ANALYSIS OF THE DOUBLE CUP EXTRUSION TEST FOR EVALUATION OF 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 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 Figure 1. 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. 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. By matching the cup height ratio and punch stroke obtained from experiments to that obtained from the FE simulations (calibration curves in Figure 2), the friction factor of the lubricants can be obtained.

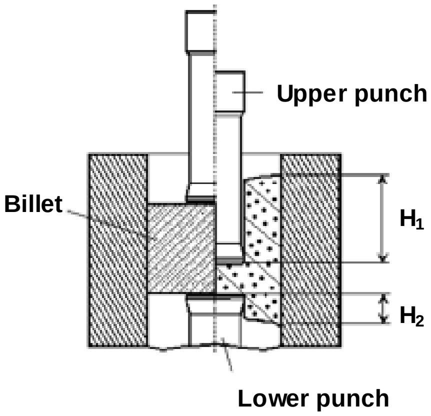

Figure 1: Double cup extrusion test (DCET).

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). The cup height ratio, R, is defined by $R = H_1/H_2$ and the real stroke, S_r, is defined by $S_r = 31.75-(H-H_1-H_2)$ where H is the total height of the extruded cup.

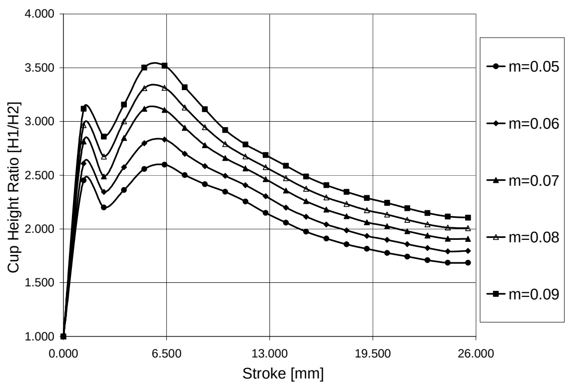

Figure 2: Friction factor calibration curves obtained for AISI 1018 for a specific tool geometry (Table 1).

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 described in Figure 3 and Table 1.

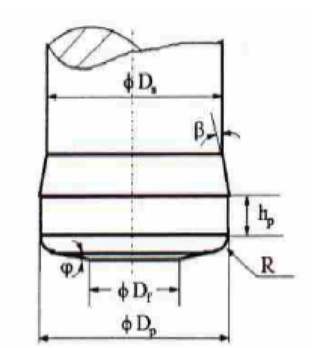

Figure 3: Geometry notation of punches [4].

Table 1: ERC tooling and workpiece geometry.

	Punch							Workpiece		Container
r	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
$\bar{\sigma} = 735\ \bar{\varepsilon}^{0.17}$
Bay's Material: work-hardened AA6082 [4]
K = 191.5 MPa ε_o=0.336   n = 0.12
$\bar{\sigma} = 191.5(0.336 + \bar{\varepsilon})^{0.12}$

In the DCET, the friction on both punches being the same, only the friction along the container wall influences the metal flow by restricting the development of the lower cup and assisting 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 keeping the friction value (m) constant at the container/workpiece interface (m=0.05) but varying it at the punch/workpiece interface (m=0.0, m=0.5 and m=1.0). Figure 4 shows that the difference between the cup height ratios for zero friction at the punches and sticking friction at the punches is very small, ΔR=0.08, which is within the range of measurement error.

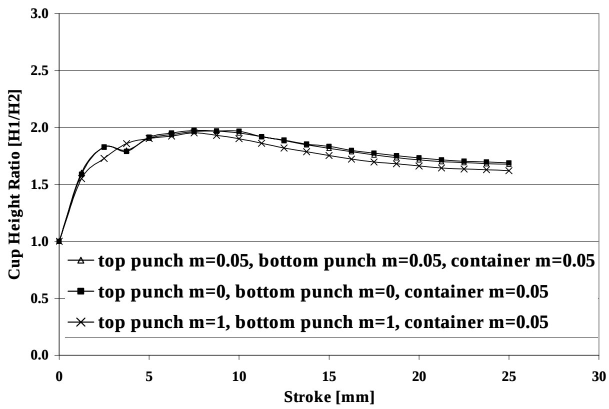

Figure 4: Influence of punch/workpiece interface friction on the cup height ratio curve when friction on both punches is the same (1018 steel).

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 ¼th 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 lubricant performance 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 ($r = d^2_{punch} / d^2_{billet}$), which is close to the minimum recommended in the literature for this test [6]. This 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, the DCET is prone to errors. For example, Figure 5 shows the results of a study where, for both materials the soap performed better at low extrusion ratios (low interface pressures) but worse at high extrusion ratios (high interface pressures) [4].

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.

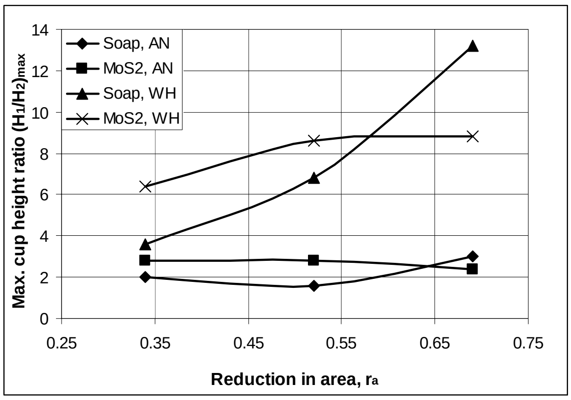

Figure 5: Experimentally measured maximum cup height ratio versus reduction in area (extrusion ratio) for annealed (AN) and work-hardened (WH) AA6082 lubricated with MoS2 and Soap [4].

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 a parametric study of the DCET was conducted using FE simulations. The predictions were compared with experimental data. 1018 steel and work-hardened AA6082 were used in this study because experimental data was available in the ERC and from Bay [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 3.

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

	Punch							Workpiece		Container
r	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 6 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. It can be seen that as the n-value decreases, the cup height ratio increases. The same trend was obtained using Bay's material [4], the work-hardened aluminum alloy AA6082 (Table 2). 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.

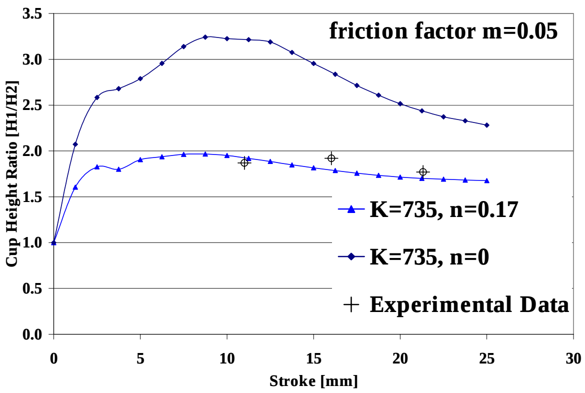

Figure 6: Effect of n-value on cup height ratio in the DCET using ERC material (Table 2) and process geometry (Table 1) with r = 0.25.

It was also observed that a decrease in the n-value causes an increase in the normal pressure at the billet/container interface. The pressure was noted at the point in the punch stroke when maximum pressure at the billet/container interface was observed. The maximum pressure for the steel with an extrusion ratio of r=0.25 was found to be roughly P = 665 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. 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

For this task, the ERC material properties (Table 2) and process geometry (Table 1) were used in the simulation. It was observed that a change in K-value produces no effect on the metal flow. However, an increase in the K-value caused an increase in the normal pressure at the billet/container interface. Therefore, a material with higher K-value results in a 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. The experimental material used in Bay's study was work-hardened by forward rod extrusion from ∅40 mm annealed bars to ∅30 mm at room temperature, then machined to the diameter shown in Table 3. This process was simulated in order to include the non-homogeneous strain distribution in the simulation of the DCET. Thus, a distinct strain gradient exists across the cross-section of the billet with higher strains at the outer radius of the billet than at the center (Figure 7).

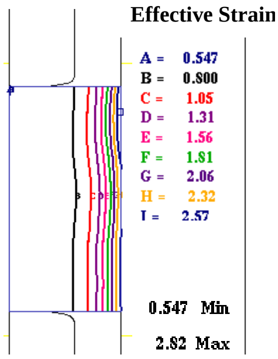

Figure 7: Strain distribution in the billet used in the simulation of the DCET.

For an extrusion ratio of r = 0.34, inclusion of non-homogeneous strain distribution in the billet had a negligible effect, though a slight increase in cup-height ratio was observed. A higher extrusion ratio of 0.69, however, exhibited a significant influence of non-homogeneous strain distribution (Figure 8). Experimental data points are included [4]. With the large extrusion ratio most of the initial deformation takes place in the region where the largest amount of work-hardening is present, at the outer surface of the billet.

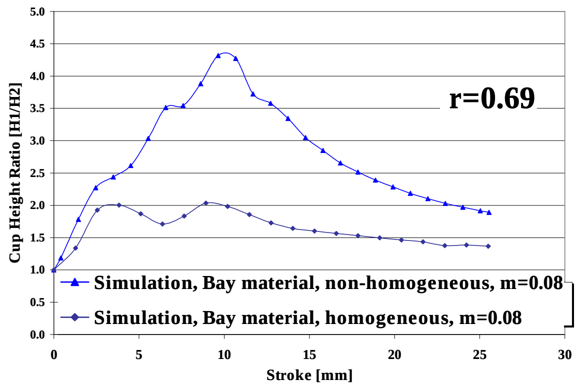

Figure 8: Effect of including a non-homogeneous strain distribution in simulation of the DCET using Bay's material (Table 2) and process geometry (Table 3) with r=0.69.

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 9 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.

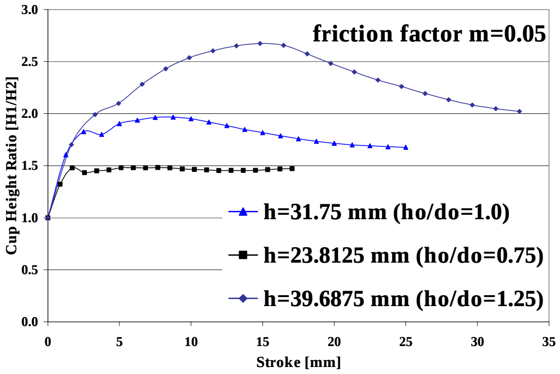

Figure 9: Effect of billet height on cup height ratio curves using ERC material (Table 2) and process geometry (Table 1) and comparing h_o/d_o=0.75, 1.0, and 1.25 (d_o=31.75 mm).

The maximum pressure for billet height h=39.6875 mm (h_o/d_o=1.25) was roughly P=672 MPa (97.4 ksi) and occurred 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) was about P=665 MPa (96.4 ksi), the billet height did 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 10 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 normal pressure at the container-billet interface increases with increasing extrusion ratio with a maximum increase of approximately 70%.

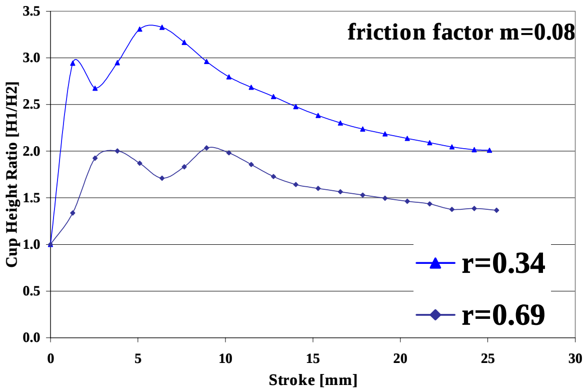

Figure 10: Effect of extrusion ratio on the cup height ratio using Bay's material (Table 2) and process geometry (Table 3) and a friction factor m=0.08.

5.6. *Effect of punch die land*

FE simulations were conducted to study the effect of doubling the punch die land (h_p in Figure 3) 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. Punch die land was not found to influence 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*

Figure 11 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.

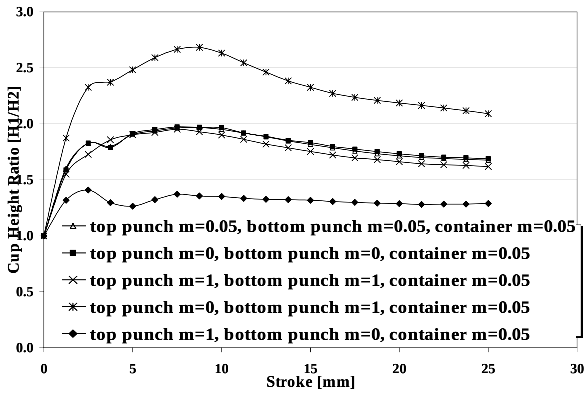

Figure 11: Effect of differing friction on the punches using ERC material (Table 2) and process geometry (Table 1).

6. Surface Generation and Metal Flow in the DCET

The point tracking feature in DEFORM® was used to determine the origin of the material on the cup surface around the punch (Figure 12) and at the container (Figure 13) for extrusion ratios of r = 0.25 and r = 0.69.

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 13).

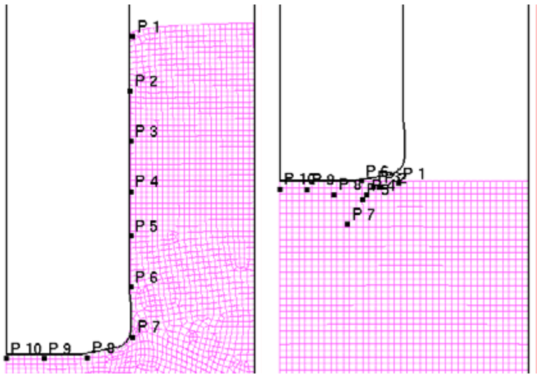

Figure 12: Reverse point tracking showing the origin of the material making up the new surface around the top punch for an extrusion ratio of r=0.25 (Full stroke [left] and before testing [right]).

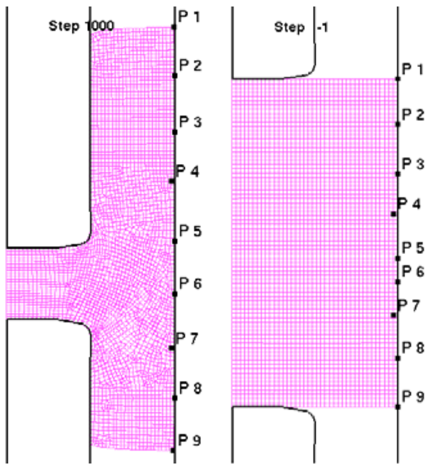

Figure 13: Reverse point tracking showing the origin of the material making up the new surface at the container for an extrusion ratio of r=0.25 (Full stroke [left] and before testing [right]).

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 and material strength coefficient (K value), and with reduction of the strain hardening exponent of the workpiece material (n value).
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 n value
    - inclusion of the non-homogeneous strain distribution of a work-hardened billet
    - increasing the billet height within limits
    - decreasing extrusion ratio, depending on the material. For a material with a) with high n-value, decrease extrusion ratio, and b) with low n-value, the sensitivity might be maintained even with increasing extrusion ratio.

One 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 based on cup height ratio without finding a friction value (since sensitivity is reduced). For the larger extrusion ratio tests simulations would not be needed.

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