are smaller and the effective stress is also lower than in the cups produced in the circular die.

Keywords: Wear simulations; Wear experiments; Deep drawing; Finite element analysis.
1. Introduction

The objective of this research work was to study the effect of tool wear in sheet metal forming and to study how the wear process can be simulated in a fast and efficient manner and with reliable results.

To start with, sheet metal forming, as a manufacturing process, can be described as a process in which a sheet of metal is formed into a product by plastic deformation without removal of material. The material and surface properties of the tool and the formed material are closely related to sheet metal forming, while wear, friction and lubrication are considered matters of tribology. The process parameters are a part of both the tribo system and the sheet metal forming system. See Figure 1.

![Figure 1. The different subjects involved in wear of sheet metal forming tools.](image)

1.1 Deep drawing

Metals are important materials, largely because they can easily be deformed into useful shapes. Literally hundreds of metalworking processes have been developed over the years for specific applications. These applications can be categorised in five broad groups, namely rolling, extrusion, drawing, forging and sheet metal forming.

In the sheet metal forming industry, especially the car manufacturing industry, a large amount of effort is put into finite element simulations of processes like deep drawing, stretching and bending. Sheet metal forming tools are often designed for a specific product, especially when it comes to deep drawing tools.
The deep drawing process is well suited for mass production as it gives parts that have net or near-net shape in one process. The tool is used for the production of many parts and after a while tool wear is observed. The shape of the product alters as the tool wears, and the surfaces of the produced parts may be rough due to rough tool surfaces. The factors influencing the wear process can be divided into four categories.

1. Surface and material properties.
2. Operating conditions, such as the stresses and strains that the tool material is subjected to and the properties of the sheet metal that is formed.
3. Type of lubricant used.
4. Geometrical properties.

Deep drawing is a metal working process in which products are manufactured from a flat sheet of metal. This process is called drawing because the sheet material is drawn into the die by a punch. Typical products are to be found in the automobile industry (doors, floors and panels), consumer electronics (shaver heads, electron guns in televisions) and the packaging industry (food packages and cans). Deep drawing starts with a disc of metal and ends up with a cup by pushing the metal through a die. The process involves plastic deformation of the sheet and a great deal of sliding of the sheet material along the tool surfaces. In Figure 2 the different steps that are involved in the deep drawing process are shown, as well as how the material is drawn into the die as the punch moves down.
Figure 2. The main parts of a deep drawing tool. During the forming process the punch (1) moves down into the die (2) while the blank (3) is held by the blankholder (4).

1.2 Tribology

Tribology is the study of the interaction of surfaces in relative motion. It includes three sub-areas: friction, lubrication and wear. Tribology is a complex interdisciplinary subject, since it involves surface physics, chemistry, metallurgy and solid and fluid mechanics.

Friction is defined as a force that resists the relative motion of one solid over another. About 20% of the engine power of automobiles is consumed in overcoming frictional forces in the moving parts. In order to minimise the frictional forces, a lubricant is often introduced between the surfaces in contact.

Surfaces in contact often transmit high loads and move relative to each other at the same time. Material is then removed from one surface or both surfaces; this process is called wear. The goal is to prevent wear from occurring. There are two basic ways to minimise the wear of a part, namely introducing a lubricant
Lubrication is defined as the introduction of various substances between sliding surfaces to reduce wear and friction. The use of lubricants to reduce frictional force is old. Lubrication in the form of water or lard on logs was used 4,400 years ago by the Babylonians [1], to ease the transportation of large statues. The use of lubricants produced from petroleum products started much later. It was not until the late 19th century, when the distillation process was improved sufficiently, that petroleum-based lubricants started to take market shares from the fatty oils used earlier [2].

There are three basic varieties of lubrication: full-film, mixed and boundary lubrication. When lubrication is of the full-film type, a lubricant layer separates the surfaces completely and transmits the forces from one surface to another. This means that, in theory, apart from when starting and stopping, no wear will occur and the coefficient of friction is governed by viscous shear. Boundary lubrication, on the other hand, occurs when the surface asperities transmit the forces between the surfaces. The wear rate will be high in this regime, as the surface asperities will wear off due to the high strains which they are subjected to, and the coefficient of friction will also be high due to this. Between full-film and boundary lubrication a third regime can be recognised, mixed lubrication. The forces are partly transmitted by the lubricant layer and partly by the asperity contact. In Figure 3 both friction and wear are shown as a function of the lubricant film factor. The lubricant film factor is defined as the ratio between the lubricant film thickness and the surface roughness. The lubricant film thickness is dependent on a large number of lubricant and process parameters. Examples of lubricant parameters are the viscosity, compressibility and pressure-viscosity coefficient, while the contact geometry, modulus of elasticity, relative velocity and load are examples of process parameters.
2. Wear models

Extensive research has been carried out in the development of a wear model that describes the wear process fully. Archard [3] was one of the first scientists who tried to describe wear, and others have followed his work. A review of a selection of the hundreds of wear models that have been presented in the literature can be found in Meng [4]. They vary from simple empirical models to complicated equations relying on physical concepts and definitions. Very few of the models have been used in practice due to the fact that many of them require specific variables and parameters that are not available in handbooks.

The predominant types of wear in deep drawing are adhesive wear, material transfer, abrasive wear as a consequence of material transfer, rough tool surfaces and hard particles entering the contact zone [5]. Abrasive wear has been investigated by Hokkirigawa [6]. De Rooij [7] has covered the tribological aspects of un lubricated deep drawing with the focus on adhesive wear, galling. When the tools are lubricated, the problems with galling are less and the abrasive wear becomes predominant. The wear model used in the present research is based on the assumption that the wear is abrasive and follows Archard’s wear equation [3], which postulates that the wear rate, i.e. the volume worn away per unit sliding distance, is proportional to the load and the material combination. The sliding distance and the contact pressure are of great importance, since they are the main parameters governing mild wear. It is, however, possible to use another wear model if necessary. In order to be able to
calculate the change in topography, Archard’s wear formula was rewritten to describe the wear depth at a certain point instead of the wear volume. In the finite element analyses the wear law is discretised with respect to time and space. The wear depth, \( h \), is calculated for each point by integrating the wear equation (1) over time.

\[
\frac{dh}{dt} = k \left( p \frac{ds}{dt} + s \frac{dp}{dt} \right)
\]

The dimensional wear coefficient is denoted by \( k \), \( p \) is the pressure and \( s \) is the sliding distance. The wear model used gives a fast and efficient way to calculate the change in shape for different geometries.

3. **Modelling and simulation of wear**

If simulation of a process is possible, then this should be used as early as possible in the product development process to maximise the benefits. The mathematical model that describes the process has to be verified before it can be used in simulating the behaviour of the process; otherwise the conclusions drawn from the simulation cannot be relied on and the modelling and simulation have no value. The main purpose of modelling and simulating processes instead of testing is that the former approach is cheaper and in many cases also less time-consuming. Evaluating and comparing different designs with respect to wear through simulation with finite elements constitute an excellent calculation tool, which is much faster than experiments and entails a minimal cost in the making of different designs.

Research in the field of wear has taken advantage of the rapid development of methods for finite element analysis of non-linear problems. The simulation of wear is non-linear due to the contact conditions, the material model used and the deformation. Process modellling in sheet metal forming has been studied by Ahmetoglu et al. [8]. They showed how metal flow simulations could be used, in an approximate manner, for practical purposes. The simulation of wear in deep drawing takes this analysis one step further, as it gives the opportunity to predict the behaviour of production as the wear of the tool is developing. Pödra [9] simulated sliding wear under the assumption that the relative sliding between the surfaces in contact was of the rigid body type. Tool wear in deep drawing has been studied by Eriksen [10]. He showed that changing the geometry of the die edge could reduce the wear of the die edge. A simulation of sliding wear was also performed in Paper C. An adaptive step size between the
geometry updates was used in the wear simulations and this gave both fast and accurate results.

3.1 The process of wear modelling

The six steps below describe the process of modelling wear. Wear simulations are recursive since the wear changes the geometry. This causes a need for regeneration of the shape as the wear evolves to obtain reliable results.

1. Perform finite element analysis on the geometry.
2. Calculate the pressure between the tool and the sheet.
3. Calculate the relative motion between the sheet material and the tool.
4. Calculate a wear index which is proportional to the pressure and the relative motion.
5. Update the geometry with respect to the wear.
6. Start once again from step 1 to wear off some more of the tool.

The finite element program calculates the pressures as well as the relative motion of the nodes in contact with one another. The program needs slidelines to be defined to calculate the relative motion, and these are defined between the nodes on the blank and the die that lie on the surfaces that come into contact with each other. The slideline accounts for separation and interface friction with Coulomb's friction law. The sliding distance is then calculated from the relative motion of the nodes on the slidelines between two successive time steps. During time step $i$ the closest point between node $n$ on the die surface and the blank is located at $y_i, z_i$. One time step later that point has moved its location to $y_{i+1}, z_{i+1}$. The difference between these two locations equals the amount of material that has passed node $n$ and is defined as the sliding distance, see Figure 4. The sliding distance was calculated within the finite element program and therefore accounts for both the kinematic motion and the deformation of the bodies in contact. The total change in location for each node was then calculated as the sum of the wear depths for the wear steps, while the wear depth in each step was calculated according to the pressure distribution and sliding distance calculated in the preceding step. The wear depth in each step was then scaled by an integer that indicates the number of punch strokes which the wear step corresponds to.

Several methods can be used to implement the geometrical changes due to wear in the finite element formulation of the problem. The most accurate method is to remesh the whole area that has been subjected to wear. This method is, however, time-consuming when the meshes are big. In the present research work two other approaches have been used in the wear modelling in order to speed up the calculations. The fastest way to describe the shape of the worn
surface is simply to move the nodes in the contact zones that have been subjected to wear. The initial element height will limit the wear depth in this case, as no remeshing will be performed between the wear calculations. Whether this is acceptable or not depends on the application in question. In Paper B, where this method was used, this was no limitation at all, as the most worn element had more than 40% of its initial height left after the simulation, see Figure 5. The method has to be used with care, as one cannot allow the elements to become too distorted, since this can cause numerical problems in the finite element analysis.

Figure 4. Definition of sliding distance.

Figure 5. Finite element mesh for a) a new and b) a worn surface without remeshing.

When deep drawing is simulated, another method for taking the change in geometry into consideration is used. The finite element model for deep drawing is axisymmetric and the die is simulated with a single row of elements, as shown in Figure 6. This is sufficient, as the die is not deformed to any greater
extent as the cup is drawn. The elements are elastic and supported by a stiff outer rim preventing the elements from deforming to such a degree that the model collapses. As the wear progresses, the nodes on the outer rim are moved to the same extent as the nodes on the worn surface. This approach has the benefit of not limiting the amount of wear and not giving any significant distortion of the elements. This model was used in Paper C.

![Finite element mesh for a new and worn surface in a deep drawing die.](image)

**Figure 6.** Finite element mesh for a) a new and b) a worn surface in a deep drawing die.

### 3.2 Finite element analysis of wear in deep drawing

Research in the field of sheet metal forming/deep drawing has been focused mainly on friction [7, 8, 11 and 12]. The present work takes the friction between the sheet and the die into consideration, but focuses on the die wear. A prescribed motion of the uppermost nodes of the punch masters the deep drawing process. A Coulomb friction model with a constant coefficient of friction of 0.15 was used between the slidelines in Paper C. This is a normal value for the coefficient of friction in deep drawing. The finite element analyses were based on implicit integration of the equations of motion and were performed with a slightly modified version of NIKE2D [13]. The models are axisymmetric and the materials are assumed to be elastic, except for the blank, where an elastoplastic material model with rate-independent plasticity, von Mises yield criteria and isotropic power law hardening are assumed. A material model for steel has been used for the blank. Young’s modulus, E, is assumed to be 210 GPa and Poisson’s ratio, ν, is assumed to be 0.3. For the elastoplastic material model the yield stress, σ_y, and the initial yield strain, ε_0 can be described according to Eq. 2 and 3.
\[ \sigma_y = k(\varepsilon_0 + \varepsilon^p)^n \]  \hspace{1cm} (2)

\[ \varepsilon_0 = \left( \frac{E}{k_s} \right)^{n-1} \]  \hspace{1cm} (3)

The effective plastic strain of the material is denoted by \( \varepsilon^p \). The strength coefficient of the sheet metal, \( k_s \), is 1.5 GPa and the hardening exponent, \( n \), is 0.48. The stresses on the different parts of the tool never exceeded the material’s yield strength. In the finite element program the effective plastic strain is calculated together with the yield stress.

4. Updated geometry with different time step approaches

Numerical simulations of a cylindrical steel roller oscillating against a steel plate were performed in Paper B. To evaluate the accuracy of the numerical simulation of wear with Archard’s wear equation, an experimental test was carried out. The aim of the work presented in Paper B was to show how wear simulations could be performed in a fast and accurate way by allowing the time step for the geometry update to vary in the simulations.

4.1 Simulation

Two different strategies in selecting the appropriate time step were used in the simulations. An adaptive time step was used in the first case, with a large time step during the first wear steps and a smaller one in the final ones. In the second case a constant time step was used throughout the simulation. A Coulomb friction model with a constant coefficient of friction of 0.07 was used in Paper B. This is in accordance with the coefficient of friction measured in the experiments. The finite element model was applied using a slightly modified version of NIKE2D [13]. The wear simulations were performed in accordance with Archard’s wear equation. No remeshing was carried out between the wear calculations.

4.2 Experiment

The simulations were verified by experiments. The test served as a source of input to the simulations, as the coefficient of friction measured in the experiments was used in the numerical simulations. The wear was simulated until the same maximal wear depth as in the experiments was achieved. The contact geometry studied was of the cylinder-plate type: a cylindrical steel roller with a radius of 3.0 mm and a length of 4.2 mm was loaded with 300 N against
a steel plate and an oscillating motion was applied to the cylinder. The oscillating frequency was 10.16 Hz and the amplitude 2.25 mm. The contact was flooded with oil and the temperature of the oil was held constant at 80°C during the test. The oil used was a synthetic ester without additives and with a viscosity of 46 mm²/s at 40°C. The roller-plate geometry was created using roller bearing material. Roller bearing steel has an elastic modulus of 205 GPa, the Poisson ratio is 0.3 and the hardness 850 MPa. The surfaces are polished and the surface roughness is 0.03 μm.

4.3 Results

In order to minimise the computational time, a strategy with varying time steps between the updates was used. This leads to discrepancies in the topography due to the fact that big wear steps will exaggerate the wear in some nodes and underestimate it in others. After the wear simulation has been truncated with some smaller wear steps, no sign will remain of the waviness. The two approaches for the time step size showed good agreement with each other as well as with the experiments. The time spent simulating the wear with the adaptive time step size was about 60% of the time needed with the constant time step size. The number of required geometry updates was 16 with the adaptive time step size approach, while the constant time step size required 27 to achieve the same result.

5. Influence of die geometry on wear

The aim of the work presented in Paper A and C was to investigate how the geometric design of the die affected the die wear. Wear of two different die geometries has been simulated in the papers. Paper A focuses on the simulation of the forces and pressures that the sheet metal forming tool has to sustain. In Paper C a wear model has been incorporated into the analysis package and the wear of the sheet metal forming tool has been studied. The two geometries, see Figure 7, can be distinguished by the transition in the upper part of the die, the first die having a circular and the second having a so-called tractrix transition. The reason for studying the die with the circular transition was that it is the most commonly used. The tractrix transition was used because it has been claimed to have some good properties with respect to wear. Eriksen [10] found that the tractrix curvature gave deep drawing tools with lower values of both average and maximum wear compared with circular and elliptic transitions. The same results have also been found in Paper C.

The definition of a tractrix curve is as follows. A tangent to a tractrix curve has a fixed length, a, and one end shall follow the tractrix curve while the other
shall follow a vertical axis. Pythagoras’ theorem and the use of uniform triangles give the differential equation that describes the tractrix curve as:

$$\frac{dy}{dx} = \frac{\sqrt{a^2 - x^2}}{x}$$  \hspace{1cm} (4)

In Eq. 4, the horizontal axis is denoted by $x$ and the vertical axis by $y$. The curvature of the tractrix curve is extrapolated as a straight line when the angle with the vertical axis reaches 3 degrees.

5.1 Simulation

Finite element simulations were performed with the two geometries, the circular and the tractrix. The models are axisymmetric and consist of the same number of nodes and elements. Note, in Figure 7, that the die with tractrix transition requires a longer punch stroke. The simulation is limited to calculating the wear of the die in order to speed up the calculations. In practice the blankholder is worn as well, but the blankholder force can be held constant and therefore it does not influence the wear of the die and the stress state in the cup to any higher degree. It is, however, possible to calculate the wear of the blankholder if necessary.

![Figure 7](image)

**Figure 7.** Finite element model of a) circular and b) tractrix transition at the die edge.
5.2 Results

As presented in Paper A, the punch forces and the radial forces on the die are higher for the cups formed in the die with circular transition than for the ones formed in the die with tractrix transition. The wear of the two different die profiles used in the simulations of Paper C is shown in Figure 8. The calculated tool wear corresponds to the simulation of the wear caused by producing the same number of parts in each of the two dies. It is clearly seen that the wear of the die with circular transition is concentrated to the area around the transition of the profile from vertical to circular. The tractrix transition has a smaller wear depth but, on the other hand, the wear is distributed over a larger area. It can be seen that the wear occurs at two different parts of the die, and that most of the wear occurs along the tractrix curvature. However, a small amount of wear can also be seen in the transition of the profile from tractrix to horizontal.

The worn circular die form becomes similar to the tractrix die. The tractrix die, on the other hand, more or less maintains its initial geometry. The total wear, i.e. the wear depth integrated over the area, is lower in the tractrix die than in the circular die.

![Figure 8](image)

**Figure 8.** Profile of the new and the worn die with a) circular and b) tractrix transition of the upper part.
6. Influence of worn dies on the parts produced

It is not only the change in shape of the deep drawing die due to wear, which is of interest. The shape of and the stresses and strains in the parts produced are in many cases of greater interest to buyers. How worn deep drawing dies affect the geometry of and the stress state in the parts produced was investigated in Paper C. There are no absolute values for how worn dies can be before the quality is too low to be acceptable. In some cases the shape is the greatest concern, while in others the stresses or the strains in the parts produced are more critical.

6.1 Results

The cup geometry calculated for the different dies has been investigated with respect to the shape of the profile, the height and the diameter at the rim. In Figure 9 the shapes of deep drawn cups simulated in new dies are compared with cups simulated in worn dies. As the die with tractrix transition wears, the rim of the cup becomes wider and the height decreases. Wear of the circular die causes the cups to become wider and decrease in height, but the profile of the cups is also changed; the curvature at the top of the cup changes considerably. Cups produced in the circular transition die tend to be more like the cups produced in the die with tractrix transition as the wear evolves.

![Figure 9](image_url)

**Figure 9** The shape of the cup formed with new and worn dies. a) circular and b) tractrix transition of the upper part of the die.
Evaluation of the stress state in the cups has focused on the location and the value of the maximum in the effective stress. The maximum effective stress is higher for the new dies than for the worn ones. A new die with tractrix transition gives an effective stress that is lower than a worn die with circular transition. The new circular die gives an effective stress of 1,120 MPa compared with 771 MPa for the worn one, whilst the new tractrix die gives an effective stress of 620 MPa compared with 566 Mpa in the old one. This implies that the effective stresses in the cup decrease as the dies wear. This is because the areas which are subjected to the highest loads wear most quickly. Both the stresses and the strains are lower for the worn dies because of this. The effective stress decreases by 31% for the circular die compared with 9% for the tractrix die.

The effective stresses for the cups produced in dies with tractrix transition can be seen in Figure 10. In Paper C the effective stress is presented for the cups produced in dies with circular transition. The maximum effective stress is located in the transition from horizontal to vertical, except in the case of a new circular die. The maximum effective stress is then located relatively high, approximately 60 mm from the top of the cup.
Figure 10. The calculated effective stress in a cup formed in a) a new die and b) a worn tractrix die.
7. Discussion

The results from the numerical simulation of a steel roller oscillating against a steel plate show good agreement with experimental results. It has also been shown that using an adaptive method for the step size between the geometry updates can minimise the simulation time. The method of simulation is good, as it gives both fast and accurate results and therefore can be used for comparison of the wear of different parts.

It can be concluded that the claim that the tractrix curvature in a deep drawing die reduces wear is only weakly confirmed in Paper A, as the contact forces are only reduced by approximately 10%. Wear simulations of deep drawing tools have been performed in Paper C. An adaptive step size between the geometry updates was used here, as well as in the wear simulation of a roller against a plate. It can be concluded that the tractrix transition gives a die with less total wear than a die with circular transition. Changes in the shape of the cups produced in the tractrix die are smaller and the effective stress is lower than in the cups produced in the circular die.

The use of tractrix profiles in deep drawing dies is well worth investigating further, as these demonstrate good properties as far as the wear rate of the die, the magnitude of changes in shape and the maximum effective stress are concerned.

The shape of deep drawn parts depends on many factors, including friction. One area that has to be included in future work is the coefficient of friction. A high coefficient of friction in the die can give excessively high stresses in the sheet material and cause tear. A low coefficient of friction can give a tendency to wrinkle in the parts. A constant coefficient of friction has been used in the simulations. It would, however, be of great interest to see how a varying coefficient both in time and in space would affect the results.
8. References

9. Appended papers

This licentiate thesis consists of a summary and the following three papers.


B Öqvist, M., *Numerical simulations of mild wear using updated geometry with different step size approaches*. Accepted for publication in WEAR.

C Öqvist, M., *The effects of tool wear on deep drawing*. To be published.
Design of die and its effect on wear in cup forming

L. Karlsson & M. Öqvist
Division of Machine Element, Luleå University of Technology Sweden

L. E. Lindgren & M. Näsström
Division of Computer Aided Design, Luleå University of Technology Sweden

ABSTRACT: The effect of the geometric design of die on tool wear is studied. The Finite Element Method is used in the simulations. Two different geometries of the upper part of the die are compared. They can be described as a circular curve in the first case and as a tractrix curve in the second case. The latter is known to have some good properties with respect to springback and residual stresses of cup. A lower maximum punch force is obtained for the tractrix case.

1 INTRODUCTION

Reducing tool wear in sheet forming can be done by lubrication and appropriate geometric design of the tools. Various theories of elastic-plastic bending of sheet metals have been presented in the literature. Considerable effort has been undertaken to develop analytical models and understand the bending process. However, these models are not easily extended in order to study the interaction between the tool and the formed material. Experimental studies to reduce tool wear have been performed (Hsu 1993, Schedin 1993). Improving wear resistance of tool can be done by material selection. Punching tools are normally made of tool steel that is heat treated after machining. For high volume production it is common to use punches and dies made of cemented carbides to obtain extended time between exchange or regrinding of tools. Another option is to reduce wear by design of tool geometry and by lubrication. This can, of course, be combined with increasing wear resistance by material selection.

This study is a first step in a study aiming at reducing tool wear. The Finite Element Method is used to study the interaction between tool and formed material. A fictive case has been investigated. The main purpose is twofold, evaluate the computational tool and evaluate the model.

The conclusions are that Nike2d (Engelmann 1991a) in combination with Island (Engelmann 1991b) is very powerful. The industrial experience that the tractrix curve reduces tool wear is only weakly confirmed in the study as the contact forces are only reduced by about 10%. A better model for integrating the effect of parameters like force, relative velocity and time on wear is needed.

2. THE ANALYSIS OF PLASTIC BENDING

Several models for the deformation in plastic or elastoplastic bending have been used in sheet metal manufacturing processes. They do have the advantage of producing relations where the influence of specific parameters can be seen directly. However, they will never be as accurate as numerical models.

Hill (1950) presented a complete solution for pure bending in which deformation of a sheet metal is achieved by a couple applied along its length. In this analysis he predicted the movement of the neutral axis but no change in thickness for rigid-perfectly plastic materials under plane strain bending. Lubahn and Sachs (1950) analysed the cases of plane stress and plane strain bending in a similar manner to Hill's, but they predicted material thinning based on the improper assumption that the neutral surface will remain at fixed positions during small increments of bending curvature. Crafoord (1970) found that the thickness change of sheet during bending is negligible. That conclusion is reinforced by the finite element analysis of Oh and Kobayashi (1980). Dadras and Majlessi (1982) conducted an analysis on bending of rigid-strain-hardening materials. Weinmann et al. (1988) carried out an experimental study of Bauschinger effect on sheet metal under cyclic reverse pure bending in an attempt to establish a plastic stress-strain relationship. However, their model did not incorporate the Bauschinger effect as expected.

The residual stresses in deep drawing with circular and tractrix die profiles have been studied both experimentally and with the FE-code LS-Dyna2D by Danckert (1994). He achieved good agreement between the FE-simulations and the experimental results.
In this study we will simulate two different curve forms of the upper part of the die. The influence of a geometrical design of the tool is the emphasis in this study and will be followed by investigations of the effects of lubrication.

3 REDUCING TOOL WEAR

The industrial objective of research in forming processes is to reduce lead times and costs in the product development cycle and to increase production speed in the production of sheet metal parts. While these objectives apply primarily to the users of punching tools, the objective for the designers and manufacturers of the tools is to enhance competitiveness among toolmakers by introducing a new and highly efficient design. The final goal is to simulate, produce and test a prototype tool in order to reduce tool wear in sheet forming. The models described in the previous chapter are not easily extended to study tool wear as it is related to the interaction between tool and formed material. Therefore the Finite Element Method has been chosen in this study.

Next to metal cutting machine tools, hydraulic and mechanical presses are the most common equipment in mechanical industries. Production speeds are generally high in press tools and the initial tool design, manufacturing and tool wear are extremely expensive and time consuming. One problem is that it is often impossible to finalise tool design before a number of parts have been produced and tested for functionality, accuracy and integration with other components in the product. Hence, for many years the challenge has been to cut down initial costs and shorten lead times in work preparation for such parts.

The first step in this work is to analyse the forming of an axisymmetric cup and investigate the influence of the geometry of the die on the contact forces between the sheet and the die. The Finite Element Method is used in the simulations. Two different geometries of the upper part of the die are compared. In the first case a normal circular radius is used and in the second case the tractrix curve is used. The latter is described in the next chapter. A study of how lubrication will reduce the tool wear in cup forming will be performed in future work. The dynamic behaviour focus on the interference between natural frequencies of punch and press. Working frequency of the machine will also be of interest in future studies.

Design modifications will be performed based on the results from computer simulations and experiments. A tool will be manufactured for testing in laboratory and in production.

4 TRACTRIX CURVE

Wang (1993a) state that "The tractrix bending die may be the optional one to reduce the sensitivity of bending angle variations to punch stroke variations, to improve the control of brake bending process, and part tolerance". A mathematical model of plane-strain bending of sheet and plate have also been studied by Wang (1993b). Drawing die with tractrix shape have been used by Kampus (1992). It is known by the designers of tools, that the curvature form in sheet metal forming techniques has an important influence on the tool wear.

The derivation and definition of the tractrix curve follows. A tangent line to the tractrix curve has a fixed length 'a' and its left end should always be at x=0, as shown in Figure 1. Pythagora's theorem and the use of uniform triangles gives the differential equation

\[ \frac{dy}{dx} = \frac{\sqrt{a^2 - x^2}}{x} \]

The solution of the equation is

\[ y(x) = a \ln \left( \frac{a + \sqrt{a^2 - x^2}}{x} \right) - \sqrt{a^2 - x^2} \]

where 0 ≤ x ≤ a. The curve is extrapolated as a straight line when the angle with the vertical axis reaches 30°.

5 COMPUTATIONAL MODEL

The Finite Element Method has been used very much for simulating drawing. Finite element codes have been based on either the flow formulation or the solid formulation. Explicit codes have gained ground in the latter case. The monograph by Oñate
Figure 2. Finite element mesh for circular case.

Figure 3. Finite element mesh for tractrix case.

Figure 4. Stress-strain relation for power law hardening.

\[ \sigma = k (\varepsilon + \bar{\varepsilon})^n \]  

(1993) gives an overview of the methods and applications. Danckert (1994) used the explicit finite element code LS-Dyna2d in simulations where the effect of the die geometry on the residual stresses of the formed cup was the main concern. He concludes that the tractrix curve is favourable but has the disadvantage of requiring an increased punch stroke.

Two computational models have been created by using the public domain codes from Lawrence Livermore National Laboratory. They are the mesh generator Maze (Hallquist 1983), the finite element code Nike2d (Engelmann 1991a) with the driver Island (Engelmann 1991b) and the postprocessor Orion (Hallquist 1985a).

The two finite element models are shown in Figures 2 and 3. The first case has a die with a circular transition at the upper edge and the second case has a tractrix curve. They will be named circular and tractrix case below. They have 980 elements and 1341 nodes. The models are axisymmetric. The material is assumed to be elastic, except for the formed plate where an elastoplastic material model is used. The Young's modulus, \( E \), is taken as 205 GPa and Poisson's ratio as 0.3. Rate-independent plasticity with von Mises yield criteria and the associated flow rule is used. Isotropic, power law hardening is assumed. The yield stress is

\[ \sigma_y = E \left( \frac{\varepsilon}{k} \right)^{n-1} \]  

The value for \( k \), the strength coefficient, is 1543 MPa and \( n \), the hardening exponent, is 0.48. The effective plastic strain, \( \bar{\varepsilon}^p \), is plotted versus stress in Figure 4.

The finite element formulation accounts for large deformations. The Green-Naghdi stress-rate (Johnson 1984) is used in combination with midpoint strain increment (Hughes 1980). The
contact algorithm, (Hallquist 1985b), permits arbitrarily large sliding. The Coulomb friction law was applied with a friction coefficient of 0.15.

The driver Island proved to be an efficient tool together with Nike2d. The incremental and iterative procedure for the simulation applied both displacement and energy criteria for convergence checks. The time steps were cut down and the convergence criteria were tightened when encountering convergence problems during the solution procedure. Starting anew from previous converged steps is also possible. Several procedures for solving the equations are available in Nike2d. The BFGS method was chosen for this case.

Island compensated for one of the drawbacks using an implicit finite element formulation instead of an explicit code like Dyna2d (Hallquist 1988). Namely, the problem in attaining convergence in the solution process. Furthermore, it includes the capacity of optimising the punch speed for controlling the strain rate in the material as one can change load curves in relation to computed variables.

6. RESULTS

The deformation process for the two cases is shown in Figures 5 and 6. Note that the same punch travelling distance in the two cases do not correspond exactly to the same amount of drawing as the punch must travel longer in the tractrix case to achieve the same shape. The punch travel distance is 3.5, 17.5 and 23 mm for the different configurations of the formed material.

The effective plastic strain is about the same for the two cases, around 0.25, in the corner where the bending is concentrated.

The punch force, Figure 7, is somewhat higher in the circular case. Therefore the difference between the computed forces is less than what it looks like in the Figure. The force is probably not more than 10% higher in the circular case.

Noticeable is the problem of getting a flat bottom of the cup in the circular case. The deformation changes behaviour at a punch travel of 23 mm, see Figure 5 and it is not possible to recover a flat bottom later on in the process. This phenomena is also visible in the force diagram in Figure 7, especially for the radial force. This force decreases when the bottom of the cup "falls out".

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590
The forces in Figure 7 are global quantities. In order to evaluate tool wear it is more of interest to have the pressure and shear stress in the die. The shear stress is the pressure multiplied by the friction coefficient, due to the Coulomb friction model. The pressure is shown in Figure 8. The pressure is locally higher in the tractrix case.

7. CONCLUSIONS AND FUTURE WORK

The main conclusion is that the claim that the tractrix curve reduces tool wear is only weakly confirmed in the study as the contact forces are only reduced by 10%. A better model for integrating the effect of parameters like force, relative velocity and time on wear is needed.

A well documented experiment will be needed in order to verify the computational model and special attention will be given to the friction model. The Coulomb friction model will be extended along the same as in Edberg (1992 and 1994). Anisotropic material models with Bauschinger effect, available in Nike2d, will also be necessary for a real test case.

It is also found that Nike2d in combination with Island is very powerful. Thus the implicit finite element formulations gain ground versus the use of explicit codes that have found their place in simulation of material processing, Edberg (1993) and Häggblad (1992).

8. REFERENCES

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Numerical Simulations of Mild Wear Using Updated Geometry

With Different Step Size Approaches

Mona Öqvist M.Sc.
Division of Machine Elements
Luleå University of Technology
SE-971 87 Luleå

Abstract

Wear of engineering components is often a critical factor influencing the product life. Prediction and simulation of wear is therefore an important matter in engineering. Numerical simulations of wear of a cylindrical steel roller oscillating against a steel plate are performed with a special version of the finite element program NIKE2D. The simulation was done in steps and the pressure and the sliding distance was recalculated as the surface geometry changed. The wear model used in the simulations is global. The global wear model gives an opportunity to predict the change in shape of the surfaces in a fast and efficient manner, it will however not incorporate information on how the wear occurs on molecular scale.

Two different strategies in selecting the time step for the geometry update were used. In the first case a larger time step was used in the first wear steps and a smaller one in the final ones, and in the second a constant time step was used. To get information on the coefficient of friction an experiment was performed. This experiment was used to evaluate the simulation as well as give the proper input to the simulation. The simulated topography of the surfaces was compared with experimental results and the agreement was good. It can be concluded that allowing the time step to differ between the wear steps will speed up the wear simulation considerably. A large time step for the geometry update will cause some waviness of the cylindrical surface but when the smaller time steps have been used at the end of the computation this error will disappear.

Keywords: Wear, Simulation, Finite element analysis, Wear experiments, Line contact, Friction, Surface topography

Nomenclature

\( f \) - Frequency [Hz]
\( h \) - Wear depth [mm]
\( H \) - Hardness [Vickers]
\( K \) - Dimensionless wear coefficient [-]
\( k \) - Dimensional wear coefficient [MPa\(^{-1}\)]
\( p \) - Pressure [MPa]
\( s \) - Sliding distance [mm]
\( t \) - Time [s]
\( \Delta h_i \) - Incremental wear depth [mm]
\( \Delta h_{\text{tot}} \) - Total wear depth for one simulation cycle [mm]
1. Introduction

Wear of engineering components is often a critical factor influencing the product life. To be able to evaluate and compare different designs with respect to wear simulation with the finite element method is an excellent tool. Wear is a dynamic process which incorporates surface and material properties, operating conditions, stresses, lubricant oil film and geometry. Extensive research has been made in the development of a wear model that describes the wear process fully. Archard [1] was one of the first to try to describe wear and his work has been followed by others. Lim and Ashby [2] made wear maps for steel using the approach that the wear coefficient is dependent on load and sliding velocity. A wear model that accounted for oxidation was suggested by Wu and Cheng [3] and adsorption models have been suggested by Kingsbury [4]. It has been argued that the critical parameters in sliding wear are the stress field in the contact and the relative sliding distance between the surfaces. Mild wear can be described accurately on a global scale with a modified version of Archard’s wear model.

The research in the field of wear has taken advantage of the rapid development of methods for finite element analysis of non-linear problems. The simulation of wear is non-linear due to the contact conditions between the interacting bodies. The material model used and the deformation of the bodies can also introduce non-linearities. Pödra [5], [6], simulated sliding wear under the assumption that the relative sliding between the surfaces was of rigid body type. The contact stress field was calculated with a finite element program. Tool wear in deep drawing has been studied by Eriksen [7]. He concluded that there is a correlation between the actual wear and a wear index based on Archard’s wear formula.

The aim of this work is to show how wear simulation can be performed in a fast and accurate way by allowing the time step, for the geometry update, to vary between the different steps in the simulation. A finite element program was used both to solve the stress state and to calculate the relative sliding distance. Similar wear calculations have been done by for example Pödra [5], [6] and Eriksen [7] but they did not calculate the sliding distance in the finite element program and therefore no elastic deformation was accounted for. In this article a model that incorporates both rigid body motion and elastic deformation of the bodies is used.

The simulations have been verified by an experiment. The experiment served as a source of input to the simulation as the coefficient of friction was taken from it. The experiments also served as a way to be able to create a suitable model that did not need any remeshing during the simulation. This gave faster simulations as the model is both simple and reliable. The simulated geometry was compared with the experimentally achieved geometries for verification.
2. Wear model

Archard’s wear equation [1] postulates that the wear rate, i.e. the volume worn away per unit sliding distance, is proportional to the load and the material combination. In order to be able to calculate the change in topography Archard’s wear formula was rewritten, Eq. 1, to describe the wear depth, $h$, at a certain point instead of wear volume.

$$h = \frac{K}{H} sp$$

(1)

The wear coefficient is denoted $K$, $H$ is the hardness of the worn surface, $s$ is the sliding distance and $p$ is pressure. In the finite element analysis the wear law is discretised with respect to time and space, and the nodal wear depths are calculated as the sum of nodal wear increments. In this case it was more appropriate to write the change in depth with time according to Eq. 2.

$$\frac{dh}{dt} = kp \frac{ds}{dt}$$

(2)

The wear coefficient and the hardness are replaced by the dimensional wear coefficient, $k$. In figure 1 the main steps of the wear calculation are shown. The wear depth is calculated, for every node laying on the surfaces that come into contact with each other, by integrating the wear equation over time. The wear model used in the simulation is global. A global model as this one describes mild wear in an accurate way, for more complex wear cases a more complicated model have too be used. The global wear model gives an opportunity to predict the change in shape of the tool in a fast and efficient manner it will however not incorporate information on how wear occurs on molecular scale.

![Figure 1. Scheme describing wear calculations in a finite element program.](image-url)
3. Experimental setup

To evaluate the accuracy of the numerical simulation an experimental test was carried out. The contact geometry was of cylinder-plate type and the contact surfaces were made of roller bearing steel. The test was performed using an oscillating high frequency friction machine, Plint and Partner (TE 77B). In figure 2 the main parts of the equipment are shown.

The oscillating frequency was 10.16 Hz and the amplitude 2.25 mm. The plate was kept stationary while the roller performed a reciprocating motion. This resulted in a maximum relative sliding speed of 0.14 m/s. The roller-plate geometry was created by using polished rollers from roller bearings. The end of a roller was used as the plate in the contact geometry. The surface roughness of the polished roller bearings was Ra 0.03 μm. The roller bearing steel has an elastic modulus of 205 GPa, Poissons ratio is 0.3 and the hardness is 850 Vickers. The maximum pressure for the rectangular conjunction was calculated according to Hertz theory to 850 MPa when the roller, with a radius of 3.0 mm and a width of 4.2 mm, was loaded with 300 N. This pressure is only present in the beginning of the wear test due to the growing wear scar. The contact area was flooded with oil during the test and the temperature of the oil was 80 °C. The local temperature in the contact was not possible to measure in this setup. The oil used was a synthetic ester without any additives with a viscosity of 46 mm²/s at 40°C. Wear measurements on this oil has also been performed by Rieglert [8]. The regimes of lubrication present in the test range from boundary to partial lubrication. The reason for this is that the velocity of the roller range from zero to 0.14 m/s. The frictional force was measured continuously during the test by a force transducer mounted on the stationary holder. A sampling period of 10 seconds was then used to see how the frictional force was affected by the growing wear scar. The wear scars on the surfaces were characterized by a stylus profilometer after the test.

![Figure 2. The main parts of the test apparatus. Moving specimen carrier (1) with a replaceable test specimen, in this case a cylindrical roller (3), stationary plate (4) with holder (2).](image-url)
4. Numerical analysis

The main purpose in using finite element analyses in the wear calculations was to compute the contact stresses and the sliding distances in the contact zone. The sliding distance may be calculated outside the finite element program as well, but in this case only the kinematic motion is accounted for and not the elastic deformation of the surfaces in contact. The finite element analyses were based on implicit integration of the equations of motion and performed with a modified version of NIKE2D [9]. The finite element model was created using two-dimensional plane strain elements with four nodes, figure 3. The load was applied as a uniformly distributed pressure on the uppermost element sides of the cylindrical roller and the relative motion between the roller and the plate was controlled by prescribing the location of the lowermost nodes of the plate.

An elastic material model was used since the forces never exceeded the materials yield strength. A Coulomb friction model with a constant coefficient of friction of 0.07 was used. This is in accordance with the coefficient of friction measured in the experiment. The total change in location for each node was calculated according to a discretised version of Eq. 2.

\[
\Delta h_{tot} = \Delta h_i f \Delta t
\]  

Where \( \Delta h_{tot} \) is the total wear depth for one wear simulation step, \( \Delta h_i \) is the increment in wear depth for one cycle, \( \Delta t \) is the wear time and \( f \) the frequency. The wear time multiplied by the time step indicate the number of revolutions that were performed between two successive wear calculations.

It should be noted that no remeshing is done between the wear calculations and that the element height therefore will limit the maximum total wear depth. This is however no limitation in this case as the worn elements have at least 40% of its initial height left after the entire wear simulation.
The wear model used in the simulations is global and based on Archard's wear equation. Therefore the simulation does not take into consideration the microstructure of the surfaces in contact e.g. it does not account for the surface roughness or the surface texture. The simulations does not take into consideration the small changes in material properties that are introduced by the temperature rise in the contact when summits come into contact as it is most unlikely that this will influence the change in shape of the surfaces in contact. The entrance of wear debris in the contact region will influence the pressure distribution in the contact during a limited time, as the wear calculation is global as mentioned earlier this will not influence the final result.

5. Results and Discussion

Both simulations and experiments have been performed. The wear simulations were performed in accordance with Archard's wear equation which does not take lubrication into consideration explicitly while the experiments were performed under lubricated conditions. The reason for this is that boundary and mixed lubrication will give wear scars that have the same shape as under unlubricated conditions, the only difference is in the rate of wear. The coefficient of friction is also more stable during the reciprocating motion when a lubricant is used. The experiment served as a source of input to the simulation as the coefficient of friction was taken from it. The geometries that resulted from the experiments was also used for verification of the simulated worn geometry.

5.1 Numerical simulation

The simulation was performed with a full reciprocating motion with sinusodial velocity. In order to minimize the computational time a strategy with varying time step between the geometry updates was used. This will lead to discrepancies in the topography due to the fact that big wear steps will exaggerate the wear in some nodes and underestimate it in others and in the next wear step there will be other nodes that are subject to exaggerated wear. In the end the results will not differ from those obtained with a constant and small time step between the geometry updates. Comparing the geometry after the 5th and 6th wear step in figure 4 below it is seen that summits will form on the surface due to the exaggerated wear and that these summits then will wear-off faster than the surroundings because the pressure on them will be higher. After the wear simulation has been truncated with some smaller wear steps no sign will remain of the waviness and the shape will be in encouraging coincidence with figure 5 where a constant and small time step have been used between the geometry updates throughout the wear simulation.

When the time step was allowed to vary the time step was increased by 50% between the wear steps. If convergence was not achieved the time step was then decreased by 33%. The numerical simulation was then terminated by 6 steps with a time step that was equal to the time step used throughout the entire simulation with a constant time step. The use of a varying time step limited the number of wear calculations that had to be done to 16 while the use of a constant time step required 27 to achieve the same wear depth.

The wear simulation has also been performed allowing the lower surface to move only in one direction, the second half of the reciprocating motion was omitted. The reason for trying this is that it cuts computational time by nearly 50%. In this case we will have similar results as for the case with reciprocating motion shown in figure 4. This is due to the fact that the coefficient of friction is low and the elastic deformations are small. If however the deformation of the surfaces are more pronounced there will be a need to simulate the whole reciprocating motion.
Figure 4. The geometry of the roller and the plate simulated with adapted time step size.

Figure 5. The geometry of the roller and the plate after wear simulation with constant time step size. The worn geometries shown in the figure correspond to the ones shown in figure 4.
5.2 Experiment

After 30 h of wear in the high frequency friction machine the surface topography of the roller and the plate were measured. This time correspond to nearly 1.1 million (1 097 280) reciprocating motions and 12 wear steps in the case where an adaptive wear time step have been used. The coefficient of friction measured 0.07 with a maximum error of 10%. It was lower at the end of the experiment than in the beginning, due to the growing wear scar. As the wear scar was growing the contact pressure was dropping and less of the motion was falling into the category of boundary lubrication. The variation of the coefficient of friction due to the growing wear scar fall into the limits given by the maximum error. The temperature of the oil was 80 °C with a maximum error of ± 0.5°C. The topography of the roller and the plate was measured with a stylus profilometer after the wear test. The topography of the worn roller, figure 6, corresponds very well to the surface that the numerical simulation resulted in. It was not possible to detect any wear of the plate in the experiments. This is due to the fact that the maximum wear depth of the plate are less than for the roller and that the plate are not entirely flat initially. The numerical simulation shows that the maximum wear depth of the plate are approximately 1/10 of the rollers.

![Figure 6](image.png)

Figure 6. The geometry of a roller after 30 h of wear, measured by a stylus profilometer. The geometry of a new roller is also indicated.

6. Conclusions

The results from the simulation show good agreement with experimental results and it can be concluded that the wear simulation method used here can be used to simulate mild wear on a global scale.

The simulation time can be minimized by using an adaptive method for the time step between the geometry updates. A greater time step was used in the early steps of simulation while a smaller one was used in the terminating steps. This exaggerated the wear in the first steps but it did not influence the result in the end as the waviness of the worn surfaces that was introduced by this disappeared during the final steps with a small time step between the geometry updates.

The method of simulation is good as it gives both fast and accurate results and therefore can be used for comparison of the wear of different parts.
7. References


Simulation of Tool Wear in Deep Drawing

Mona Öqvist M.Sc.
Division of Machine Elements
Luleå University of Technology
Sweden

Abstract
Sheet metal forming, including deep drawing plays an important role in modern manufacturing industry. A significant problem associated with deep drawing is tool wear which results in parts which do not have the desired dimensions and/or shape. In order to compensate for the effects of wear, tools must be exchanged or reground which increases costs for production. In order to obtain some level of control over the effects of wear, it is important to have an accurate method to predict tool wear. One method that can be used is numerical simulation.

The wear model used in the simulations is global which gives an opportunity to predict the change in shape of the tool in a fast and efficient manner. However, the model does not provide information about the effects of wear at the molecular scale.

The aim of the work presented in this paper was to investigate how two alternative geometries for deep drawing dies wear and how the worn tools will affect the produced parts. The two dies differ in the transition in the upper part. In the first case, a circular radius is used whilst in the second case a tractrix curve is used. The results of the investigation demonstrate that the use of a die with a tractrix transition lowers the total wear considerably. The distribution of the wear is also more favourably since the geometry of the die does not alter considerably. The predicted shape of the cup produced in the die with tractrix transition changes less as the die wears compared with the cups produced in the circular die. The decrease in cup height as the tool wears is the same for both cases. The effective stresses computed for the cups produced in both the new and the worn tractrix dies are lower than for the cups produced in the circular die.

Keywords: Deep drawing; Wear simulation; Finite element analysis
1. Introduction

Wear of engineering components is often a critical factor as far as product life is concerned. Simulation using finite elements is an excellent tool for evaluating and comparing different designs with respect to wear. Wear is a dynamic process, which is affected by surface and material properties, operating conditions, stresses, lubrication and geometry. Wear should therefore be considered as a system dependent characteristic that must be studied as part of the total tribological system, Czichos [1].

In the sheet metal forming industry, especially the car manufacturing industry, considerable effort is put into finite element simulations of processes such as deep drawing, stretching and bending. The objective of these simulations is to minimise costs in the development phase of a product and to analyse potential problems that may occur during the production phase. Process modelling of sheet metal forming has been studied by Ahmetoglu et al. [2] who showed how metal flow simulations can be used, in an approximate manner, for practical problems. The simulation of wear in deep drawing takes this analysis one step further as it gives the opportunity to predict the behaviour of the production process as the tool wears. Extensive research has been carried out to develop a wear model that fully describes the wear process. Archard [3] was one of the first to try to describe wear and others have followed his work. A review of a selection of the hundreds of wear models that have been presented in the literature can be found in Meng [4]. These models range from simple empirical relationships to complicated equations relying on physical concepts and definitions. Very few of the models have been used in practice due to the fact that many of them require specific variables and parameters that are not available in handbooks.

Research in the field of wear has taken advantage of the rapid development of methods for finite element analysis of non-linear problems. The simulation of wear is non-linear due to the contact conditions between the interacting bodies. The material model used and deformation of the bodies can also introduce non-linearities. Pödra [5] simulated sliding wear under the assumption that the relative sliding between the surfaces in contact was of the rigid body type. Tool wear in deep drawing was studied by Eriksen [6] who showed that changing the geometry of the die edges could reduce the wear in these regions significantly. Simulations of mild sliding wear have been performed by Öqvist [7] where an adaptive step size between the geometry updates was used in the simulation of wear along a line contact in oscillating motion. The model produced gave both fast and accurate results. The same method has also been used in the current work.
The present work compares two different tool geometries with respect to wear and the shape of the product achieved. This work aimed to develop a fast and efficient way to calculate the wear of different tool geometry's and also to show how tool wear influences both the stress state and the geometry of the deep drawn cup. The wear model used is based on Archard's wear equation as this gives a fast and efficient way to calculate the change in shape for different geometries. Archard's equations incorporate information about the main parameters for mild wear in deep drawing such as surface pressure and sliding distance, and may therefore be used in this case. It is, however, possible to use another wear model if necessary. A finite element program was used to solve the stress state for the sheet metal part and the tool and to calculate the relative sliding distances between the nodes located on the sheet metal blank and those on the tool surface.

The major parts of a deep drawing tool are shown in Figure 1. The two tool geometries studied can be distinguished by the transition in the upper part of the die; the first having a circular profile and the second a tractrix profile. Danckert [8] studied the residual stresses in deep drawn cups produced in dies with circular and tractrix transitions. The residual stresses in the cups produced were significantly reduced when a tractrix geometry was used. Eriksen [6] showed that the total amount of wear is lower for a die with tractrix profile than for a die with circular or elliptical profile. In this work, the effect of die wear in both circular and tractrix profile dies on the produced parts has been investigated.

Figure 1. The main parts of a deep drawing tool. During the forming process the punch (1) moves down into the die (2) while the blank (3) is held by the blankholder (4).
2. Wear model

The predominant wear mechanisms in deep drawing are adhesive and abrasive, Christiansen [9]. Adhesive wear occurs when material transfers from one surface to the other via some contact mechanism such as cold welding. Abrasive wear is the result of rough tool surfaces and/or hard particles entering the contact zone and mechanically removing material. Abrasive wear has been studied by Hokkirigawa [10] whilst de Rooij [11] investigated tribological aspects of unlubricated deep drawing; focusing on adhesive wear or galling. When the contact surfaces between tool and workpiece are lubricated, problems with galling are reduced and abrasive wear becomes dominant. Forming deep drawing steels will normally cause abrasive wear of the tool with a resulting change in the dimensions and form of the tool. The wear model used in this work is based on the assumption that the wear is abrasive and follows Archard’s wear equation [3] which postulates that the wear rate, i.e. the volume worn away per unit sliding distance, is proportional to the load and the materials in contact. In order to be able to calculate the change in topography, Archard’s wear formula was rewritten to describe the wear depth at a given point rather than wear volume. In the finite element analyses, the wear law is discretised with respect to time and space Wear depths, $h$, are calculated for each point by integrating the wear equation (1) over time.

$$\frac{dh}{dt} = kp \frac{ds}{dt} + ks \frac{dp}{dt} \quad (1)$$

The dimensional wear coefficient is denoted $k$, whilst $p$ is the pressure and $s$ the sliding distance. The wear model used gives a fast and efficient way to calculate the change in shape for different geometries. It is, however, global and therefore does not incorporate any information about what is happening at a molecular scale. In Figure 2 the main steps of a wear calculation shown.
Perform finite element analysis on the geometry.

Evaluate $p(t)$ and $s(t)$ for nodes on the surfaces in contact.

Compute the total wear depth $dh$ for nodes on the surfaces in contact.

Figure 2. Schema showing wear calculations in a finite element program.

The finite element program calculates the pressures at, as well as the relative motion of, the nodes in contact with one another. The program needs slidelines to be defined to calculate the relative motion and therefore slidelines are defined between the nodes on the blank and tool surfaces that comes into contact with each other. The slideline accounts for separation and interface friction with Coulomb’s friction law. The sliding distances are then calculated from the relative motion of the nodes on the slidelines between two successive timesteps. During timestep $i$, the closest point between node $n$ on the tool surface and the blank is located at $y_i$, $z_i$. One timestep later that point will have moved to $y_{i+1}$, $z_{i+1}$. The difference between these two locations is equal to the amount of material that has passed node $n$ and is defined as the sliding distance, Figure 3.

Figure 3. Definition of sliding distance.
3. Deep drawing simulation

Research into simulation of sheet metal forming / deep drawing has been focused mainly on friction, Sniekers [12], Lubbinge [13], Ahmetoglu [2] and de Rooij [11]. The present work takes the friction between the sheet and the tool into consideration but the focus is on tool wear. The finite element analyses were based on implicit integration of the equations of motion and performed with a slightly modified version of NIKE2D [14]. The models are axisymmetric and the tool material is assumed to be elastic. For the workpiece material an elastoplastic material model with rate independent plasticity, von Mises yield criteria and isotropic power law hardening were assumed. For the elastoplastic material model, the yield stress, $\sigma_y$, and the initial yield strain, $\varepsilon_0$ can be described according to Eq. 2 and 3.

$$\sigma_y = k_s (\varepsilon_0 + \bar{\varepsilon}^P)^n$$  \hspace{1cm} (2)

$$\varepsilon_0 = \left(\frac{E}{k_s}\right)^{-\frac{1}{n-1}}$$  \hspace{1cm} (3)

The effective plastic strain of the material is denoted $\bar{\varepsilon}^P$. The strength coefficient of the material, $k_s$, is 1.5 GPa and the hardening exponent, $n$, is 0.48. The Young’s modulus, $E$, is taken as 210 GPa and Poisson’s ratio, $\nu$, as 0.3. These material parameters give the stress-strain relation for the workpiece material. An effective plastic strain of 0.25 corresponds to a stress of 770 Mpa with the power law hardening used above. The pressure on the different parts of the tool never exceeds the yield strength of the material.

Figure 4 shows a part of the finite element mesh used to describe the geometry; both the initial geometry and the final worn geometry are shown. The whole mesh is moved as the wear process progresses and the element height is constant throughout the wear simulation. It should be noted that the die is completely remeshed between the wear simulations and therefore the wear is not limited by geometry. If, however, the wear of the die in a single wear step is too large there can be problems in achieving convergence in the next simulation.

A prescribed motion of the uppermost nodes of the punch defines the deep drawing process. A Coulomb friction model with a constant coefficient of friction of 0.15 was used between the slidelines. The main reason for using finite element analyses for wear calculations was to compute the contact stresses and the sliding distances in the contact zone. The sliding distance was calculated
within the finite element program and took account of both kinematic motion and deformation of the bodies in contact. The total change in location for each node on the slideline was then calculated as the sum of the wear depths while the wear depth in each step was calculated according to the pressure distribution and sliding distance calculated in the preceding step. The wear depth for each step was then scaled by the number of punch strokes being simulated in order to obtain the total wear depth for the step. Any nodes that not were located on the slideline were then moved in accordance with the nodes on the slideline in order to maintain the same element size in the mesh irrespective of the amount of wear.

![Figure 4](image-url)

*Figure 4. Part of the finite element mesh of the circular transitions of the upper part of the die. Both original and worn geometries are shown.*

### 4. Tool geometry

The wear behaviour of two different die geometries has been simulated. The two geometries can be distinguished by the transition in the upper part of the die; the first die having a circular transition and the second one a so-called tractrix transition. The definition of a tractrix curve is as follows. A tangent to a tractrix curve has a fixed length, a, and one end shall follow the tractrix curve while the other shall follow a vertical axis. Pythagora's theorem and the use of uniform triangles gives the differential equation that describes the tractrix curve as:

$$\frac{dy}{dx} = \frac{\sqrt{a^2 - x^2}}{x} \quad (4)$$

In equation 4, the horizontal axis is denoted x and the vertical axis y. The curvature of the tractrix curve is extrapolated as a straight line when the angle
with the vertical axis reaches 3 degrees. The reason for studying dies with circular transitions is that this geometry is the most commonly used one, however, the tractrix transition is sometimes used as it has been shown to demonstrate good properties as far as wear is concerned. Eriksen [6] found that the use of tractrix curvature transitions resulted in deep drawing tools with lower average and maximum wear compared to circular and elliptical transitions.

The finite element meshes for the two geometries are shown in Figure 5. The models are axisymmetric and consist of the same number of nodes and elements. It is noticeable in Figure 5 that the die with the tractrix transition requires a longer punch stroke. The simulation was limited to calculate only die wear in order to speed up the calculations. In practice the blankholder also wears, but the blankholder force can be held constant and therefore it does not influence the wear of the die and the stress state in the cup to any great extent. It is, however, possible to calculate the wear of the blankholder if necessary.

Figure 5. Finite element model of a) circular and b) tractrix transitions at the die edge.
5. Results from the numerical simulations

There are a number of different ways to look at the effects of tool wear; concentrating on the tool or the deep drawn part or both. The focus of the present work has been on changes in the shape of the tool as well as the shape of and the stress state in the deep drawn part. Any tool wear that occurs will result in parts which do not have the required dimensions and/or shape. Worn tools must be exchanged or reground which increase the manufacturing costs for the parts. There are no overall criteria describing what is or isn’t acceptable cups since this depends on the application. The parameters that can be use for classification are the stresses and strains in the cups as well as the shape of the cup.

5.1 Tool wear

The wear of the two different die profiles used is shown in Figure 6. The calculated tool wear corresponds to the simulation of the same number of parts produced in the two dies. The actual numbers of cups that correspond to the calculated tool wear have not been investigated since it depends on the wear resistance of the tool material as well as the material combination, tool/blank. It is clearly seen that the wear of the die with circular transition is concentrated to the area around the transition of the profile from vertical to circular. The tractrix transition has got less wear depth but on the other hand the wear is distributed over a larger area. It can be seen that the wear occurs at two different parts of the die, and that most of the wear occurs along the tractrix curvature but a small amount can also be seen in the transition of the profile from tractrix to horizontal.

The worn circular die form becomes similar to the tractrix die. The tractrix die, on the other hand, more or less maintains its initial geometry. The total wear, i.e. the wear depth integrated over area, is lower in the tractrix die than in the circular die.
5.2 The shape of the produced cups

It is not only the amount of wear but also the effect of worn dies on the geometry of cups that are produced that is important. The cup geometry calculated for the different dies have been investigated with respect to the shape of the profile, the height and the outer diameter at the rim. Figure 7 shows the simulated profile of the cups from with new dies compared with the cups produced with the simulated worn dies. The change in height and diameter of the cups between new and worn dies are nearly the same for the two cases. The simulated height of the cups produced in the new tractrix die is 223 mm while the new circular die will give cups that are slightly higher; 240 mm. The new die gives cups that are approximately 6% higher than the cups produced in the worn dies. The difference in height between the cups produced in a new die with tractrix transition and a worn die with circular transition is only 3 mm. The outer diameter at the rim of the cup was found to vary from 16.0 mm for the new to 15.8 mm for the worn circular die, compared to 16.9 mm for the new and 16.8 mm for the worn tractrix die. As the tractrix die wears, the rim of the cups gets wider and the height decrease. Wear of the circular die causes the cups to get wider and decrease in height, but the profile of the cups is also changed; the curvature at the top of the cup changes considerably as can be seen in Figure 7. Cups produced in the circular transition die tend towards being more like the cups produced in the die with tractrix transition as the wear evolves.
5.3 Effective stress in the produced cups

Figures 8 and 9 show the calculated effective stresses in the cups for the four different cases, new and worn, circular or tractrix die. Evaluation of the stress state in the cups has focused on the location and maximum value of the effective stress. The maximum effective stress is higher for the new dies than for the worn ones. The new circular die gives an effective stress of 1120 MPa compared to 771 MPa for the worn one, whilst the new tractrix die gives an effective stress of 620 MPa compared to 566 MPa. This implies that the effective stresses in the cup decreases as the dies wear. This is because the areas, which are subjected to the highest loads, wear quickest. Both the stresses and the strains are lower for the worn dies because of this. The effective stress decreases by 31% for the circular die compare with 9% for the tractrix die. The new and the worn tractrix die as well as the worn circular die have a maximum effective stress located in the same area, the transition from horizontal to vertical, as can be seen in Figure 8 and 9. For the new circular die the maximum in effective stress is located relatively high, approximately 60 mm from the top of the cup.
Figure 8. The calculated effective stress in the cup after forming in a) a new and b) a worn die with circular transition.
Figure 9. The calculated effective stress in the cup after forming in  a) a new and b) a worn die with tractrix transition.
6. Conclusions

A global wear model, based on Archard's wear equation, has been developed and wear simulations of deep drawing tools performed. A finite element program that accounted for non linearity's such as large deformations and contact phenomena together with an adaptive step size between the geometry updates were used for the simulations. This technique gives a simple model, which speeds up the calculations considerably whilst still taking the most important parameters into consideration. The wear model take sliding distance as well as surface pressure into consideration along with accurate material models.

It is clearly shown in this work that the amount of wear is less for a deep drawing tool with a tractrix transition compared with dies with circular transition. The maximum effective stress as well as the strain is lower for the cups produced in the tractrix die. The effective stress and the strain were lower for the worn dies than for the new ones in both cases, however, the difference is less for the tractrix die. The effective stresses and strains calculated for the cups produced in both the new and the worn tractrix dies are lower than in the cups produced in the circular die. High stresses and strains in the cup may cause tearing of the material and are therefore to be avoided. The worn die with the circular transition has a shape more like the tractrix profile after wear whilst the tractrix die retains its initial shape despite the wear. The calculated shape of the cups produced in the tractrix die alters less as the wear of the die evolves than the cups produced in the circular die. The difference in cup height between cups produced in new and worn dies is approximately 6%.

It can be concluded that the tractrix transition gives a die with less total wear than a tool with a circular transition. Changes in the shape of the cups produced in the tractrix die are less, and the effective stress are also lower, than in the cups produced in the circular die.

The use of a tractrix profiles in deep drawing dies is well worth investigating further as these demonstrate good properties as far as the wear rate of the tool and the magnitude of changes in shape of the cups produced are concerned. The effective stresses are also lower in the cups produced using this die geometry than in the cup that is manufactured using die with a circular transition.
7. References


Numerical Simulations of Wear

The objective of this licentiate thesis was to study the effect of tool wear for sheet metal forming tools and how the wear process can be simulated in an efficient manner.

Three Papers are appended to this licentiate thesis. Paper A covers the influence of tool geometry in deep drawing. In paper B is the way of calculating with finite element analysis described. The wear of a steel cylinder oscillating against a steel plate was studied experimentally. The worn shape of the cylinder was then compared with a numerical simulation of the shape. Paper C shows how numerical simulations can be used to simulate wear of deep drawing tools. The wear of two different deep drawing tools has been investigated. The shape of the tools before and after wear have been compared as well as the stresses and strains in the formed cups.

Uppdragsgivare
The work has been carried out at the Division of Machine Elements, Department of Mechanical Engineering at Luleå University of Technology, Sweden.

Granskare/Handledare
Elisabet Kassfeldt/Erik Höglund

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