

A CRITICAL EVALUATION OF THE DOUBLE CUP EXTRUSION TEST FOR SELECTION OF COLD FORGING LUBRICANTS

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Abstract

The performance evaluation of cold forging lubricants and coatings as well as determination of the friction coefficients is necessary for production as well as Finite Element (FE) simulations. The Double Cup Extrusion Test (DCET) has been widely used to evaluate cold forging lubricants, since it was believed to accurately emulate the practical conditions (severity of deformation and surface expansion) found in most cold forging applications. However, recent research and previous studies using Finite Element (FE) simulation as well as experiments indicated that the interface pressure conditions and surface generation in the DCET may not be comparable to those found in cold forging. Thus, the aim of this work was to evaluate the DCET by studying the influence of various geometrical and process parameters on the cup height ratio and contact pressure at the tool-workpiece interface. Based on this evaluation, recommendations are made on how to re-design the DCET and make it more sensitive to changes in interface friction.

Keywords: Cold forging lubricants, double cup extrusion test, FE simulations.

1. Introduction

In cold forging operations, tool-workpiece interface pressures can reach 2500 MPa (363 ksi) with interface temperatures of up to 600°C, while surface enlargement can be as large as 3000% [1]. Since the friction at the tool-workpiece interface plays such an important role in the process, it is essential that the lubricants used in cold forging withstand the interface conditions encountered in production, in order to form quality parts. Failure of the lubricant can lead to part surface defects and significant die wear or even die failure. A good lubrication system is essential for successful cold forging and it is often the determining factor for making the process competitive.

Test methods such as the Ring Compression Test (RCT) and the Double Cup Extrusion Test (DCET) have been employed to test lubricants used in cold forging operations [2, 3]. The present study evaluates the DCET critically by fundamentally studying a) the factors that affect the cup height development and b) interface pressures.

2. Evaluation of Lubricants used in Cold Forging

Several tests are commonly used to evaluate the performance of cold forging lubricants. These tests should emulate the interface conditions that exist in production as nearly as possible. Two common “tribotests” used for this purpose are the Ring Compression Test (RCT) and the Double Cup Extrusion Test (DCET). The advantage of these tests is that the final geometries of the specimen are dependent on the interface friction and the lubricity of the lubricant used. In both cases, calibration curves are generated by FEM using different friction values. By measuring the geometry of the tested specimen, and comparing it to the calibration curves, a friction value can be assigned to the lubricant tested.

The DCET is considered to have the following advantages over the RCT:

- The test emulates severe deformation conditions similar to that occurring in actual cold forging operations.
- The test is easy to conduct and lubricants can easily be ranked based on the difference in the cup heights.

The principle of the DCET is illustrated in Figures 1 through 3. The ratio of the cup heights after deformation, H_1/H_2 , is an indication of lubricity. This ratio increases as the friction factor increases. Thus, if there is no friction, the cup heights are the same and the ratio, H_1/H_2 , is equal to one.

The upper punch moves down with the ram while the lower punch and container are stationary. Thus, the container has relative velocity with respect to the upper punch, but not to the lower punch. Therefore, the material flow towards the lower punch is more restricted. In the presence of friction, the height of the upper cup is larger than the height of the lower cup.

With the use of the commercial FEM code DEFORM®, friction factor calibration curves (cup height ratio vs. stroke) can be established for different friction factor values (m) (Figure 4). By matching the cup height ratio and punch stroke obtained from experiments to that obtained from FE simulations, the friction factor of the lubricants can be obtained.

In the tooling used for the present study the billet has a height of 31.75 mm and a diameter of 31.75 mm (1.25 inches). Thus, the cup height ratio, R , is defined by Equation 1 and the real stroke, S_r , is defined by Equation 2 [Figure 3].

Cup Height Ratio:

$$R = \frac{H_1}{H_2} . \quad \text{(Equation 1)}$$

Real Stroke

$$S_r = 31.75 - (H - H_1 - H_2) \quad \text{(Equation 2)}$$

3. DCET as a Tribotest – Rationale for the Current Study

The tooling available at the Engineering Research Center (ERC) at the Ohio State University is used to evaluate lubricants for cold forging (Figure 5 and Table 1). With surface expansion of up to 500% - 730% in some regions of the workpiece, the test was believed to better emulate actual cold forging conditions than other friction tests, such as the Ring Compression Test.

Table 1: ERC tooling and workpiece geometry.

r	Punch							Workpiece		Container
	D_p (mm)	D_f (mm)	D_s (mm)	R (mm)	h_p (mm)	Φ (deg)	β (deg)	d_o (mm)	h_o (mm)	D_c (mm)
0.25	15.88	9.53	15.72	1.17	1.57	10.0	5.0	31.75	31.75	31.75

Table 2: Properties of materials used in simulations.

ERC Material: AISI 1018		
K = 735 MPa	n = 0.17	
$\bar{\sigma} = 735 \bar{\epsilon}^{0.17}$		
Bay's Material: work-hardened AA6082 [4]		
K = 191.5 MPa	$\epsilon_0 = 0.336$	n = 0.12
$\bar{\sigma} = 191.5(0.336 + \bar{\epsilon})^{0.12}$		

In the DCET, the ratio of the height of the upper cup to the height of the lower cup is extremely sensitive to friction. However, the friction on both punches is the same. Thus, only the friction along the container wall influences the metal flow. This friction along the container wall restricts the development of the lower cup and assists the development of the upper cup. Therefore, the test mainly evaluates friction at the container/workpiece interface. FEM simulations were run to verify this by investigating the effect of the punch/workpiece friction on the cup height ratio. The material used in these simulations was 1018 steel (Table 2). In three simulations the constant shear friction law $[\tau_f = m\bar{\sigma}/\sqrt{3}]$ was used. The friction value (m) was kept constant at the container/workpiece interface (m=0.05) but varied at the punch/workpiece interface (m=0.0, m=0.5 and m=1.0). Figure 6 shows the variation of cup height ratio with stroke. It can be seen that the difference between the cup height ratios for zero friction at the punches and sticking friction at the punches is very small, $\Delta R = 0.08$, which is within the range of measurement error. In other words, as long as the friction at the top punch is the same as the friction at the bottom punch, the punch friction has no effect on the cup height ratio.

This is significant because the conditions at the container/workpiece interface, especially in the ERC design (Table 1), are not severe. At this interface, the surface expansion (A_f/A_i) during the process is only around 120%, and the maximum contact pressures are only about $\frac{1}{4}$ th the magnitude of the contact pressures at the punch/workpiece interface. In fact, a previous study [5] showed that the normal pressures at the container/workpiece interface are low enough to make the friction predominantly Coulomb friction, which is not representative of most cold forging operations.

These observations indicate that the DCET does not evaluate how the lubricant performs in the region where large interface pressures exist (punch-billet interface) but only at the container-billet interface, where the interface pressures may not be very large.

The tool design used at the ERC has a small extrusion ratio, $r = 0.25$ ($r = \frac{d_{punch}^2}{d_{billet}^2}$). This is close

to the smallest extrusion ratio recommended in the literature for this test [6]. The extrusion ratio was chosen because it offers high sensitivity to changes in friction. The trade-off is that while sensitivity to small changes in friction increases with decreasing extrusion ratio (for most materials), the severity of the conditions at the container/workpiece interface decreases.

With the current design and method of evaluation, it is possible that the evaluation of a lubricant could be only partially accurate. For example, Figure 7 shows the results of a study where, among other parameters, the effect of change in extrusion ratio was investigated [4]. In this study, three extrusion ratios (r=0.34, r=0.52 and r=0.69), two materials (one work-hardened (WH) and the other annealed (AN) AA6082) and two lubricants (MoS₂ and soap) were

evaluated. Figure 7 shows that for both materials the soap performed better at low extrusion ratios (low interface pressures) but worse at high extrusion ratios (high interface pressures). With the current extrusion ratio employed by the ERC design ($r=0.25$, even smaller than the smallest extrusion ratio recommended by Altan et al, 1993), this observation would have been missed.

It is within the context of this background that the current study was necessary, to acquire a more fundamental understanding of the DCET. We would like to determine whether or not the test could be improved to more accurately evaluate the performance of lubricants under severe cold forging conditions.

4. Objectives and Approach

4.1. Objectives

The main objectives of this study are to:

- determine and interpret the factors that affect metal flow in the Double Cup Extrusion Test (DCET).
- determine the parameters that can be modified to improve the DCET so that it can accurately evaluate lubricants under practical cold forging conditions.

4.2. Approach

To achieve the objectives of the study we conducted a parametric study of the DCET using FE simulations and compared the predictions with experimental data. 1018 steel and work-hardened AA6082 were used in this study because experimental data was available in the ERC and from [4] for comparison of simulation results. The flow stress data for both materials is given in Table 2.

The geometry of the ERC tooling and workpiece is found in Table 1, while the geometry of the tooling and workpiece used by Bay is found in Table 3. The notation describing the geometry of the punches is shown in Figure 5.

Table 3: Tooling and workpiece geometry used in [4].

r	Punch							Workpiece		Container
	D_p (mm)	D_f (mm)	D_s (mm)	R (mm)	h_p (mm)	Φ (deg)	β (deg)	d_o (mm)	h_o (mm)	D_c (mm)
0.34	15.8	9.7	15.7	1.1	2	7.5	4.0	27.0	27.0	27.0
0.69	22.4	13.6	22.3	1.6	2.4					

5. Parametric Study of the Double Cup Extrusion Test

5.1. Effect of strain hardening coefficient, n

Figure 8 shows the effect of the n-value using 1018 steel (ERC material, Table 2). The results with the actual n-value of the material, $n=0.17$, is compared to a fictitious non-strain hardening material ($n=0$) by plotting the cup height ratio vs. stroke curve. Actual experimental data from tests are also shown in Figure 8. It can be seen that as the n-value decreases, the cup height ratio increases. This is likely due to the fact that the more work-hardened a material is (lower n-value), the more resistant to deformation it will be. Thus, all other parameters, including friction,

being equal, since a backward extrusion process requires less energy than a forward extrusion process, the upper cup will form faster than the lower cup in the initial stage of the process.

Figure 9 shows the same trend using Bay's material, the work-hardened aluminum alloy AA6082 (Table 2). The material's n-value, $n=0.12$, is compared to an artificial value of $n=0$ by plotting the cup height ratio vs. stroke curve. Actual experimental data given in [4] are plotted as well. Again, it is seen that decreasing n-value results in increasing cup height ratio (Figure 9).

Figure 10 shows the effect of n-value on the normal pressure at the billet/container interface using the 1018 steel (Table 2) and the process geometry used at the ERC (Table 1). This plot corresponds to the point in the punch stroke when maximum pressure at the billet/container interface was observed. A chart of the cup height ratio curves is included to show the point in the stroke at which the pressure readings are taken.

It can be seen that a decrease in the n-value causes an increase in the normal pressure at the billet/container interface. The plot shows that the maximum pressure for the steel with an extrusion ratio of $r=0.25$ was roughly $P = 665 \text{ MPa}$ (97 ksi). Ideally, in order to emulate cold forging conditions where pressures can reach 2500 MPa (363 ksi), higher pressures should be attained in order to make the DCET more useful to evaluate cold forging lubricants. As shown in Figure 10, a material with lower n-value results in higher pressure at the billet-container interface leading to more accurate evaluation of the lubricant performance.

5.2. Effect of strength coefficient, K

Figure 11 shows the influence of the strength coefficient, K, on the cup height ratio. For this task, the ERC material properties (Table 2) and process geometry (Table 1) were used in the simulation. It can be seen that a change in K-value produces no effect on the metal flow.

Figure 12 shows the effect of K-value on the normal pressure at the billet/container interface using the ERC process geometry (Table 1) and the K value found in the ERC material (Table 2, 1018 steel). In these simulations the n-value is assumed to be $n=0$. This plot corresponds to the point in the stroke where maximum pressure at the billet/container interface is seen. A chart of the cup height ratio curves is included to show the point in the stroke at which the pressure readings are taken.

It can be seen that an increase in the K-value causes an increase in the normal pressure at the billet/container interface. Therefore, a material with higher K-value results in more severe conditions at the billet-container interface leading to more accurate evaluation of the lubricant performance.

5.3. Effect of prior work-hardening of the billet in the simulation

In all the previous FE analyses of the DCET, the strain in the billet has been assumed to be homogeneous throughout the length and cross-section. In reality, if a billet has been work-hardened by forward rod extrusion to its final diameter, and has not been annealed, a non-homogeneous strain distribution will be present.

The experimental material used in Bay's study was work-hardened by forward rod extrusion from $\varnothing 40 \text{ mm}$ annealed bars to $\varnothing 30 \text{ mm}$ at room temperature, then machined to the diameter shown in Table 3. A simulation of this extrusion operation was conducted (Figure 13). A billet of predetermined length (27 mm) and diameter (27 mm) was then obtained from this virtual extrusion. This procedure yields a billet of the required dimensions with the prior strain history from the extrusion process. Thus, a distinct strain gradient exists across the cross-section of the billet.

Figure 14 shows the resulting strain distribution in the extruded billet before the DCET simulation. It can be seen that the effective strain at the outer radius of the billet is higher than at the center.

Figures 15 and 16 show the effect of including the non-homogeneous strain distribution across the billet in the simulation of the DCET. Figure 15 shows the results using an extrusion ratio of $r=0.34$ with a friction value of $m=0.08$. Experimental data points are included [4]. From this plot it is hard to tell if either of the curves matches the experimental data more closely than the other. However, it can be seen that including the strain distribution in the simulation does indeed have an effect on the cup height ratio. The cup height ratio is increased in the case of the non-homogeneous strain distribution.

Figure 16 shows the results for an extrusion ratio of $r=0.69$ and friction value of $m=0.08$. It can be seen that the effect of the strain gradient in the billet has an even greater influence with a larger extrusion ratio. This is expected since most of the initial deformation of the billet, with the large extrusion ratio, takes place in the region where the largest amount of work-hardening is present, at the outer surface of the billet.

As seen in Figure 16, not only is the cup height ratio significantly higher when the non-homogeneous strain distribution is included, but the maximum peak is also much more pronounced.

5.4. Effect of billet height

In earlier studies at the ERC, a billet height of $h_o=31.75$ mm was used with a billet height-to-diameter ratio of $h_o/d_o=1$. This was compared to $h_o/d_o=0.75$ and $h_o/d_o=1.25$. Figure 17 shows the comparison of the cup height ratio curves for the three cases. A friction factor of $m=0.05$ was used in the simulations. It can be seen that the cup height ratio increases with increasing h_o/d_o .

Figure 18 shows the effect of billet height on the normal pressure at the billet/container interface using the ERC material (Table 2) and process geometry (Table 1). A chart of the cup height ratio curves is included to show the point in the stroke at which the pressure readings are taken. This is very close to the point where maximum pressure is seen for the case of $h=31.75$ mm ($h_o/d_o=1.0$), which is the billet height currently used by the ERC.

In fact, the maximum pressure for billet height $h=39.6875$ mm ($h_o/d_o=1.25$) is roughly $P=672$ MPa (97.4 ksi) and occurs at a stroke of about 11.5 mm. Since the maximum pressure for the billet height $h=31.75$ mm ($h_o/d_o=1.0$) is about $P=665$ MPa (96.4 ksi), it can be seen that the billet height does not have a great effect on the normal pressures at the billet/container interface.

5.5. Effect of extrusion ratio

The effect of cup extrusion ratio on cup height ratio is seen in Figure 19 for the material and tool geometry used by Bay [4]. In these simulations the billet material was assumed to be homogeneous. It is seen that the cup height ratio is much less in the case of $r=0.69$ than for $r=0.34$.

The simulations, as expected, also indicated that the normal pressure at the container-billet interface increases with increasing cup extrusion ratio. In the present case the maximum increase was approximately 70%.

5.6. Effect of punch die land

Figure 20 shows the effect of doubling the punch die land (h_p in Figure 5) on both (upper and lower) punches. In this task, the ERC material (1018 steel) (Table 2) and process geometry (Table 1) were used in the simulations. Experimental data is plotted along with cup height ratio

vs. stroke curves corresponding to the two different punch geometries. It can be seen that there is very little change in the cup height ratio.

These simulations also showed that the normal pressures at the container-billet interface did not change with increasing die land length.

5.7. Effect of punch friction

As seen in Figure 6, when the friction at both punches is the same, there is only negligible change in the cup height ratio curves when that value of friction on the punch surface is changed. Figure 21 shows the effect of different friction on the top punch as opposed to the bottom punch. It is seen that with zero friction on the bottom punch ($m=0$) and sticking friction on the top punch ($m=1$), the cup height ratio is increased, as flow is restricted to the bottom cup. The opposite is seen when the friction conditions are reversed. These results, though interesting, have little practical value because under realistic cold forging conditions, the friction conditions are nearly the same for the top and bottom punches.

6. Surface Generation and Metal Flow in the DCET

Simulations were run for cup extrusion ratios of $r=0.25$ and $r=0.34$ to determine how the new surface is generated in DCET. For this purpose, the point tracking feature in DEFORM® was used. Nodes were selected on the surface of the upper cup at the end of the stroke and then by returning the stroke to the beginning of the process, the origin of the material could be determined. Figures 22 and 23 show the point tracking around the punch and the container, respectively, for an extrusion ratio of $r=0.25$. A similar analysis was done for an extrusion ratio of $r=0.69$. Figure 22 shows the node numbers (before and after deformation) illustrate the origin of the material that ends up on the inner surface of the upper cup.

It is seen that around the top punch new surface was generated from below the surface of the untested sample, especially for the small extrusion ratio. More material actually slides along the surface of the punch for the large extrusion ratio than for the small extrusion ratio. Along the container wall the new surface originates from the original surface for both small and large extrusion ratios (Figure 23).

7. Summary and Future Work

The results of this study can be summarized as follows:

1. The contact pressure at the billet/container interface increases with
 - increasing extrusion ratio, as expected,
 - reduction of the strain hardening exponent of the workpiece material (n value),
 - increase in the material strength co-efficient (K value), as expected.
2. As is well known, surface generation at the billet/container interface increases with increasing extrusion ratio.
3. Sensitivity to changes in friction (increase in R) increases with
 - reduction of the strain hardening exponent of the workpiece material (n value)
 - inclusion of the non-homogeneous strain distribution of a work-hardened billet in the simulation (this should be done mainly to correctly simulate the process and achieve more accurate results)
 - increasing the height of the billet (more simulations should be run to see where the limit exists)

- in general, decreasing extrusion ratio, depending on the material. For material with a) high n-value, decrease extrusion ratio, and b) with low n-value, the sensitivity might be maintained even with increasing extrusion ratio.

Some of these parameters are more easily changed than others, depending upon the tool design, dimensions and fabrication costs.

One possible suggestion for improving the evaluation of lubricants with the DCET would be to test each lubricant using both a smaller and larger extrusion ratio [4]. The smaller one (optimized as discussed above) could be used to assign a friction value. The larger extrusion ratio could then be used to compare several lubricants at severe conditions without finding a friction value (since sensitivity is reduced). For the larger extrusion ratio tests simulations would not be needed. The measurement of the cup height ratios would be used to compare the performance of the tested lubricants.

References:

- [1] Bay, N., "The State of the Art in Cold Forging Lubrication," J. of Materials Processing Technology Vol. 46, pp. 19-40, 1994.
- [2] Buschhausen, A., Lee, J.Y., Weinmann, K. and Altan, T. "Evaluation of Lubrication and Friction in Cold Forging Using a Double Backward Extrusion Process," J. of Materials Processing Technology, 1992 (Vol. 33(1-2), pp. 95-108.
- [3] Arentoft, M., Vigsø, C., Lindegren, M. Bay, N., (1996) "A Study of the Double Cup Extrusion Process as a Friction Test," Advanced Technology of Plasticity 1996, Vol. I, 5th ICTP, edited by Altan, T., pp. 243-250.
- [4] Tan, X., Zhang, W., and Bay, N., "On parameters affecting metal flow and friction in the double cup extrusion test," Scandinavian Journal of Metallurgy, 1998 (Vol. 27, Issue 6), pp. 246-252.
- [5] Vigsø, C., Kim, H., Sweeney, K., Shen, G., Altan, T., (1994) "Evaluation of Friction in Cold Forging by the Single/Double Cup Extrusion Test," Report No. ERC/NSM-B-94-59, the Ohio State University.
- [6] Ghobrial, M.I., Lee, J.Y., Altan, T., Bay, N., and Hansen, B.G. "Factors Affecting the Double Cup Extrusion Test for Evaluation of Friction in Cold and Warm Forging," Annals of the CIRP, 1993 (Vol. 42), pp. 347-351.

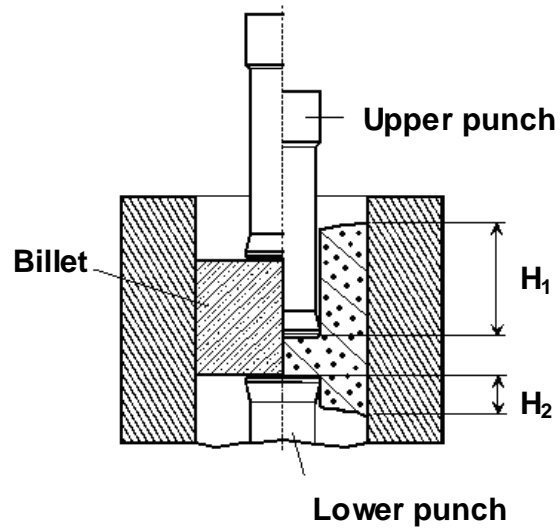


Figure 1: Double cup extrusion test (DCET).

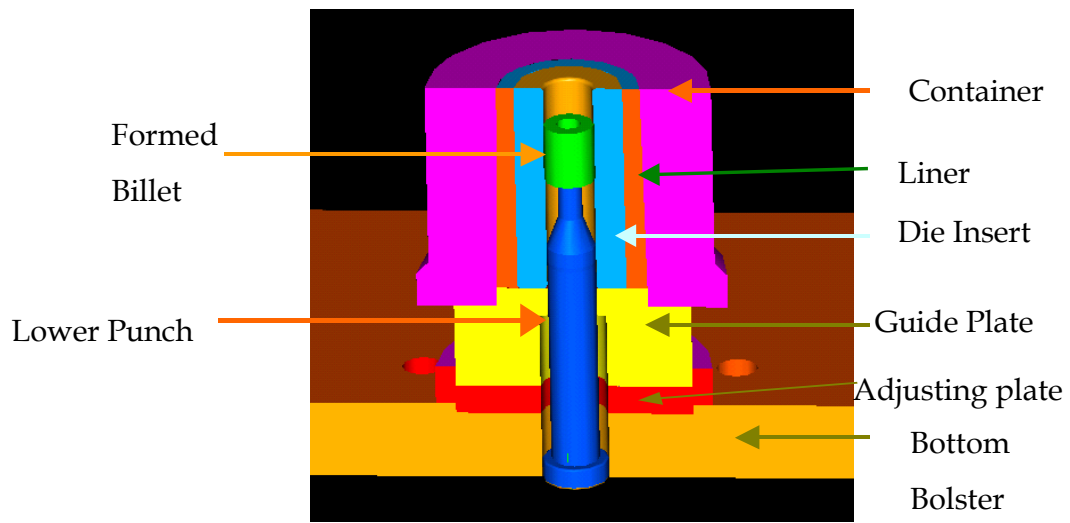


Figure 2: Double cup extrusion tooling (3-D cross-sectional view).

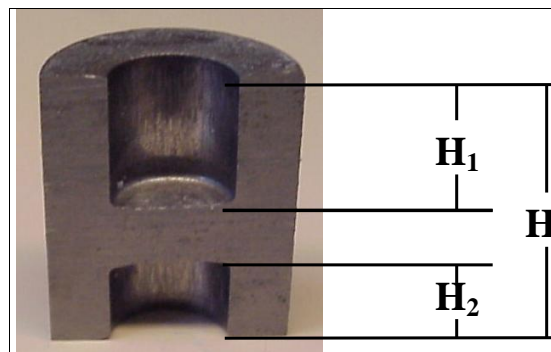


Figure 3: DCET test sample.

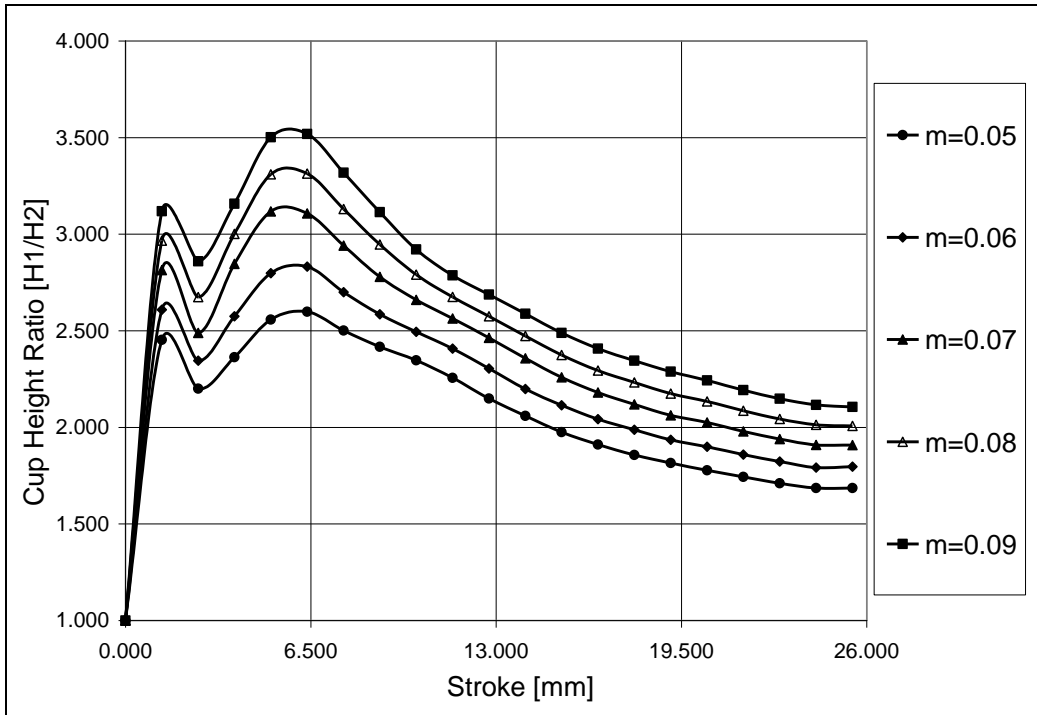


Figure 4: Friction factor calibration curves obtained for AISI 1018 for a specific tool geometry (Table 1).

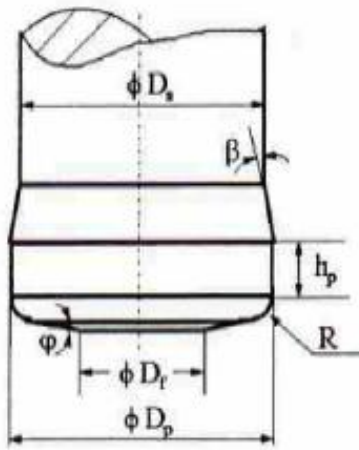


Figure 5: Geometry notation of punches [4].

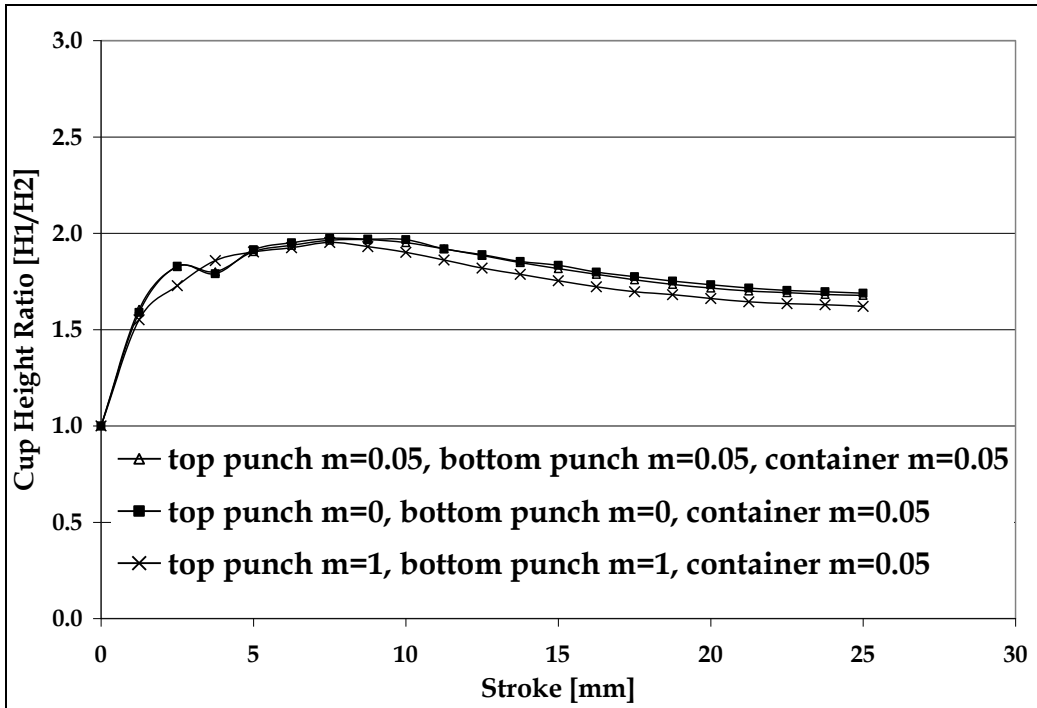


Figure 6: Influence of punch/workpiece interface friction on the cup height ratio curve when friction on both punches is the same (1018 steel).

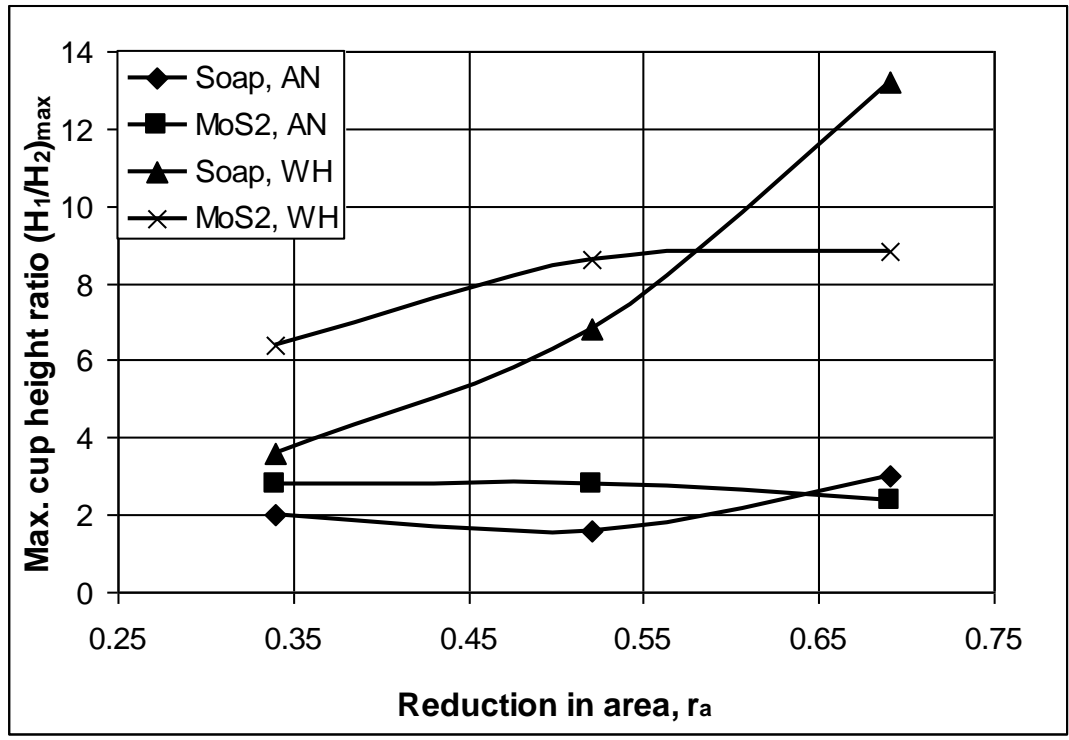


Figure 7: Experimentally-measured maximum cup height ratio versus reduction in area (extrusion ratio) for annealed (AN) and work-hardened (WH) AA6082 lubricated with MoS₂ and Soap [4].

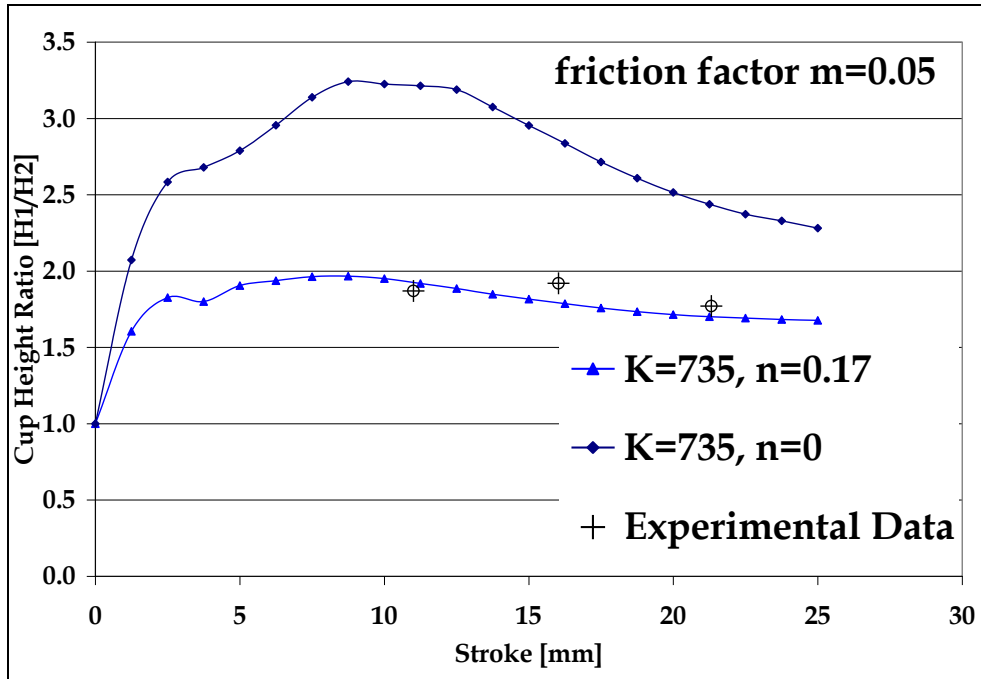


Figure 8: Effect of n -value on cup height ratio in the DCET using ERC material (Table 2) and process geometry (Table 1) with $r = 0.25$.

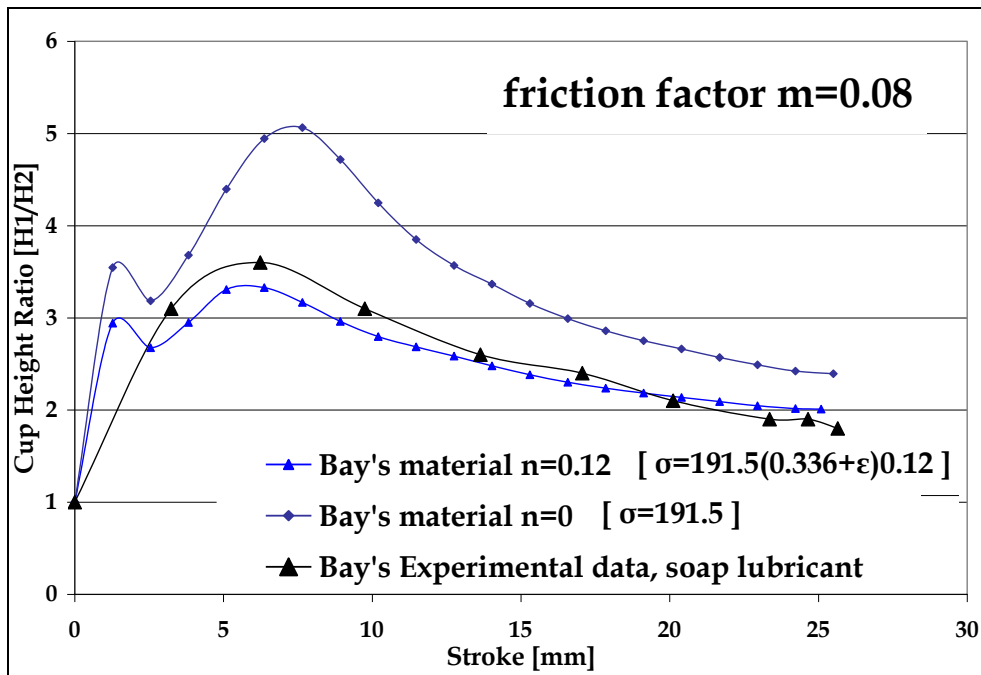


Figure 9: Effect of n -value on the cup height ratio in the DCET using Bay's material (Table 2) and process geometry (Table 3) with $r=0.34$.

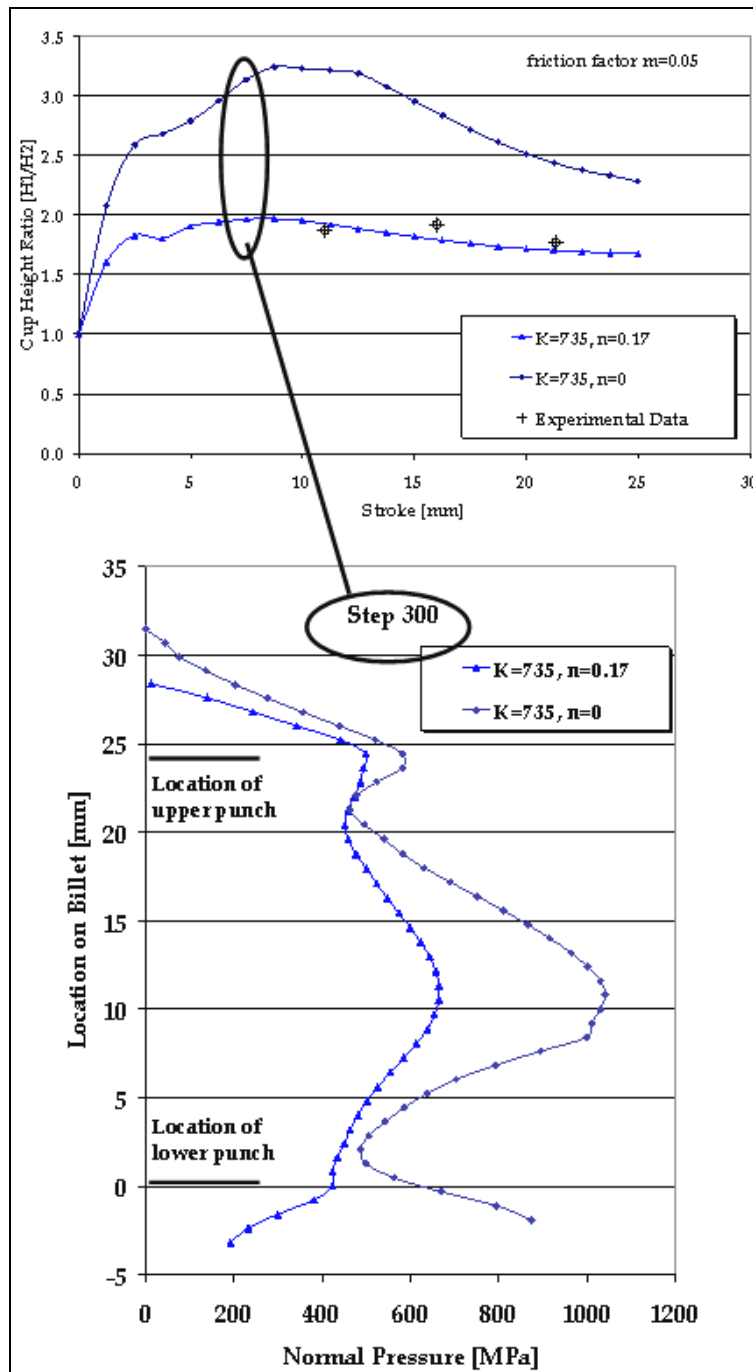


Figure 10: Effect of n-value on normal pressure at the billet/container interface using ERC material (Table 2) and process geometry (Table 1) and $m=0.05$.

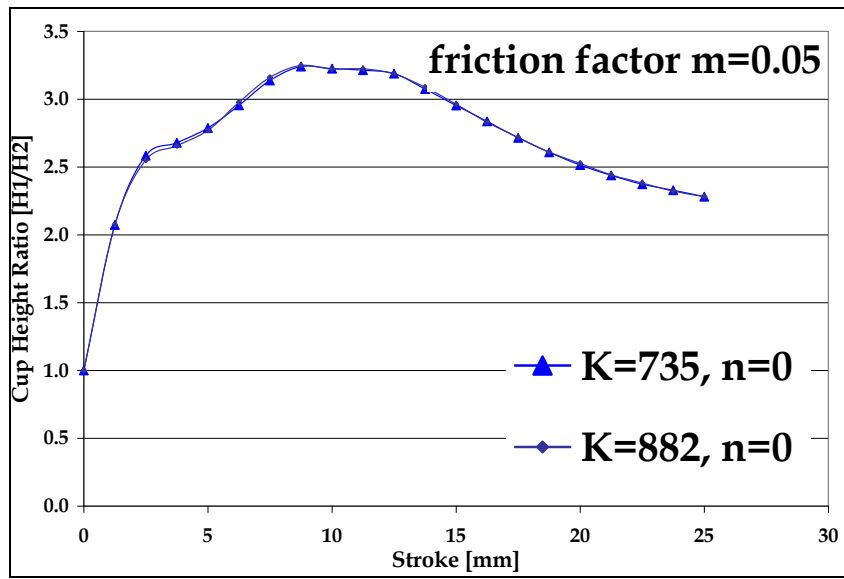


Figure 11: Effect of K-value on the cup height ratio in the DCET using ERC material (Table 2) and process geometry (Table 1).

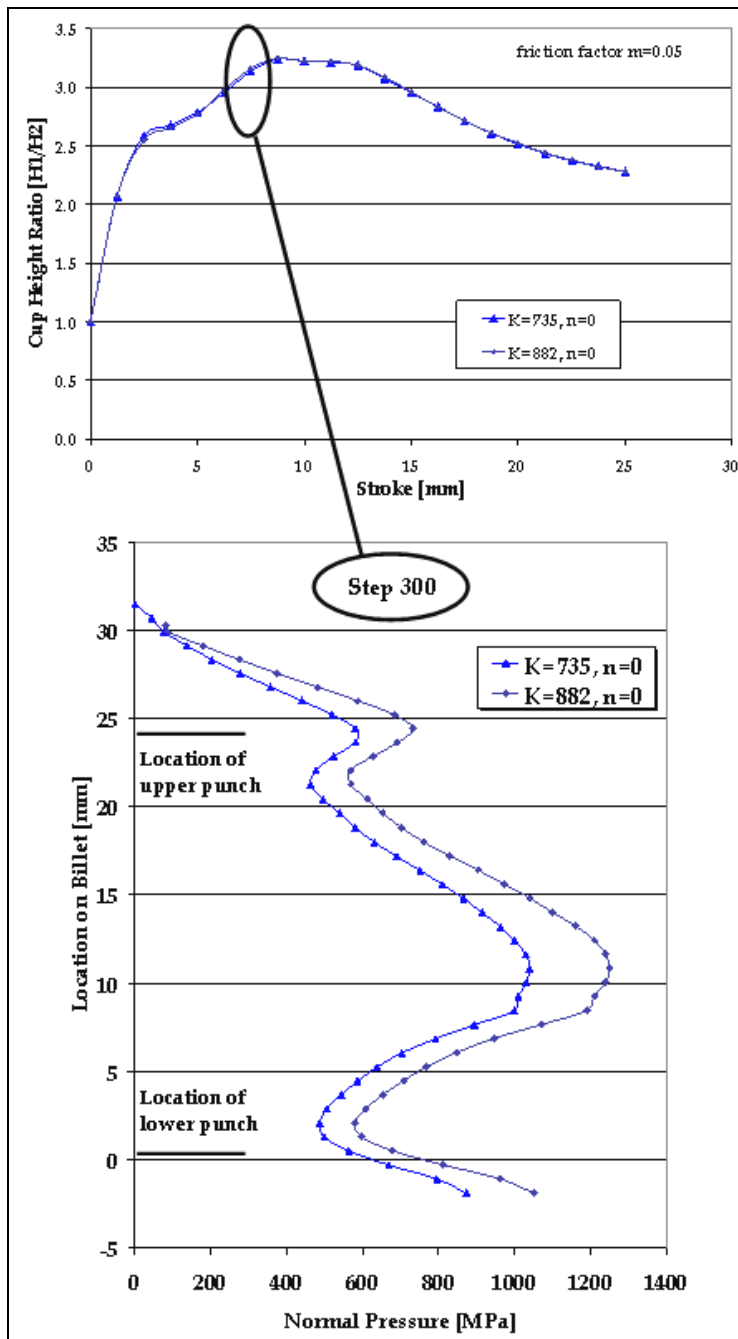


Figure 12: Effect of K-value on normal pressure at the billet/container interface using ERC material (Table 2) and process geometry (Table 1) assuming $n=0$ and $m=0.05$.

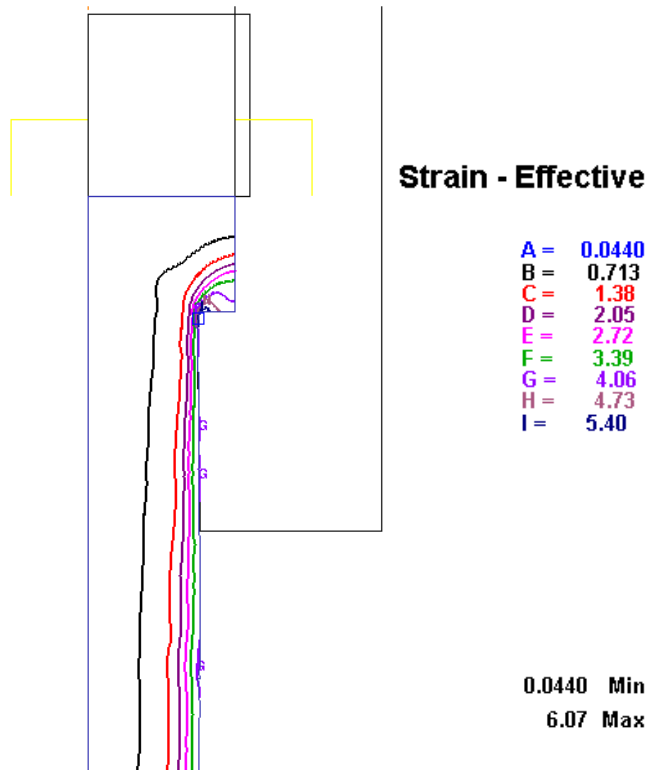


Figure 13: Strain distribution obtained from the simulation of extrusion from \varnothing 40 mm to \varnothing 30 mm.

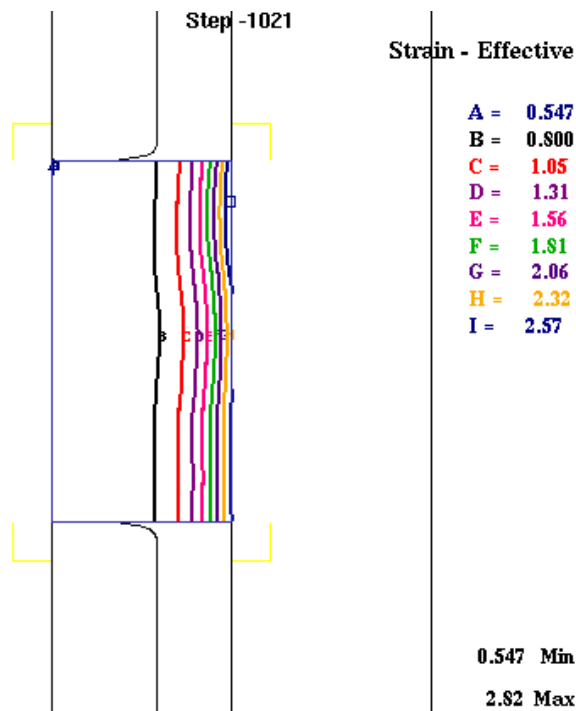


Figure 14: Strain distribution in the billet used in the simulation of the DCET.

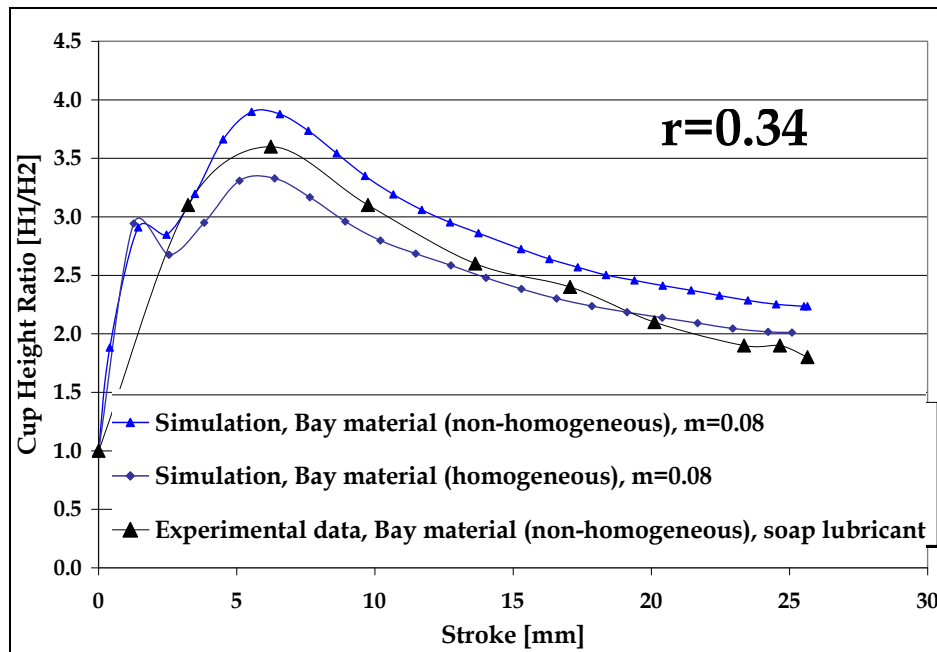


Figure 15: Effect of including a non-homogeneous strain distribution in simulation of the DCET using Bay's material (Table 2) process geometry (Table 3) with $r=0.34$.

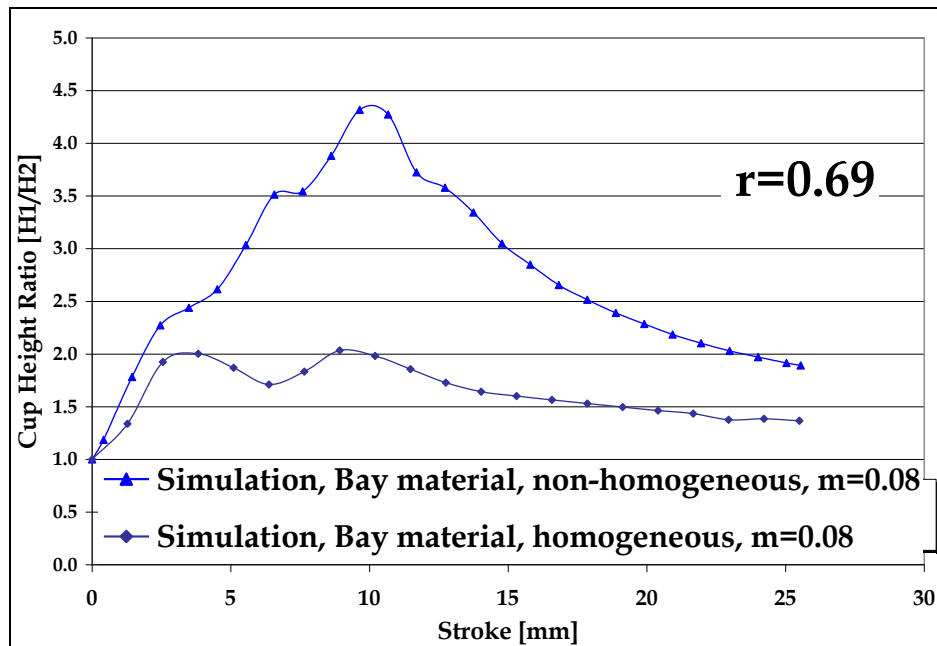


Figure 16: Effect of including a non-homogeneous strain distribution in simulation of the DCET using Bay's material (Table 2) and process geometry (Table 3) with $r=0.69$.

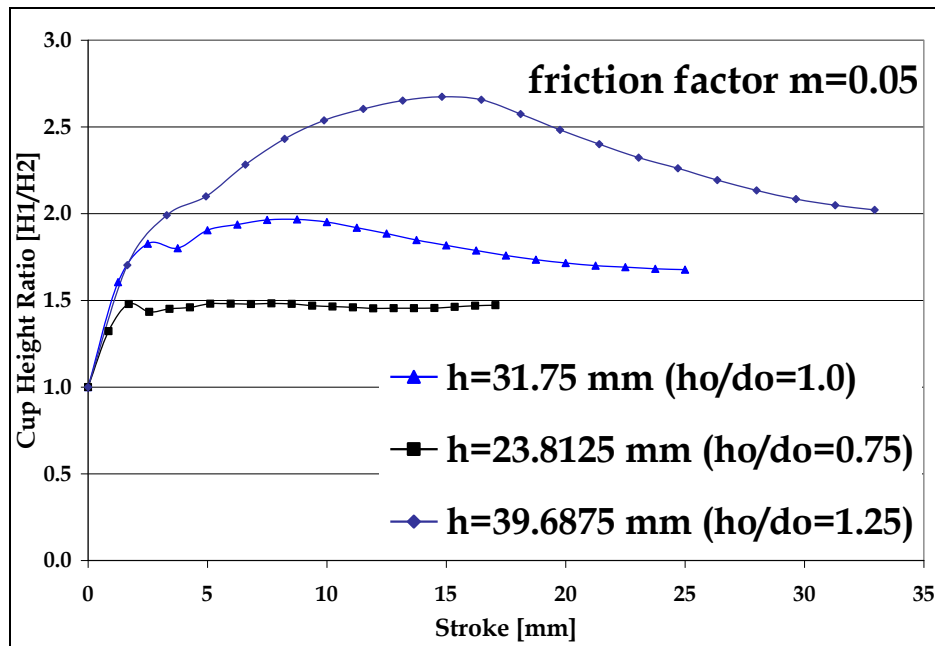


Figure 17: Effect of billet height on cup height ratio curves using ERC material (Table 2) and process geometry (Table 1) and comparing $h_o/d_o=0.75$, 1.0, and 1.25 ($d_o=31.75$ mm).

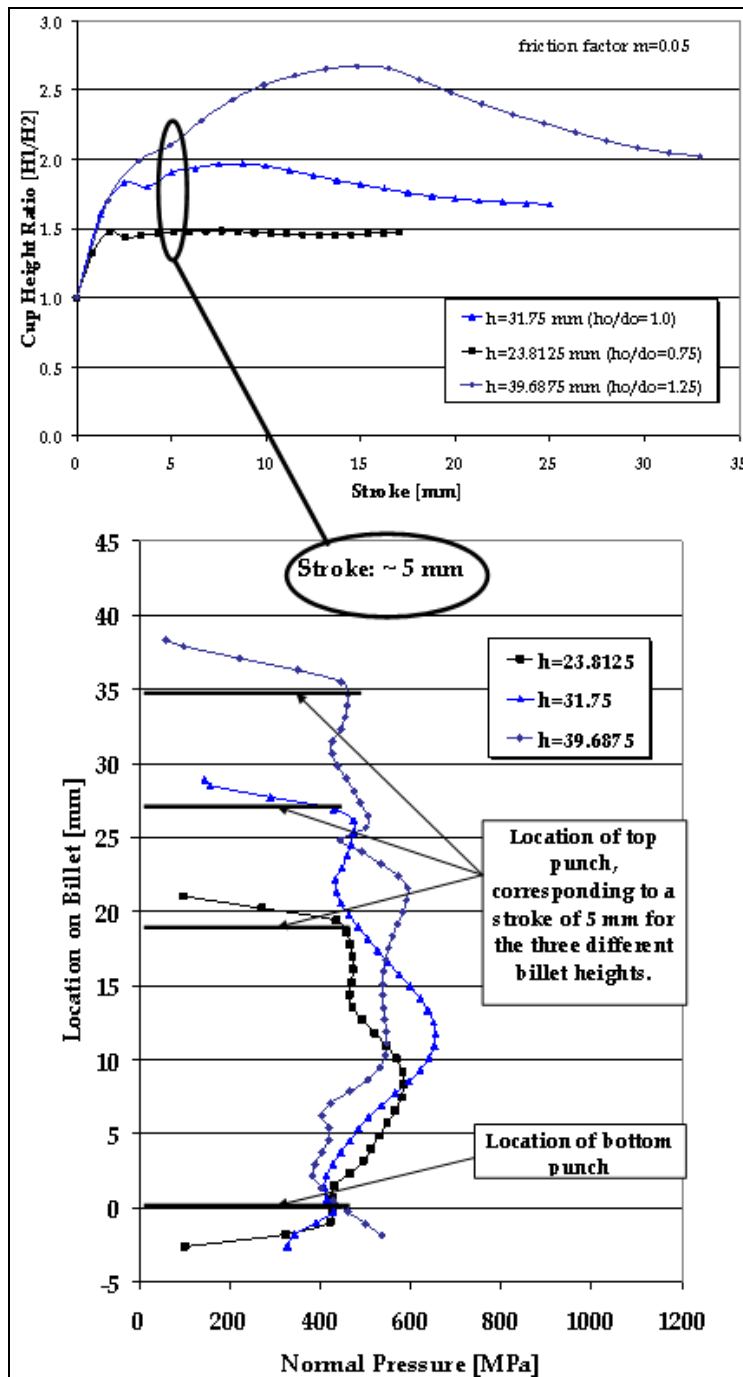


Figure 18: Effect of billet height on normal pressure at the billet/container interface using ERC material (Table 2) and process geometry (Table 1) and $m=0.05$.

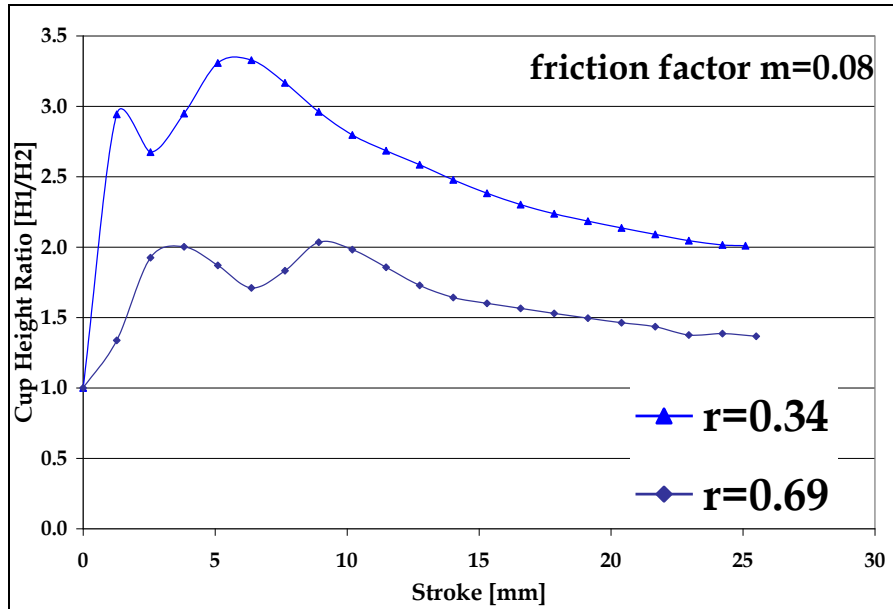


Figure 19: Effect of extrusion ratio on the cup height ratio using Bay's material (Table 2) and process geometry (Table 3) and a friction factor $m=0.08$.

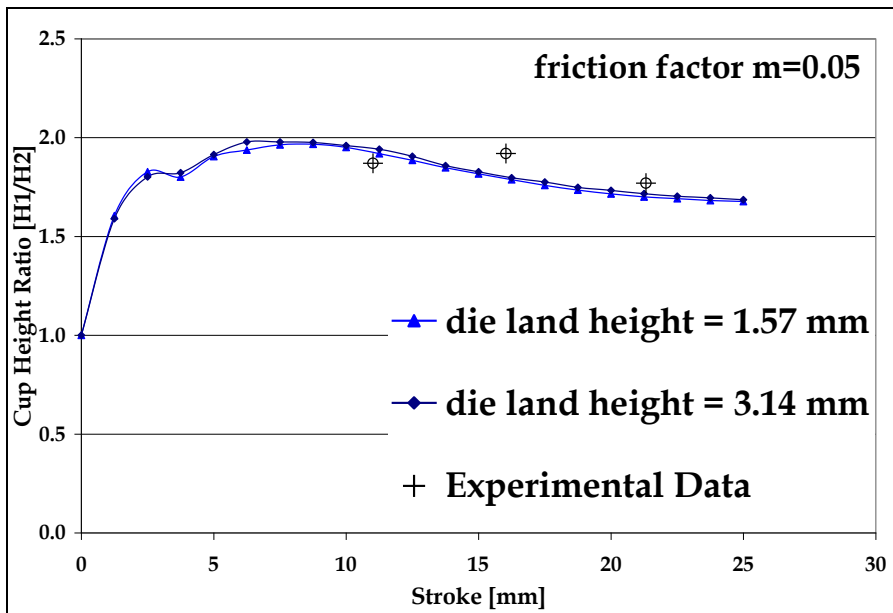


Figure 20: Effect of punch die land on cup height ratio curves using ERC material (Table 2) and process geometry (Table 1).

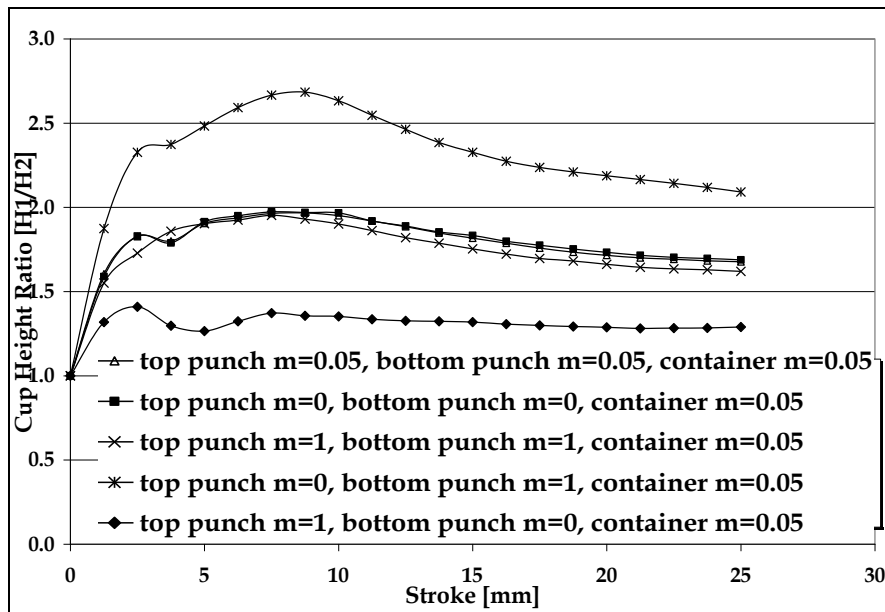


Figure 21: Effect of differing friction on the punches using ERC material (Table 2) and process geometry (Table 1).

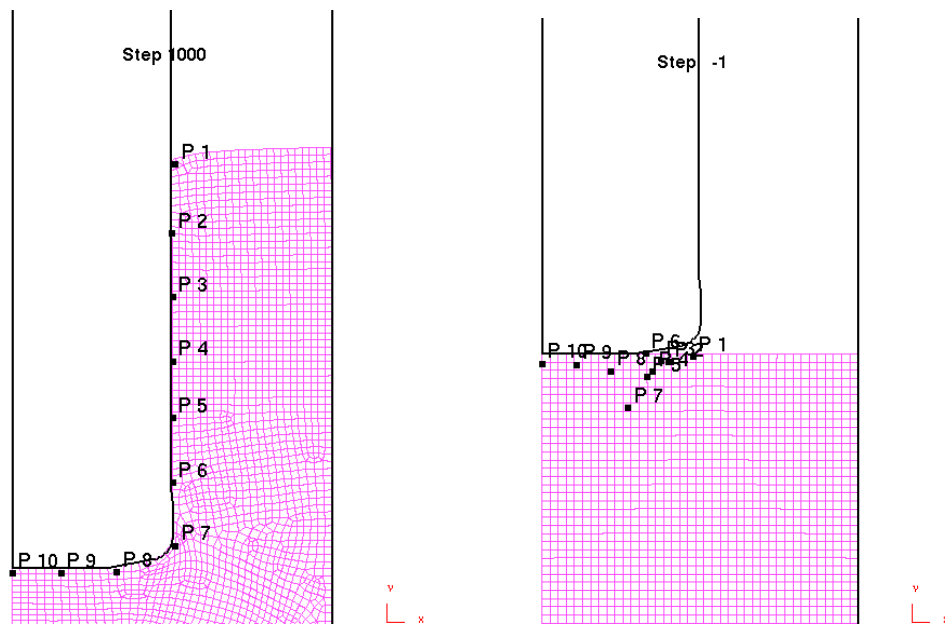


Figure 22: Reverse point tracking showing the origin of the material making up the new surface around the top punch for an extrusion ratio of $r=0.25$ (Full stroke [top] and before testing [bottom]).

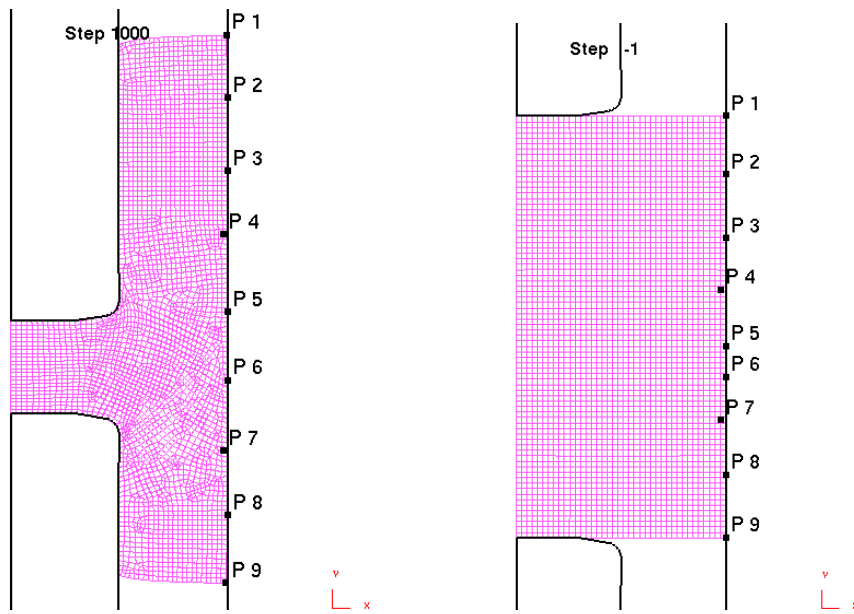


Figure 23: Reverse point tracking showing the origin of the material making up the new surface at the container for an extrusion ratio of $r=0.25$ (Full stroke [top] and before testing [bottom]).