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Contact pressure evolution at the die radius in sheet metal stamping

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ABSTRACT

The contact conditions at the die radius are of primary importance to the wear response for many sheet metal forming processes. In particular, a detailed understanding of the contact pressure at the wearing interface is essential for the application of representative wear tests, the use of wear resistant materials and coatings, the development of suitable wear models, and for the ultimate goal of predicting tool life. However, there is a lack of information concerning the time-dependant nature of the contact pressure response in sheet metal stamping. This work provides a qualitative description of the evolution and distribution of contact pressure at the die radius for a typical channel forming process. Through an analysis of the deformation conditions, contact phenomena and underlying mechanics, it was identified that three distinct phases exist. Significantly, the initial and intermediate stages resulted in severe and localised contact conditions, with contact pressures significantly greater than the blank material yield strength. The final phase corresponds to a larger contact area, with steady and smaller contact pressures. The proposed contact pressure behaviour was compared to other results available in the literature and also discussed with respect to tool wear.

1. Introduction

In recent years, there has been an increase in wear-related problems associated with the die radius of automotive sheet metal forming tools (Sandberg et al., 2004). These problems have mainly been a consequence of the implementation of higher strength steels to meet crash requirements, and the reduced use of lubricants owing to environmental concerns. As a result, forming tools, and the die radii in particular, are required to withstand higher forming forces and more severe tribological stresses. This can result in high costs due to unscheduled stoppages and maintenance, and lead to poor part quality in terms of surface finish, geometric accuracy and possible part failure.

If the side-wall of a part is examined after forming, a demarcation known as the 'die impact line' is easily visible (Karima, 1994). This line separates the burnished material that has travelled over the die radius and the free surface that has not contacted the tooling, clearly indicating that severe surface effects exist at the die radius. It is therefore important to understand the contact phenomena at this location of the tooling.

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1.1. Bending-under-tension test

The bending-under-tension test – in which a strip is bent over a cylindrical tool surface and pulled against a specified back tension – has been used in the laboratory for many years to simulate conditions at the die radius (Ranta-Eskola et al., 1982). The literature contains numerous experimental investigations that examine surface degradation over the die radius after repeated or continuous bending-under-tension operations. For example, in independent studies with differing test conditions and materials, Mortensen et al. (1994), Hortig and Schmoeckel (2001) and Attaf et al. (2002), each visually observed wear in two localised regions on the die radius. More detailed examination of the worn die radius surface, through measurement of surface roughness (Christiansen and De Chiffre, 1997), determination of wear depth (Eriksen, 1997) and scanning electron microscope imaging (Boher et al., 2005), has also confirmed the existence of similar localised wear regions.

In addition to the experimental analyses, Mortensen et al. (1994), Hortig and Schmoeckel (2001) and Attaf et al. (2002), each conducted finite element analyses of the bending-under-tension process. In all cases, the finite element models predicted the existence of distinct contact pressure peaks on the die radius surface, correlating well with the regions of localised wear. Using *in situ* sensors Hanaki and Kato (1984) and more recently Coubrough et al. (2002) experimentally demonstrated that similar contact pressure peaks exist at locations on the die radius near the entry and exit of the strip during the bending-under-tension test.

It is evident that despite covering a wide range of die materials (both coated and un-coated), lubrication, surface roughness, bend ratio and work-piece materials, each of the studies discussed in the preceding paragraphs were found to exhibit similar characteristic two-peak contact pressure distributions and localised regions of wear over the die radius. These results, and the documented power law relation between wear and normal load for sliding contacts (Rhee, 1970), indicate that contact pressure is of primary significance to the wear response.

1.2. Sheet metal stamping

The contact conditions occurring during sheet metal stamping operations have not been studied as extensively as those of the bending-under-tension process. Through finite element analyses of axisymmetric cup-drawing processes, Mortensen et al. (1994) and Jensen et al. (1998) identified that time-dependant contact conditions occur at the die radius, as opposed to the 'stationary' conditions of the bending-under-tension test (Hortig and Schmoeckel, 2001). In recent numerical studies on a plane strain channel forming process, Pereira et al. (2007, 2008) also reported time-dependant behaviour. Complex contact conditions over the die radius were found to occur, with regions of highly localised and severe contact pressure. Selected results of the finite element analysis by Pereira et al. (2008) are given in Fig. 1, where the dynamic nature of the contact pressure distribution can be seen. Additionally, the Mises stress contours show the corresponding deformation of the blank and provide an indication of where yielding occurs.

Although each of the above investigations report time-dependant contact conditions for sheet metal stamping processes, the authors in each case provide little explanation into the reasons for the identified contact behaviour. Further analysis of this phenomenon has not been found in the literature.

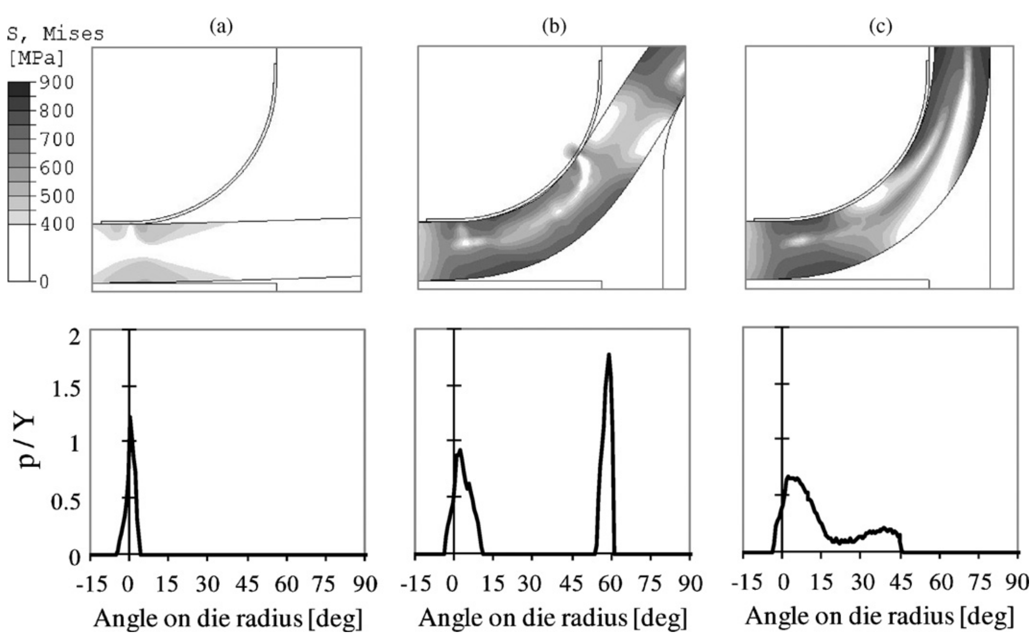

Fig. 1 – Mises stress contours and normalised contact pressure distributions predicted by finite element analysis at the three distinct stages during a channel forming process (see Section 4.1 for more details). The regions in white in the Mises contours indicate values of stress below the blank material initial yield strength.

1.3. Motivation

In order to understand tool wear in sheet metal stamping, or to use representative tests (bending-under-tension, slider-on-sheet, etc.) to characterise the wear response of tool materials and coatings, knowledge of the local contact conditions that occur during the stamping operation is essential. As discussed, the contact pressure is of particular significance. However, a description of the evolution and distribution of contact stresses experienced by sheet metal forming tooling, including an explanation for this behaviour, has not been found in the literature.

In this work, a qualitative description of the contact pressure evolution at the die radius and the associated stress distributions in the blank during a channel forming process is given. The description is based on experimental observations and the results of finite element analyses. Through an analysis of the deformation conditions, contact phenomena and underlying mechanics, it will be shown that three distinct phases exist. Due to the unique deformation and contact conditions that are found to occur, the initial and intermediate stages exhibit localised regions of severe contact pressure, with peak contact stresses that are significantly greater than the blank material yield strength. The final stage, which can be considered as steady state with regards to the conditions at the die radius, corresponds to a larger contact area with stable and smaller contact pressures.

It is noted that the magnitude of the contact stress peaks will depend on variables such as back tension on the sheet, the die radius to sheet thickness ratio, and the clearance between the punch and die. These effects are not investigated in this work. The objective of this work is to provide an understanding of an important aspect of sheet metal forming, rather than a quantitative analysis of a specific case. This should assist in understanding die wear, which is an increasing problem with the implementation of higher strength sheet in stamped automotive components.

2. The sheet metal stamping process

The stamping or draw die process is shown schematically in Fig. 2. Sheet metal is clamped between the die and blankholder and stretched over the punch. The sheet slides over the die radius surface with high velocity in the presence of contact pressure and friction, as it undergoes complex bending, thinning and straightening deformation (Fig. 2c). In the most rudimentary analysis of sheet metal forming, bending is neglected and the deformation is studied under the action of principal tensions (Marciniak et al., 2002). The tension is the force per unit width transmitted in the sheet and is a product of stress and thickness. For two-dimensional plane strain deformation around the die radius, the well-known analysis indicates that the contact pressure p is

$$p = \frac{T}{R} = \frac{\sigma_1}{R/t} \tag{1}$$

where σ_1 is the longitudinal principal stress, T is the longitudinal tension, R is the die radius, t is the sheet thickness, and R/t the bend ratio. Due to the effect of friction, the longitudinal tension in the sheet varies along the die radius. If the tension at one point, j, on the die radius is known, then the tension at some other point, k, further along the radius can be found according to:

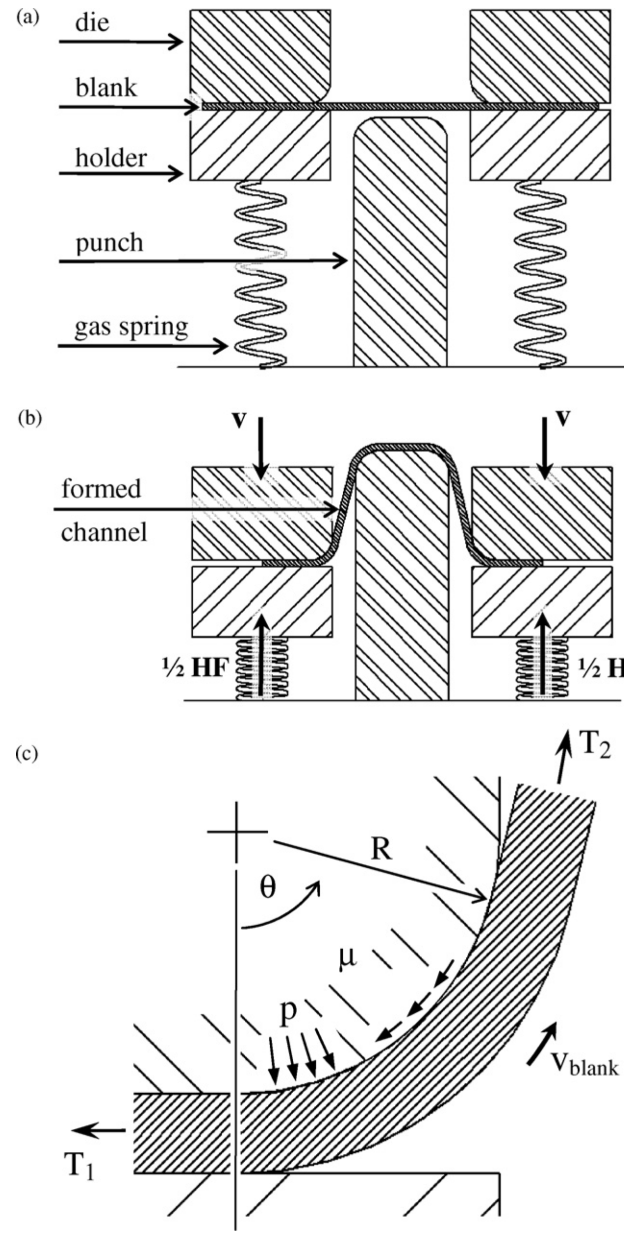

Fig. 2 – (a) The beginning of a typical sheet metal stamping process. (b) The motion and forces exerted by the tools cause the blank to be formed into a channel shape during the stamping process. (c) Forces acting on the sheet at the die radius region.

$$T_k = T_j \exp(\mu\theta_{jk}) \tag{2}$$

where θ_{jk} is the angle turned through between the two points, and μ is the coefficient of friction between the tool and sheet surfaces.

Eq. (1) provides a useful relationship that shows the contact pressure is inversely proportional to the bend ratio. Given that the tension is usually close to the yield tension and that the bend ratio in typical tooling is often less than 10, Eq. (1) indicates that the contact stress is an appreciable fraction of the yield stress. This implies that the assumption of plane stress in the strip may not be valid. Additionally, a numerical study of a bending-under-tension process with a bend ratio of 3.3 revealed that the restraint forces attributed to bending (and unbending) were almost 50% of the total restraint forces on the sheet (Groche and Nitzsche, 2006). Although Eqs. (1) and (2) can be modified to include the work done in bending and straightening, these simple models are unlikely to adequately describe the contact pressure distribution.

Furthermore, such an analysis assumes that the sheet slides continuously over the die radius under steady-state-type conditions analogous to a bending-under-tension process. However, as discussed in Section 1, several studies in the literature have shown that the contact conditions are not steady during typical sheet metal stamping. For these reasons, it is evident that a more detailed analysis, including examination of the stress states and yielding in the sheet, is required in order to understand the complex and time-dependant contact conditions at the die radius.

3. Contact pressure at the die radius

In this work, a qualitative description of the development of peak contact pressures at the die radius for the channel forming process shown in Fig. 2 is given. For simplicity, the deformation of the sheet is considered as a two-dimensional, plane strain process. A linear-elastic, perfectly plastic sheet material model, obeying a Tresca yield criterion is used. The material curve is shown in Fig. 3, where the flow stress is S, with zero Bauschinger effect on reverse loading. It is assumed that if there is a draw-bead, it is at some distance from the die radius so that the sheet entering the die radius is undeformed but has some tension applied.

In this study, the deformation and contact conditions at the die radius for a typical sheet metal forming process are divided into three distinct phases (Fig. 4). A material element on the blank, Point A, is initially located at the beginning of the die radius, as shown in Fig. 4a. At this instant, contact is limited to a line across the die radius. During the next stage, Point A has travelled around the die radius, but has not yet reached the exit or tangent point (Fig. 4b). At this instant, the material in the side-wall (between the die radius and punch radius) remains straight and has not previously contacted the tools. A state of approximately steady conditions at the die radius is reached in Fig. 4c, where Point A is now in the side-wall region.

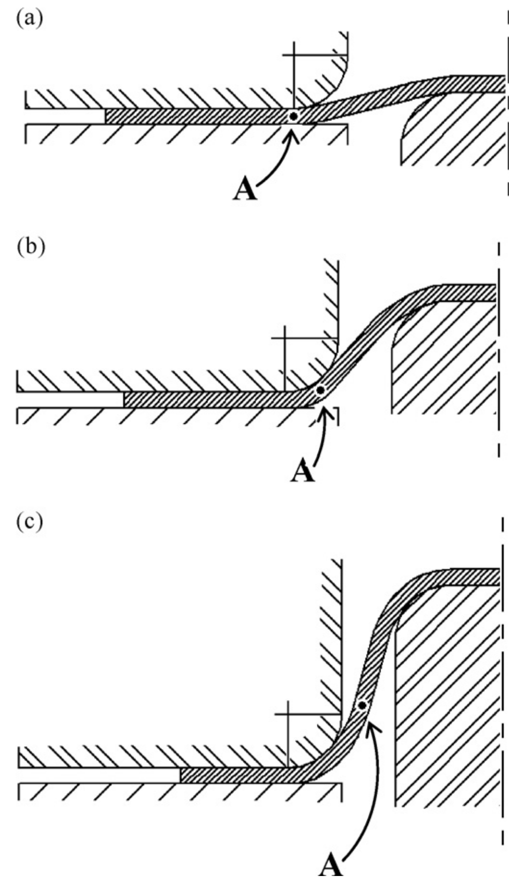

Fig. 4 – Three distinct phases of deformation and contact, which occur during the channel forming process: (a) initial deformation, (b) intermediate conditions, and (c) steady-state conditions at die radius.

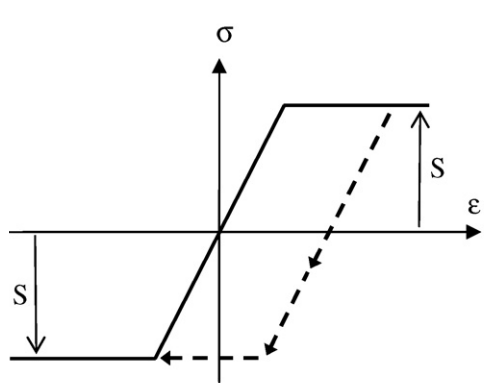

Fig. 3 – Simplified plane strain material response with reverse loading.

3.1. *Initial deformation*

At the start of the forming stroke, contact between the blank and die occurs near the start of the die radius at an angle of $\theta = \alpha$, as shown in Fig. 5a. The Mohr circle of stress at the contacting inner surface and the stress distribution through the thickness of the sheet are given schematically in this diagram. The regions of plastic deformation in the sheet are indicated by shading.

The sheet is bent by the transverse force F shown, so that a compressive bending stress σ_1 exists on the upper surface. Due to the initial lack of conformance of the blank to the radius, contact occurs almost along a line, resulting in a contact pressure P_α that can be very high. As a result, the normal stress σ_3, which is equal to $-P_\alpha$, is greatest at the surface and diminishes to zero at the outer, free surface. At this location, approx-

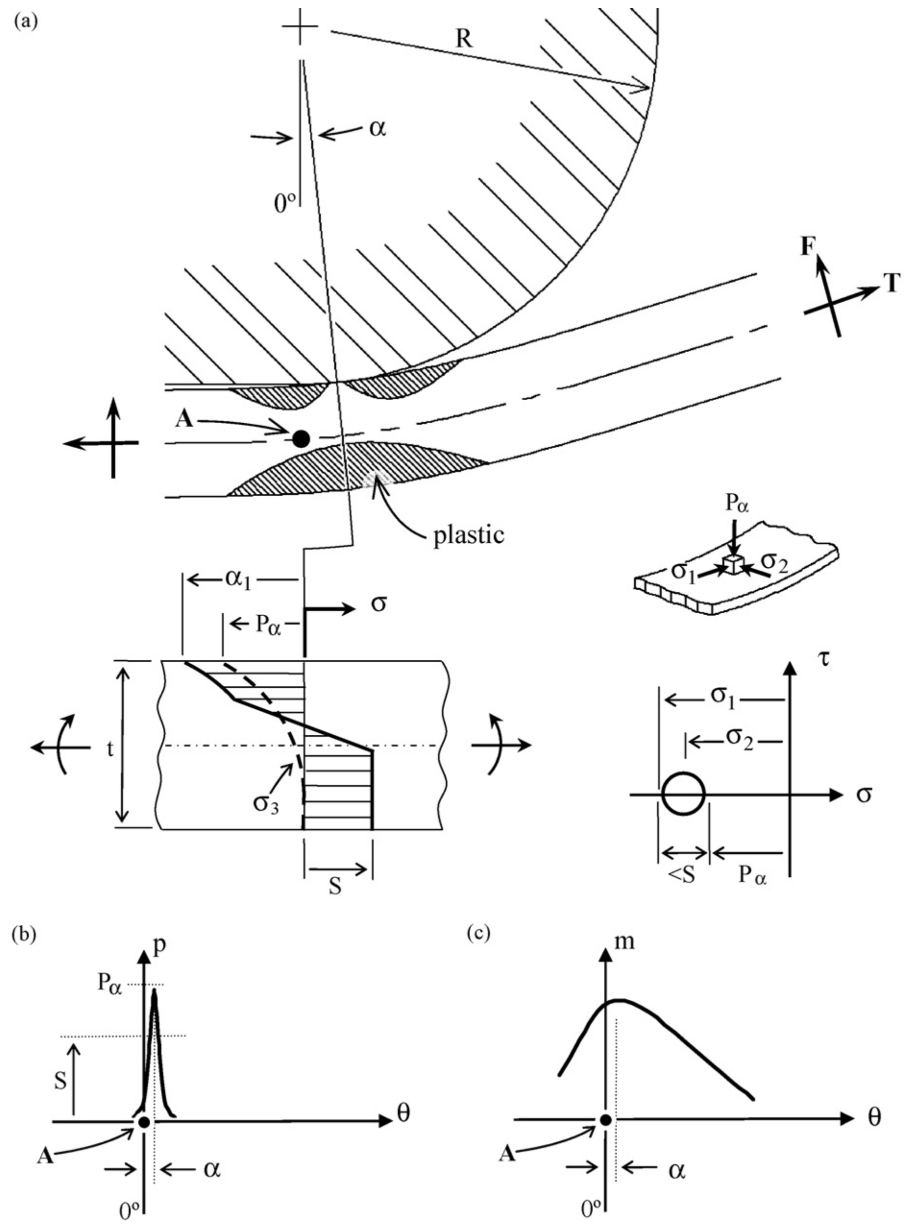

Fig. 5 – (a) Schematic of the blank to die radius interface during the initial deformation stage—the stress distribution through the thickness and the Mohr's circle at the surface of the contact zone are shown. Corresponding distributions around the die radius of (b) contact pressure and (c) bending moment in the sheet.

imately plane stress conditions exist and the sheet yields under tension at the plane strain yield stress S. The transverse stress σ_2 at the inner surface will have an intermediate value, since the process is plane strain. In the plastic case, this is the mean of the other principal stresses. In the elastic case, this is only approximately so.

The bending stress and contact pressure at the inner surface generate a high compressive hydrostatic stress, such that yielding can be suppressed (the diameter of the Mohr circle is <S). This phenomenon is supported by the finite element simulation results of the case study shown in Fig. 1a. The bending moment *m* is greatest at the contact line, as shown in Fig. 5c; yet plastic bending only takes place either side of this region, where the inhibiting compressive hydrostatic stress is lower. The result is that a very high-pressure peak occurs at the contact line, greater in magnitude than the sheet yield stress (Fig. 5b). This initial line contact, causing a localised peak contact pressure, is a momentary event.

3.2. *Intermediate conditions*

As the punch draws the sheet to slide into the die cavity, Point A moves away from the start of the radius, as shown in Fig. 6a. Due to the plastic bending of the sheet that occurs near the beginning of the die radius, in the vicinity of $\theta = 0°$, the material entering the die radius has greater conformance with the

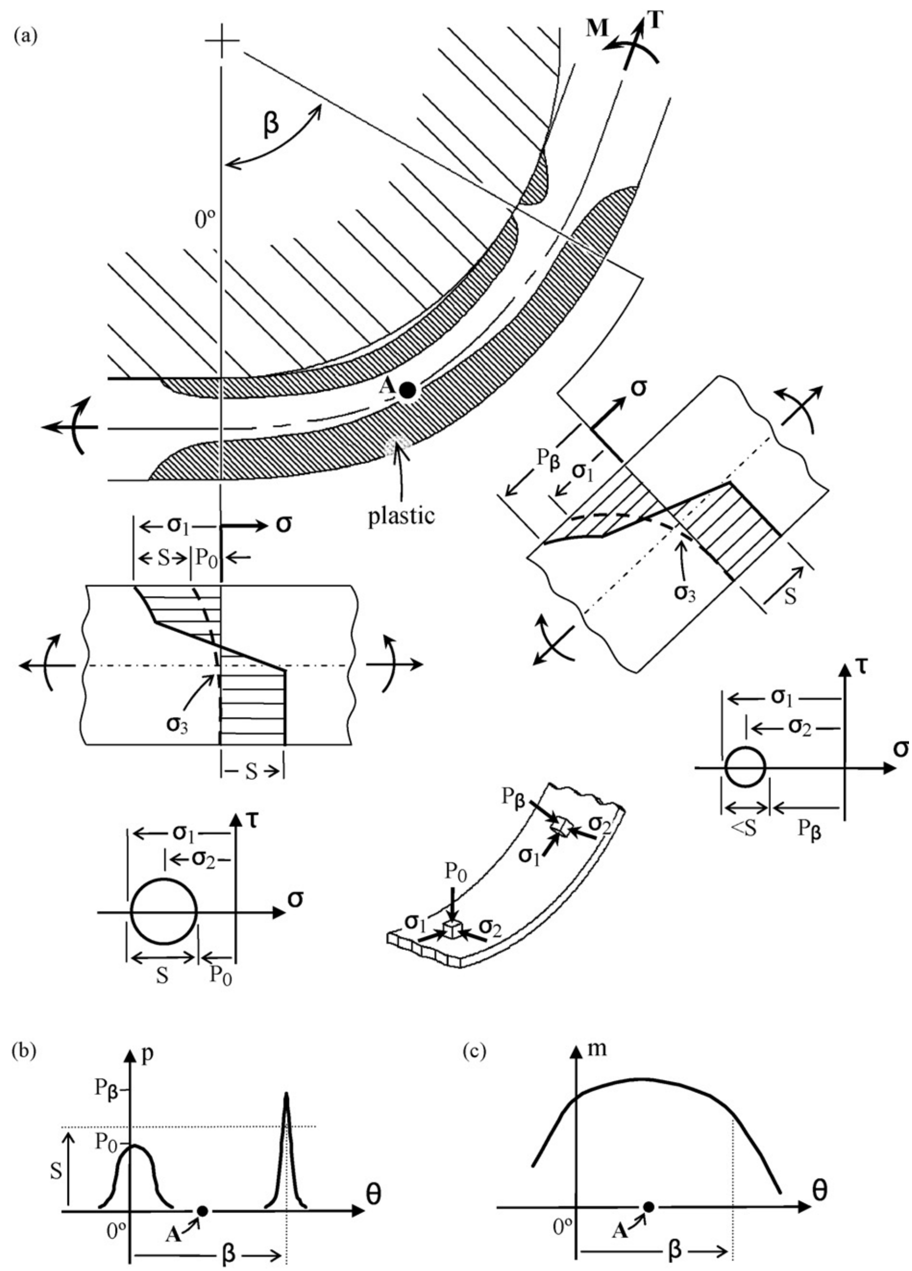

Fig. 6 – (a) Schematic of the blank to die radius interface during the intermediate conditions—the stress distribution through the thickness and the Mohr's circle at the surface of the contact zones are shown. Corresponding distributions around the die radius of (b) contact pressure and (c) bending moment in the sheet.

die radius surface. This causes a reduction in contact pressure, due to the change from line contact in Fig. 5 to a broader contact area in Fig. 6. Consequently, the compressive hydrostatic stress is reduced and plastic deformation at the blank surface occurs (the diameter of the Mohr circle is S).

The bending moment on the sheet is greatest near the Point A, as shown in Fig. 6c, such that the strip may be over-bent at this point, causing a loss of contact between the sheet and the die radius. A similar effect can exist over the nose of the punch in vee-die bending (Marciniak et al., 2002). As such, a second contact point with the die occurs further along the radius, at $\theta = \beta$. Point A, which began at the start of the radius, has not yet reached the tangent point at β. Hence, the material currently at β is largely undeformed, despite the fact that the angle of wrap of the blank over the die radius is relatively large. With similar contact conditions to the initial deformation stage, line contact occurs at β. As seen previously, these conditions result in high contact pressure, large compressive hydrostatic stress, and can suppress plastic deformation at the blank surface as supported by the case study in Fig. 1b.

Fig. 6b shows the contact pressure distribution for the intermediate stage. The magnitude of the contact pressure at the start of the radius is less than the yield stress, where contact is distributed over a wider area. Conversely, a sharp peak exists at the tangent point at β, where the sheet is still being bent and the contact area is small. In many punch and die configurations, the punch displacement needed to draw the material from the beginning of the die radius (Point A in this case) around to the tangent point is significant. Therefore, the intermediate phase may be long and the maximum contact angle, β_{max}, quite large.

3.3. Steady-state conditions at the die radius

Steady-state conditions at the die radius are reached when Point A, which began at the start of the die radius, has moved around and become part of the side-wall, as shown in Fig. 7a. *New* material is plastically bent as it enters the die radius from the blank-holder region. Here, the contact pressure and stress distributions are similar to those of the intermediate stage, due to the bending and conformance of the blank to the die radius. Beyond this region, the sheet remains in contact with the die without further plastic deformation, and the resulting contact pressure is small.

Further along the radius, under the action of an increasing opposite moment, the sheet is partially straightened, where

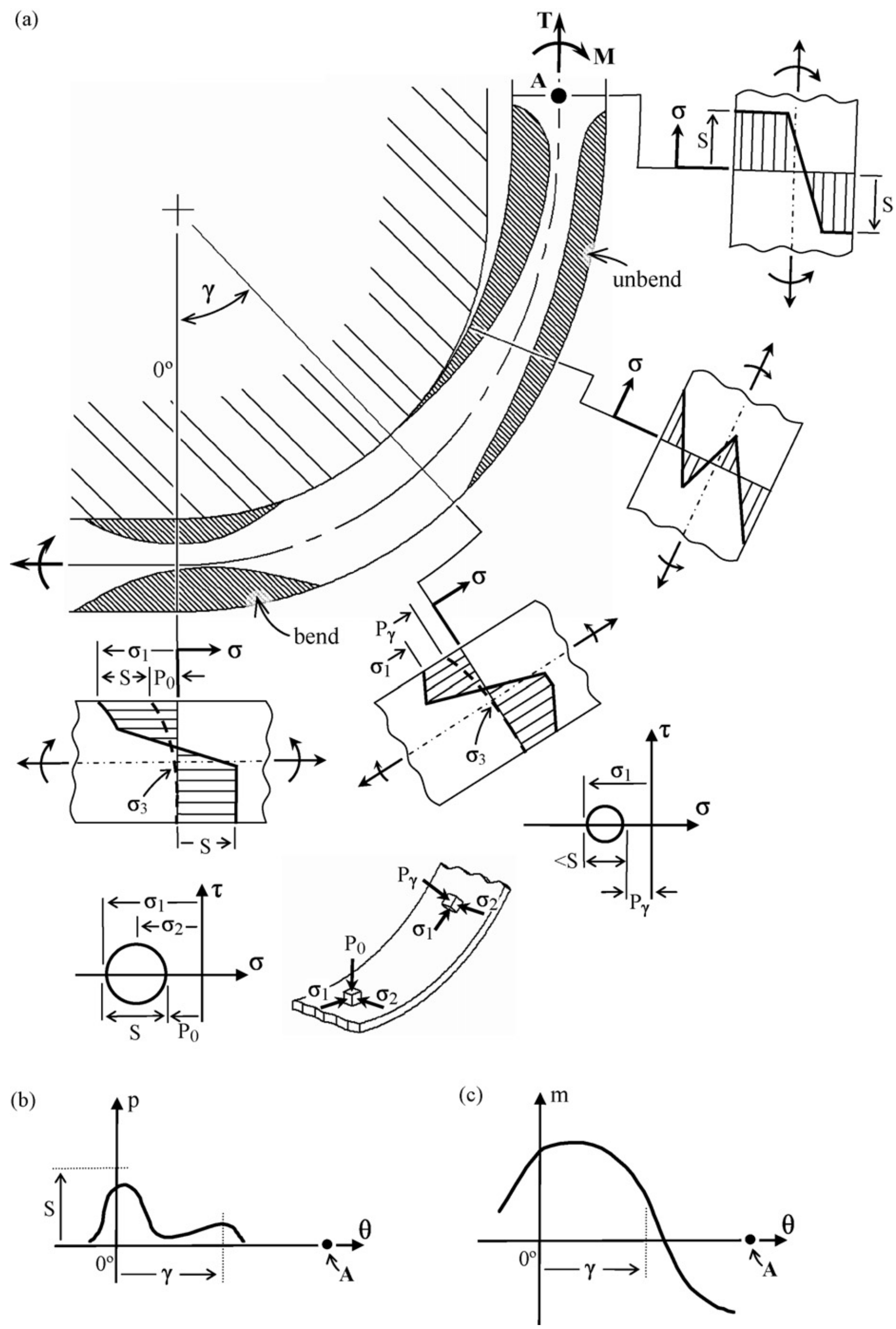

Fig. 7 – (a) Schematic of the blank to die radius interface during the steady-state deformation stage—the stress distribution through the thickness and the Mohr's circle at the surface of the contact zones are shown. The stress distribution through the thickness at two locations in the side-wall region is also shown. Corresponding distributions around the die radius of (b) contact pressure and (c) bending moment in the sheet.

it loses contact with the die radius. A second, smaller contact pressure peak occurs at the location $\theta = \gamma$. This peak can be explained, at least in part, by examining the simplified analysis presented in Section 2. According to Eq. (1), the contact pressure is proportional to the tension in the sheet—which itself increases with increasing angle θ along the radius, according to Eq. (2). Therefore, the contact pressure increases with angle along the radius, causing a peak pressure near the sheet exit point, indicated by P_γ in Fig. 7b. Here, the sheet unloads elastically and the stress distribution is shown (the diameter of the Mohr circle is <S).

Beyond the contact pressure peak, the bending moment on the sheet becomes reversed, as shown in Fig. 7c, and straightening begins at the tangent point. The straightening process continues beyond the contact point; the extent of which depends on the tooling conditions and the tension generated by the blank-holder. 'Side-wall curl' is a well-known phenomenon in channel forming and is greatest with smaller blank-holder tension. As a result of the curl in the side-wall, the angle of contact is less than in the intermediate stage, where the entire side-wall was approximately straight. This indicates that there is a region on the die radius that only makes contact with the blank during the intermediate stage—i.e. an *intermediate-only* contact region.

It is worth emphasizing that, despite the approximately steady contact conditions that occur at the die radius during this stage, the forming process itself does not reach a true steady state. This is because the blank continues to experience significant deformation and displacement as it is drawn over the die radius by the action of the moving punch. As a result, there will be a continual reduction in the flange length and a subsequent changing of contact conditions in the blank-holder region.

4. Discussion

In Section 3, a qualitative description of the deformation and contact pressure response at the die radius of a sheet metal stamping process was given. This section will discuss the identified response, with particular reference to results from other analyses in the literature, comparison to the bending-under-tension process, and wear at the die radius.

4.1. *Correlation with finite element model predictions*

In recent studies, Pereira et al. (2007, 2008) used finite element analysis to examine the contact pressure at the die radius for a channel forming process. A 2 mm thick high strength steel blank was formed over an R5 mm die radius ($R/t = 2.5$), with a punch stroke of 50 mm. The contact pressure response predicted by Pereira et al. (2008) was re-plotted at three distinct instances in Fig. 1. In this figure, the contact pressure is normalised by the constant Y, which can be considered as the flow stress of the blank material if a perfectly plastic approximation of the material stress–strain response was adopted (see Marciniak et al. (2002) for an explanation of the approximation method and calculation of Y). As such, the use of the normalised contact pressure allows better comparison between the analysis employing a blank material with considerable strain hardening (Fig. 1) to that which assumes the blank material has zero strain hardening (Figs. 5–7).

The normalised contact pressure distributions in Fig. 1 clearly demonstrate the existence of the three phases identified in Section 3. Notably, the first two stages in Section 3 correspond to the single transient phase reported in the previous numerical study (Pereira et al., 2008). The discrepancy is caused by the fact that the initial contact stage, which is a momentary event, is easily overlooked without a detailed analysis of the deformation and contact conditions occurring at the die radius.

The results by Pereira et al. (2007, 2008) verify that the initial and intermediate phases of the process result in the most severe and localised contact loads. Fig. 1 shows that at the regions of line contact, identified in Sections 3.1 and 3.2, the peak contact pressures are well in excess of Y. In fact, the maximum contact pressure for the entire process was found to occur during the intermediate stage, with a magnitude of approximately 3 times the material's initial yield strength (Pereira et al., 2008). Examination of the Mises stress plots in Fig. 1 at the regions of line contact also confirm the hypothesis of suppressed plasticity due the localised zones of large contact pressure, and hence large compressive hydrostatic stress.

The results in Fig. 1c confirm that the contact pressure is significantly reduced during the steady phase, with the magnitude of pressure less than Y due to the increased contact area. The finite element results also show that the maximum angles of contact between the blank and die radius during the intermediate and steady phases are approximately 80° and 45°, respectively (Pereira et al., 2008). This confirms the existence of an *intermediate-only* contact region, corresponding to the region of $45° < \theta \leq 80°$ for the case examined.

4.2. *Comparison to the bending-under-tension test*

The identified steady-state behaviour at the die radius during the stamping process shows numerous similarities to a typical bending-under-tension test. For example, the stress distributions through the thickness of the sheet shown in Fig. 7a, compare well to those proposed by Swift (1948), in his analysis of a plastic bending-under-tension process for a rigid, perfectly plastic strip. Additionally, the angle of contact and shape of contact pressure distributions presented in Figs. 7b and 1c, show good correlation with the results recorded by Hanaki and Kato (1984) for experimental bending-under-tension tests.

The separate finite element studies of bending-under-tension processes by Hortig and Schmoeckel (2001) and by Boher et al. (2005) also show similarly shaped two-peak contact pressure distributions. The distributions are characterised by large and relatively localised pressure peaks at the beginning of the contact zone, with smaller and more distributed secondary peaks at the end of the contact zone. Additionally, these investigations each show that the angle of contact is significantly less than the geometric angle of wrap, confirming the existence of the unbending of the blank and curl that occurs in the side-wall region. These attributes of the bending-under-tension test have direct similarities to the contact pressure response predicted by Pereira et al. (2008) and described previously in Section 3.3, despite the obvious differences in materials, processes, bend ratios and back tensions considered. Although there are numerous similarities, direct quantitative comparison between the bending-under-tension test and the steady-state phase of the channel forming process cannot be made, due to the differences in the application of the back and forward tensions.

4.3. *Contradictions with finite element model predictions*

As stated in Section 1, there are a limited number of other investigations in the literature that examine the time-dependant contact pressure response of sheet metal stamping processes. Finite element analyses by Mortensen et al. (1994) and Jensen et al. (1998) predicted that time-dependant contact conditions do occur. However, these results do not show the same trends as presented in this study and shown by Pereira et al. (2007, 2008) in previous finite element investigations. This section will briefly discuss the possible reasons for such discrepancies.

Firstly, considering the finite element analysis of a cup-drawing process by Mortensen et al. (1994), the predicted contact pressure over the die radius was presented at only three distinct intervals during the process. By comparison, Pereira et al. (2008) recorded the contact pressure at approximately 140 intervals throughout the finite element results history, in order to completely characterise the complex pressure evolution. Therefore, it is likely that the transient effects, which are reported in this study, were not captured by Mortensen et al. (1994) due to the limited number of instances at which the contact pressure was recorded.

The finite element investigation by Jensen et al. (1998) examined the contact conditions at approximately 100 intervals during a cup-drawing process, but also did not observe a severe and localised transient response, as seen in this study. (Significantly varied and localised contact conditions were observed at the end of the process, but these were identified to be due to the blank-rim effect, and are not relevant to this study.) Close examination of the results by Jensen et al. (1998) show that some localised contact conditions do occur at the beginning of the process—however, these appear relatively mild and were not discussed in the text. This reduced severity of the transient response, compared to that predicted by Pereira et al. (2008), can be partly explained by the fact that the actual contact pressure at the die radius was not shown by Jensen et al. (1998). Instead, Z_{xt}, which was defined to be a function of contact pressure and sliding velocity, was used to characterise the contact conditions. This could have effectively reduced the *appearance* of the initial localised contact conditions, due to the slower sliding velocity shown to exist during the initial stage. Additionally, Jensen et al. (1998) used 20 finite elements to describe the die radius surface, compared to 240 elements used by Pereira et al. (2008). The reduced number of elements at the die radius surface can have the effect of averaging the extremely localised contact loads over a larger area, thus reducing the magnitude of the observed contact pressure peaks. Finally, the different processes examined (cup drawing vs. channel forming) may also result in a different transient response.

4.4. *Relevance to tool wear*

Wear is related to contact pressure through a power law relationship (Rhee, 1970). Therefore, the regions of severe contact pressure during the initial and intermediate stages may be particularly relevant to tool wear at the die radius. The finite element investigations by Pereira et al. (2007, 2008) showed that the maximum contact pressure for the entire process occurs in the *intermediate-only* contact region, at approximately $\theta = 59^{\circ}$, indicating that the intermediate stage is likely to be of primary significance to the wear response. This result was validated by laboratory-based channel forming wear tests, for the particular case examined (Pereira et al., 2008).

However, for each stamping operation, it can be seen that the relative sliding distance between the blank and die radius associated with the initial and intermediate stages is small—i.e. no greater than the arc length of the die radius surface. In comparison, the steady contact pressure phase corresponds to a much larger sliding distance—i.e. the sliding distance will be approximately in the same order of magnitude as the punch travel. Therefore, despite the smaller contact pressures, it is possible that the steady phase may also influence the tool life; depending on the process conditions used (e.g. materials, surface conditions, sliding speed, lubrication) and the resulting wear mechanisms that occur.

The existence of an *intermediate-only* contact zone (i.e. the region $\gamma < \theta \leq \beta_{\max}$), is convenient for future wear analyses. Due to the lack of sliding contact in this region during the steady-state phase, any surface degradation of the die radius at angles of $\theta > \gamma$ must be attributed to the intermediate stage of the sheet metal stamping process. Therefore, it is recommended that future wear analysis examine this region to assess the importance of the intermediate contact conditions on the overall tool wear response of the sheet metal stamping process.

The existence of the initial and intermediate stages highlight that the bending-under-tension test, due to its inherently steady nature, is unable to capture the complete contact conditions that exists during a typical sheet metal stamping process. Therefore, the applicability of the bending-under-tension test for sheet metal stamping wear simulation may be questionable.

5. Summary

In this work, a qualitative description of the development of peak contact pressures at the die radius for a sheet metal stamping process was given. It was shown that three distinct phases exist:

(i) At the start of the process, the blank is bent by the action of the punch and a high contact pressure peak exists at the start of the die radius.

(ii) During the intermediate stage, the region of the sheet that was deformed at the start of the die radius has not reached the side-wall. Therefore, the side-wall remains straight and the arc of contact is a maximum. The largest pressure, which is significantly greater than the sheet material flow stress, exists towards the end of the die radius, at the tangent point between the die radius and the side-wall.

(iii) The final stage, which exhibits steady contact conditions at the die radius, occurs when the material initially at the start of the radius reaches the side-wall. The arc of contact is reduced and the greatest contact pressure occurs at the start of the die radius. The peak pressure is significantly less than in the previous stages.

This analysis allows a better understanding of the contact conditions that occur at the die radii of sheet metal stamping processes. The results will assist future research into developing and applying suitable wear tests, which correctly replicate the contact and deformation conditions occurring in the actual stamping processes. Further work is required in order to assess the importance of the identified transient contact pressure response on the wear of the system.

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