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CONTACT PRESSURE AND WEAR IN SHEET METAL FORMING – AN FEM ANALYSIS

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ABSTRACT

Wear is the principal cause of tool failure in most sheet metal forming processes. It is well known that the contact pressure between the blank and the tool has a large influence on the wear of the tool, and hence the tool life. This investigation utilises the finite element method to analyse the contact pressure distribution over the die radius for a particular deep drawing process. Furthermore, the evolution of the predicted contact pressure distribution throughout the entire stroke of the punch is also examined. It was found that the majority of the process shows a steady state pressure distribution, with two characteristic peaks over the die radius, at the beginning and end of the sheet contact area. Interestingly, the initial transient contact pressure response showed extremely high localised peak pressures; more than twice that of the steady state peaks. Results are compared to wear reported in the literature, during similar experimental deep drawing processes. Finally, the significance and effect of the results on wear and wear-testing techniques are discussed.

1 INTRODUCTION

In recent years, an increased demand has been placed on automotive sheet metal forming tools. This is due to the implementation of higher strength steels to meet crash requirements; the reduced use of lubricants owing to environmental concerns; and the requirement of increased tool life resulting from the development of common vehicle platforms. Consequently, forming tools are now required to withstand higher forming forces and more severe tribological stresses, for longer periods of time, leading to the increased likelihood of unacceptable levels of wear. Wear problems not only result in high costs due to unscheduled stoppages and maintenance, but can also lead to poor part quality in terms of surface finish, geometric accuracy and possible part failure. For these reasons, an accurate prediction of tool life for a given stamping process is an ever increasing requirement.

Unfortunately, wear is a complex systems response, and not simply an individual material property or unique physical mechanism. There are hundreds of equations in the literature to describe many types of wear. Hence, it can be very difficult for a designer to successfully identify and utilise any of these equations to confidently predict tool life for a given stamping process. Furthermore, most of the available models are empirical or semi-empirical in nature. This means that they are system specific; only accurate for a particular materials pair, contact geometry, operating condition range, and the particular environment and lubricant.

At the design stage, an ideal wear model should aid in the development and assessment of an optimum design for a given process. Therefore, typical correlational-based equations, which may be reasonably accurate for only a small operating window, can provide a useful design tool, with the aid of suitable numerical analysis and minimal experimental testing.

Some of the empirical-based relationships in the literature include equations presented by Rhee, Bayer, and Archard, which are often used to correlate data from wear experiments. These equations, which typically describe surface wear mechanisms in sliding contact (both abrasive and adhesive), commonly express wear rate as a function of the normal load , the sliding distance (or sliding velocity), and the wear coefficient . Although the wear coefficient is a function of the materials and environment, it has been shown that it is practically constant for a given system. Considering this, the following is a typical form of an equation to describe wear rate :

\[ W = K.L^n.S^m \]  (1)

where and are empirical constants, fitted by the use of experimental data obtained in simulative laboratory testing.

Considering the above discussion and relationship, it is perceivable that the accurate determination of the normal load (contact pressure) distribution for a given process is a vital step towards the application and/or development of a suitable wear model. For a deep drawing process, the die radius region of the tool is subjected to the most severe tribological stresses, indicated by high wear levels typically seen in this vicinity. This is due to the large amount of sliding and high pressures experienced in this region.

This paper investigates the contact pressure distribution over the die radius for a particular deep drawing process. A two-dimensional finite element model of a semi-industrial channel forming test was developed. The model definition includes an elastic-plastic blank and elastic tools, both of which have a finely discretised mesh at the contacting surfaces. The steady state distribution and the transient evolution of the contact pressure was analysed, and compared to experimental
wear observations reported in the literature. The significance and effect of the results on wear and wear-testing techniques are discussed.

2 EXPERIMENTAL SETUP

Semi-industrial wear tests were conducted to characterise the wear performance of numerous combinations of tool, tool coating and sheet material. The reader is directed to the stated references for a detailed description of these tests and the associated results.

Figure 1 shows a schematic of the experimental setup, with a summary of key parameters listed in Table 1. As illustrated, the tooling includes cylindrical draw radii inserts, which can be removed for examination or replacement, as necessary. The blank material for this investigation is an uncoated Dual Phase 600 grade steel (DP600). The as-delivered mill oil was the only lubrication used.

![Figure 1: Schematic of the semi-industrial channel forming test](image)

**Table 1: Summary of process parameters for channel forming test**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Die to punch clearance</td>
<td>c</td>
</tr>
<tr>
<td>Die radius</td>
<td>rd</td>
</tr>
<tr>
<td>Punch radius</td>
<td>rp</td>
</tr>
<tr>
<td>Punch width</td>
<td>a</td>
</tr>
<tr>
<td>Blank thickness</td>
<td>t</td>
</tr>
<tr>
<td>Blank length</td>
<td>l</td>
</tr>
<tr>
<td>Blank width</td>
<td>w</td>
</tr>
<tr>
<td>Initial blank holder pressure</td>
<td>P</td>
</tr>
<tr>
<td>Draw depth</td>
<td>d</td>
</tr>
<tr>
<td>Press rate</td>
<td></td>
</tr>
</tbody>
</table>

During the test, the surface quality of each of the stamped channels was continually examined until a predefined grade of scratches was observed. At this point, the test was stopped, and the relative wear performance of the particular tool and sheet pair was determined by the total number parts formed before the part surface quality degraded to an unacceptable level.

3 NUMERICAL SETUP

The experimental channel forming process, detailed above, was replicated in the numerical simulation, using a non-linear implicit finite element code (ABAQUS/Standard version 6.5-1). The problem was simplified to a one half symmetric, two-dimensional plane strain finite element model, with appropriate boundary conditions applied (see Figure 2). Due to the simulation of contact and significant bending in the blank, all parts were meshed using CPE4R elements (4-node bilinear plane strain quadrilateral, reduced integration, with enhanced hourglass control). The mesh was refined in the regions near the interface between the blank and the die radius, as indicated in Figure 2.

![Figure 2: 2D finite element model (right), showing local mesh refinement at the blank-die radius interface (left).](image)

Preliminary analysis indicated that the predicted contact pressure distribution was particularly sensitive to the level of mesh refinement, and to the ratio of the blank-to-die element length, at the interacting surfaces. Based on numerous simulations, the mesh shown in Figure 2 was developed, ensuring that the final simulation produced a suitably converged contact pressure distribution, without using excessively large computational resources. Details of the finite element mesh used are shown in Table 2.

**Table 2: Details of the finite element mesh**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of blank elements</td>
<td>8400</td>
</tr>
<tr>
<td>No. of die elements</td>
<td>3117</td>
</tr>
<tr>
<td>Total no. of elements</td>
<td>12475</td>
</tr>
<tr>
<td>Min. blank element length</td>
<td>0.0625 mm</td>
</tr>
<tr>
<td>Min. die element length</td>
<td>0.0327 mm</td>
</tr>
<tr>
<td>Blank-to-die elem. length @ interface</td>
<td>approx 2:1</td>
</tr>
</tbody>
</table>

The DP600 blank was modelled using an elastic-plastic isotropic material definition, in which the plastic response was defined using measured tensile test data. This was input in the form of a tabulated flow stress curve. The tools' material was defined as elastic isotropic, using the standard 205 GPa modulus of steel.
The material properties of the blank and tools are summarised in Table 3.

Table 3: Material properties of blank and tools (die, punch, blank holder)

<table>
<thead>
<tr>
<th>Material definition</th>
<th>Blank</th>
<th>Tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus</td>
<td>205 GPa</td>
<td>205 GPa</td>
</tr>
<tr>
<td>Yield strength</td>
<td>430 MPa</td>
<td>-</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>650 MPa</td>
<td>-</td>
</tr>
<tr>
<td>Strain hardening index, n</td>
<td>0.14</td>
<td>-</td>
</tr>
</tbody>
</table>

The interaction between the blank and the tools was defined using the default ‘master-slave’ algorithm, with a ‘hard contact’ pressure overclosure relationship. Since the tools are significantly stiffer than the blank, the tools were set as the master surfaces in each of the contact interactions. Friction was modelled using a penalty friction formulation. The coefficient of friction was used to correlate the flange length and punch force between the simulation predictions and experimental results. Good correlation was achieved with a friction coefficient of 0.15.

4 RESULTS AND DISCUSSION

Figure 3 shows the predicted contact pressure distribution over the die radius region, at the end of the simulation (i.e. when the punch is at full stroke). It is evident that there is a peak in contact pressure near the beginning point and near the end point of contact between the sheet and the die. These two distinct peaks are expected, and compare well with measured and predicted distributions of similar deep drawing processes presented in the literature\(^9\),\(^{10}\),\(^{11}\),\(^{12}\).

The contact pressure distribution in Figure 3 shows that the peak pressure of 482 MPa occurs in a comparatively localised region, approximately 0.3 mm from the beginning of the die radius. Furthermore, the contact pressure is zero beyond a distance of 4 mm along the die radius. Hence, at the end of the simulation, contact between the blank and the die radius only occurs over approximately half of the radius. It should be noted that the distribution shown only represents the contact pressure distribution at the end of the channel forming process, and does not represent the response over the entire simulation. However, it is expected that this distribution would be effectively constant for the majority of the forming process (as will be shown in Figure 4). For this reason, the contact pressure distribution shown in Figure 3 can be referred to as the steady state response.

From the initial discussion, it was stated that wear, for a given process, is a function of the relative sliding distance between the two bodies and the contact pressure at the interface. Therefore, when considering the wear response as a result of the steady state pressure distribution shown, it is evident that each point along the die radius will experience practically the same sliding distance. Hence, measurement or inspection of wear over the die radius in an experimental situation should show a similar trend to the contact pressure shown in Figure 3. Horig et al.\(^9\) and Jensen et al.\(^{11}\) have both reported that localised wear is observed in regions over the die radii that are comparable to the locations of peak pressure predicted in this analysis. Additionally, Eriksen\(^9\) published a graph of experimental wear depth over the die radius for St1403 steel drawn over a 5 mm cast iron die radius. The shape of the measured wear distribution is in good agreement with the steady state contact pressure distribution presented in Figure 3. Accordingly, these results highlight that contact pressure has a significant affect on the rate of sliding wear.

However, when attempting to qualitatively compare the wear results from the aforementioned references, it should be noted that each of these tests examined used bending-under-tension or strip-drawing type tests to represent the deep drawing process. These tests can reproduce the steady state contact conditions of a channel forming test quite well. However, the channel forming process (as with any industrial stamping process) does not produce steady state contact conditions for the entire process. This fact is highlighted in Figure 4, which shows the evolution of the predicted contact pressure distribution at approximately 20 intervals over the entire punch stroke.
Inspection of the contact pressure evolution (Figure 4) reveals that a steady state contact pressure response is developed at approximately one quarter of the complete punch stroke, and continues until the end of the simulation. However, it is evident that large spikes in contact pressure exist in the transient region prior to the steady state response. Figure 5, which plots the evolution of the predicted contact pressure distribution at approximately 30 intervals over the first 12.5 mm of punch stroke, illustrates this transient response in further detail. Due to the larger number of peaks in the graph, it seems as though the transient response shown in Figure 5 is different to the distribution shown in Figure 4, during the first 12.5 mm of punch travel. This difference arises from the fact that, in Figure 5, the contact pressure distribution over the die radius is plotted at 30 intervals over one quarter of the punch stroke. Whereas, for clarity, Figure 4 is plotted using only 20 intervals over the entire punch stroke.

Figure 5: Contact pressure evolution over first 12.5 mm of punch stroke

Figure 5 shows that localised severe contact conditions exist at the beginning of the deep drawing operation. At the point where the punch has moved approximately 9 mm, a peak contact pressure of 1190 MPa is produced at a distance of 5.1 mm along the die radius. This peak is approximately 2.5 times the peak observed in the steady state distribution. Furthermore, it is evident that pressures greater than 800 MPa occur over most of the die radius, and are not simply confined to a localised region.

The reason for the peak contact pressure can be understood by examining how the blank deforms over the die. Figure 6 shows the progression of the Von Mises stress in the blank and die throughout the process. Of particular importance is the localised peak stresses experienced in die, near the surface of the radius. These regions correspond to the location of the peak contact pressure. Figure 6a shows an initial single peak in contact pressure, as the punch begins its stroke. As the blank begins to contact a larger area of the die radius, a second peak is developed (Figure 6b). As the punch travels further, the second pressure peak moves further along the die radius and the blank no longer contacts the die (zero contact pressure) at a zone between the two pressure peaks (Figure 6c). At the same time the contact zone near the beginning of the radius increases. Finally, as the blank is stretched further upwards by the punch, the first contact zone continues to increase in area, whilst the pressure peak at the second contact zone reduces as it merges with the final single contact zone.

Figure 6: Von Mises stress distribution in the blank and die during the process, at punch stroke (a) 0.5mm, (b) 4mm, (c) 10mm, and (d) 50mm

It should be highlighted that, at any given time during the process, the transient peak pressures occur in a highly localised region. Therefore, each element along the radius experiences this extreme contact condition for only a short period of time. Accordingly, the corresponding sliding distance at these high pressure levels would be very small. Considering this in view of the empirical relationship for wear rate presented earlier (Eq. 1); it is evident that the values obtained for exponents and for the given system, will provide an indication as to whether the transient response (high load, short distance) or steady state response (moderate load, long distance) will have a significant affect on the wear behaviour.

Considering the mechanisms of both abrasive and adhesive wear, it is likely that the localised contact pressure spikes due to the transient response may be of significance to the wear response in a channel forming process. If such transient behaviour is dominant in the wear process, it suggests that the contact conditions represented by strip-drawing and bending-under-tension tests will not be entirely applicable to the wear of channel forming dies.

Further investigation into the reliability of the predicted transient response needs to be undertaken. Future work will include an explicit dynamic analysis of the channel forming process, to assess whether the simulation of the true forming process speed affects both the steady state and transient contact pressure distributions. An explicit simulation will also allow an accurate prediction of the relative speed between the blank and the die radius, which may be useful for future wear analyses.
A detailed analysis of the results from channel forming wear tests is also required. Such research should include inspection of the wear on the die radius at numerous intervals during the test, and precise measurement of the wear depth profile along the radius, rather than simple visual inspection. These results will aid in the validation of the finite element model predictions, and thus advance the aim towards the application and/or development of a suitable wear model for industrial deep drawing processes.

5 CONCLUSION

The steady state distribution and transient evolution of the contact pressure for a channel forming process was analysed using a finite element model. It was found that the majority of the process shows a steady state pressure distribution, with two characteristic peaks over the die radius, at the beginning and end of the sheet contact area. Interestingly, the initial transient contact pressure response showed extremely high localised peak pressures; more than twice that of the steady state peaks. It was speculated that if such transient behaviour is dominant in the wear process, the contact conditions represented by strip-drawing and bending-under-tension tests will not be entirely applicable to the wear of channel forming dies.

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References