Determination of the coefficient of friction in partially penetrated draw beads

In the draw die process for stretch formed sheet metal parts, control is achieved partly by drawbeads placed in the flanged section of the blank. A draw bead is said to be fully penetrated when the sheet metal conforms fully to the geometry of the bead and the strip covers a total angle of wrap of 360° around the male and female beads. In many real forming applications partial penetration of draw beads occurs where the wrap of the sheet metal does not reach 360°. Therefore the standard equation by H D Nine [1] for fully penetrated draw beads may not be appropriate for partial penetration and it is shown that reduction in the angle of wrap with partial penetration is not taken into account in this equation. An equation is developed giving a weight factor which accounts for the change in the actual angle of wrap for the partial penetration of the sheet surface by the bead. By considering the equilbrium of forces on the bead, the strip tension, contact pressure and friction effect can be determined approximately. Constant Coulomb friction was assumed to prevail during the forming. Changes in the strip thickness in passing through the draw bead were neglected and the radius of curvature to thickness ratio was assumed to be constant. Drawbead experiments were performed for a range of bead depths. The friction coefficients as calculated by each of the equations were compared with the coefficient measured in a Flat Face Friction test. The analysis appears to represent the process for partial penetration in an acceptable manner provided the bead depth is greater than about a half that of full penetration.

In automotive stamping, the control of the metal flow is highly important because it directly affects the quality of the stamped or formed part. Poor control of the forces that governs metal flow will result in forming defects such as wrinkles, fracture, surface distortion and spring back. Control of the metal flow is achieved by punch and die geometry, friction, lubrication and the use of draw beads placed in the flanged section of the blank.

With a flat binder, or blankholder surface, tension in the sheet depends on the blankholder force, friction and lubrication. In real situations, however, the friction at a flat binder is not sufficient to control the metal flow towards the die cavity. Draw beads are used to increase the tension and restrain the metal from flowing too freely into the die cavity. The configuration of the draw beads, i.e. the geometry, size and position, surface properties and also the number of draw beads used in a particular operation are important issues that have to be considered. The draw bead configuration determines not only the forces that restrain the metal flow but also causes workhardening prior to the forming process [2]. There are three basic types of drawbeads: circular beads, square beads and edge beads. When circular beads are used, the material strip undergoes six bending and unbending cycles.

The tension in the sheet, referred to as the Draw Beam Restraining Force (DBRF) is achieved by two or three beads at smaller penetrations or one with full penetration, depending on the requirement. A draw bead is said to be fully penetrated when the sheet metal conforms to the geometry of the bead and the strip covers 360° angle of wrap around the male and female beads; the *intemesh* depth of full penetration is the sum of male and female bead radii and the sheet thickness. In this configuration the sheet undergoes the maximum deformation and the frictional forces are higher because the sheet is sliding over the entire bead surface.

For a fully penetrated bead, the coefficient of friction, μ is given by [1],

$$\mu = \frac{1}{\pi} \frac{F (Pull)_{Fixed\,Bead} - F (Pull)_{Roller\,Bead}}{F_C} \quad (1)$$

Where $F (Pull)_{Roller\,Bead}$ is the Pulling Force in the roller bead test, $F (Pull)_{Fixed\,Bead}$ is the Pulling Force in the fixed bead test and $F_C$ is the lateral force in the fixed bead test with identical testing parameters.

Equation (1) was derived assuming that the total angle of contact is 360° around the male and female beads. The validity of the above equation is therefore limited to situations where the male draw bead is fully penetrated through the female beads. In many draw die forming processes, full penetration of the draw beads are not achieved and equation (1) cannot be applied directly to calculate the coefficient of friction. In order to assess the frictional behaviour of such partially penetrated draw beads correctly, an equation is developed here based on a more realistic assessment of contact angle.

For a partially penetrated bead, the tension developed in the sheet is reduced. The contribution of bending to the restraining force may be reduced because the sheet metal is deformed to a smaller curvature and it is no longer constrained to conform to the radii of the draw bead surfaces. The frictional contribution is reduced due to the reduction in the amount of surface contact. The Coulomb friction law assumes that for a body sliding on a flat surface, the frictional force is independent of the contact area and pressure; for a strip sliding over a convex surface, the change in tension depends on the angle of wrap and it is observed [7] that the Coulomb coefficient of friction varies with contact pressure.
Friction and Contact Phenomena

In this work, the geometry of a strip in a partial penetration bead is that shown in Figure 1. This assumes that the radius of curvature confirms to the tool surface in the regions AB, CD, and EF and that the strip is straight in the unsupported segments BC and DE (It should be noticed that for small penetrations, this assumptions may not be valid).

For a strip in which the tensions (force per unit width) in the segment BCDE are $T_C$ and $T_D$ in Figure 2, the forces acting on the male bead is,

$$(T_C + T_D)w \sin \theta = F_C$$  \hspace{1cm} (2)

where $w$ is the strip width.

The average tension ($T_{avg}$) in the strip in the segment AF is taken as

$$T_{avg} = \frac{T_C + T_D}{2} = \frac{F_C}{2w \sin \theta}$$  \hspace{1cm} (3)

and the average contact pressure on the strip is,

$$q_{avg} = \frac{T_{avg}}{\rho}$$  \hspace{1cm} (3)

where $\rho$ is the radius of curvature.

The friction developed in the strip due to friction alone can be taken as the difference between the tension with fixed and friction when these are replaced by freely turning rollers, i.e.,

$$F_{frictional} = F_{fixed} - F_{free}$$  \hspace{1cm} (5)

Since the total area of wrap around the beads per unit width is $4\rho \theta$, $w$,

$$F_{frictional} = 4\rho \theta w q_{avg} \mu$$  \hspace{1cm} (6)

Substituting,

$$F_{fix} = F_{free} = 4\rho \theta w (T_{avg})$$  \hspace{1cm} (8)

and the coefficient of friction can be given as,

$$\mu = \frac{(F_{fixed} - F_{free}) \sin \theta}{F_C}$$  \hspace{1cm} (10)

The angle of $\theta$ can be represented as,

$$\theta = \frac{\pi}{2} - 2\alpha$$  \hspace{1cm} (11)

$$\tan \alpha = \frac{2r + t - h}{2r + t + s}$$  \hspace{1cm} (12)

where,

$r$ = radius of the male/female bead
$t$ = sheet thickness
$h$ = penetration (measured intermesh depth)
$s$ = shim (0.77 mm for 0.80 mm sheet thickness)
$c$ = side clearance ($t+s$)

When $h-t = 2r$, $\theta$ will be $\pi/2$ confirming the full penetration and this can be obtained when $h= 10.3mm$ for a sheet thickness of 0.8 mm. In this work, it is assumed that $\rho - r$, although, as mentioned, this assumption does not appear to be valid for small penetrations.
Experimental

The Draw Bead Simulator (DBS) Test was used to evaluate lubrication and to predict the coefficient of friction in stamping of coated steel sheets. DBS experiments for this investigation were carried out in the BlueScope Steel Research Laboratories in Port Kembla, Australia using an Instron test frame. The experiments were performed with freely rotating roller beads and with the fixed beads.

The radius of the roller and fixed beads were identical, 9.5 mm, and made from K245 tool steel. Controllable penetration of the draw beads can be achieved with the test rig and the intermesh distance or penetration was measured with the aid of a dial gauge mounted in the test frame. The lateral clamping force was applied using a hand operated pneumatic pump. The samples (330mmx50mm and 0.8mm thick) were de-burred and degreased with ethanol. The lubricant was applied uniformly with a rubber sponge over both surfaces of the specimen and also on the tooling. In each draw, the clamping force and the drawing force were recorded at 0.4mm intervals. The coefficient of friction was calculated in each step of the fixed bead test using equation (1). The steady state coefficient of friction for each test was taken as the representative value for that test. Observations were taken for two different lubricants shown in Table 1 and two different coated steels over a range of intermesh values at a speed of 50mm/s.

Zincanneal and Galvanized steels were used for the experiments; they are drawing quality sheet steels manufactured by BlueScope Steel with the Tensile Strength of 295 ±3MPa and 301±4MPa, respectively. The surface roughness was measured at 1.10μm and 0.40μm, respectively, for the Zincanneal and Galvanized strips.

Table 1: Testing Lubricants

<table>
<thead>
<tr>
<th>Manufacturer's Code</th>
<th>Lubricant 1 (L1)</th>
<th>Lubricant 2 (L2)</th>
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<tbody>
<tr>
<td>Description</td>
<td>Water based high viscosity forming lubricant free of chloride</td>
<td>Heavily compounded water soluble full synthetic oil based on Poly Alkaline Glycol (PAG) Technology</td>
</tr>
<tr>
<td>Density (15°C)</td>
<td>0.925 g/ml</td>
<td>1.045 g/ml</td>
</tr>
<tr>
<td>Viscosity (20°C)</td>
<td>224 cP</td>
<td>114 cP</td>
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</table>

Evaluation of the results. The coefficient of friction values obtained with Equation (1) are shown in Fig. 4. These values show a coefficient of friction variation of only ± 0.06 even though the degree of penetration varied. For Zincanneal steel, the coefficient of friction values were scattered between 0.108 and 0.115 and for galvanized steel it was 0.085 and 0.096. When equation (10), which accounts for the angle of wrap, was used, it was observed that the coefficient of friction tends to reduce with the increasing penetration.

During this study it was also found that for tests between half and the full penetration, the contact pressure increases with the penetration, even though the amount of contact area is increased and the coefficient of friction reduces. Results for very low penetrations were omitted because of the considerable difference between the bead radius r, and the radius of curvature of the sheet p. During DBS trials the clearance between the male and female beads and the sheet was kept constant and therefore it was seen that even at full penetrations, the angle of wrap is slightly less than the estimated value of 360°.

Discussion of results

It was found that the angle of wrap which corresponds to the actual engagement of the strip with the roller or bead was not taken into account in the derivation by Nine [1]. Green [2] states that, not until very deep penetrations is the tangent-to-tangent bead wrap assumption approximately valid. Green's comments [2] support the argument that the validity of the equation by Nine [1] is only limited to complete penetrations. Later researchers [2, 4, 5, and 6] have discussed the issues of partial penetration and the material behaviour in partially penetrated drawbeads, but no mathematical model has been presented for the calculation of coefficient of friction. Very shallow penetrations were omitted in the study because the assumptions are not valid.

It was assumed that the radius of curvature to thickness ratio (p/t) is a constant. However, during deformation, the p/t ratio decreases slightly due to thinning resulting a decrease in the bending forces. During the very low penetrations, the radius of curvature was observed to be much higher than the bead radius and the equation obtained could not be applied successfully. Green [2] found that at shallow penetrations, the bend radius of the strip over the entry shoulder radius was significantly larger (5-6 times larger) than the bead radius and the strip typically marked contact with the bead only at one point.
Friction and Contact Phenomena

In the experimental setup the applied back tension was zero whereas in the industrial draw beads clamping between the two die flanges provides a considerable restraining force. This could make some uncertainties in applying the result in industrial stamping. Michler et al [5] have raised this issue against the Nine's draw bead model and suggested a modified apparatus to apply a measurable back tension with flange clamping. Green [2] has found that when back tension was applied to a strip being pulled through a draw bead, the bend radii in the strip were noticeably modified.

According to Strubeck curve [7], in the mixed lubrication regime, log $\mu$ shows an inverse relationship with log ($\eta$/$\rho$), where, $\eta$ is the lubricant viscosity, $v$ is the drawing speed and $\rho$ is the contact pressure. During the DBS experiments, the drawing speed was kept constant and it was assumed that the lubricant viscosity also remains unchanged. An inverse relationship was observed between the modified coefficient of friction (equation 10) and contact pressure (Fig. 4 (a) and (b)). This suggests that conditions are in the mixed lubrication regime; this outcome is in accordance with the comments from Dalton et al [8]. According to their observations, in DBS Test with heavy and medium lubricants, the mixed film lubrication dominated. Further studies with Flat Face Friction (FFF) test results are being conducted by the authors to investigate the prevailing lubrication regime for the same experimental combination.

Stoughton [4] explains that in low penetration, the friction is reduced due to the reduction in both the amount of surface contact and the bending force which gives rise to the pressure against the bead. It is possible that this agrees with our observations for very low penetrations; probably less than 25% of the full penetration. The coefficient of friction in the DBS test is influenced by the surface roughness and the coating hardness [8], but this effect is still not quantified [4]. The experimental coated steel used here with a higher degree of surface roughness did show a higher degree of coefficient of friction.

Conclusions

The validity of the standard formulae for the friction coefficient in the DBS test is limited only for the cases where the beads are fully penetrated and the sheet conforms fully around the male and the female beads. In the new equation presented here, the angle of wrap which determines the area of contact around the beads has to be taken into account when determining the coefficient of friction in partially penetrated drawbeads.

An inverse relationship was obtained between the coefficient of friction and the contact pressure within the experimental range. The coefficient of friction variation with the amount of bead penetration agrees qualitatively with other observed properties of mixed lubrication regime where the coefficient of friction is inversely changing with the contact pressure if the lubricant viscosity and the drawing speed are kept constant.

The mathematical formulae derived here could not be applied for situations with penetrations lower than half of the full penetration. The fact is that in low degree of penetrations the assumption of the equality of the radius of curvature of the sheet and the bead radius breaks down. This equation could be further modified for very low penetrations by adding a correction factor for the difference between the radius of curvature of the sheet and the radius of the bead.

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References