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Factors Affecting the Double Cup Extrusion Test for Evaluation of Friction in Cold and Warm Forging

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SUMMARY. The objective of this study is to expand the double cup extrusion test, used for evaluating lubrication in cold forging, to determine the friction factor m and study factors affecting the sensitivity of this test at the same time. An FEM analysis was used to predict metal flow and forming load for different reductions in area, using a fixed billet geometry. Based on this study a procedure is suggested to estimate friction at large effective strains and interface pressures that occur in cold and warm forging, and factors affecting the results of this test are identified.

KEY WORDS: FEM Simulation, Double Cup Extrusion, Friction Test

1. INTRODUCTION

In order to evaluate lubrication in cold forging it is useful to have a test method that represents the actual forging conditions realistically. The well-known ring test has been suggested, investigated and improved by many researchers experimentally and theoretically using different numerical schemes [1-8]. In this test, the amount of strain and new surface generation are relatively small compared with the actual conditions present in cold forging. Thus, the ring test has a limited value in evaluating lubrication in cold forging. Recently, the "bucket" test, which is similar to backward extrusion, has been used with success for lubricant evaluation [5, 7]. Based on experiments conducted by Geiger [9] a new lubrication test, using a double cup extrusion process, has been proposed [10] in the ERC for Net Shape Manufacturing at the Ohio State University.

In the present work further investigation of this test is carried out studying the process parameters which affect the sensitivity of this method with respect to strain hardening and contact area between the tool surface and deforming billet. The theoretical analysis performed at the Ohio State University by the first three authors is compared with experiments carried out by the last two authors at the Technical University of Denmark.

2. DOUBLE CUP EXTRUSION TEST TO DETERMINE FRICTION VALUES IN COLD FORGING

Figure 1(a) [10], shows a schematic outline of the double cup extrusion process. The top punch is moving downwards, while the bottom punch and the container are kept stationary. The cylindrical billet fits into the container bore. In case of zero friction the lower and upper cups develop identically. The presence of friction along the container wall slows down the development of the lower cup and increases the development of the upper one. The difference between the two cup heights increase with increasing friction.

Metal flow in the double cup extrusion, Figure 1(a), is theoretically simulated using the FEM based program DEFORM for various friction factors, m. The extrusion conditions and the geometries investigated are:

1. Container bore diameter, D_c=20.0 mm
2. Billet dimensions : 20 mm in dia. x 20 mm high
3. Top and bottom punch dimensions for three different punches, selected according to Table 1 and with the symbols given in Figure 1(b)
4. The extrusion ratios, $e=D^2{}_p/D^2{}_c$, are
   - $e=0.36$ with $D_p=12$ mm
   - $e=0.46$ with $D_p=14$ mm
   - $e=0.64$ with $D_p=16$ mm

The material selected for FEM simulations is the same as that used in experiments, Al 99.5%. The flow stress, $\bar{\sigma}$, was measured as: $\bar{\sigma}=k\,\bar{\varepsilon}^n$ with $k=160$ N/mm^2 and $n=0.223$.

Table 1. Punch dimensions (equal for top & bottom and recommended by the Int. Cold Forging Group, [11]) used for DEFORM simulations

	set 1	set 2	set 3
D_p [mm]	12.0	14.0	16.0
d_1 [mm]	7.0	8.0	10.0
R [mm]	1.0	1.0	1.0
h [mm]	0.2	0.2	0.2
d_2 [mm]	11.6	13.6	15.6
2α [°]	160.0	160.0	160.0
β [°]	5.0	5.0	5.0

3. THEORETICAL ANALYSIS

The theoretical analysis is based on the rigid-plastic FEM technique. The fundamentals, mathematical formulae, and equations used to develop the computer program DEFORM are given elsewhere [12]. DEFORM is capable of simulating metal flow with rigid-plastic, visco-plastic and porous materials under isothermal and non-isothermal forging conditions.

All analyses were carried out assuming constant friction factor m at the interfaces between billet and punch and container and m was varied between 0.01 and 0.3. From plots of the extruded cups obtained by DEFORM simulations the predicted heights h_1 of the upper and h_2 of the lower cup were measured. Values of the punch force and the mean equivalent stress in the deformation zone were extracted from the data base of DEFORM for various values of the punch stroke.

4. EXPERIMENTAL WORK

In order to obtain good lubrication under well defined conditions three different kinds of solid film lubricating systems were employed:

1. Zincstearate
2. Aluminate coating and alkali soap lubrication
3. Aluminate coating and MoS_2 lubrication

Before lubrication the billets were degreased in an alkaline bath, rinsed in cold water, pickled in a solution of fluoric acid and rinsed in cold water again. After this pretreatment the three different lubricating systems were applied as follows:

Re. 1: The pretreated slugs were tumbled in zincstearate powder. The film weight was controlled to be 5-6 g/m^2 by adjusting the amount of lubricant and the number of slugs when tumbling.

Re. 2: The pretreated slugs were provided with a conversion coating by dipping in an aluminate bath (Zieh Bonder 171) depositing a film of calcium aluminum hydroxide. Bath temperature was 70°C, dipping time 10 minutes. The film weight was controlled by the dipping time and the bath concentration to 7.5 g/m^2. Alkali soap (Bonderlube 235) was applied on top of the conversion coating by dipping 1 minute in a Bonderlube 235 bath, temperature 75°C, dipping time 1 minute. After dipping the lubricated slugs were dried.

Re. 3: The pretreated slugs were provided with the same aluminate conversion coating as in case no.2 and then heated to 100°C, dipped in an aqueous dispersion of MoS_2 with a bath temperature of 75°C, dipping time 30 seconds. After dipping the lubricated slugs were dried.

The extrusion experiments were performed in an 18 tons hydraulic press with tools as described in section 2. Tool material was AISI D2 and the active tool surfaces, contacting the workpiece during testing, were polished with 1 μm diamond paste.

5. RESULTS AND DISCUSSIONS

5-1. Calibration curves for determining friction values in cold forging

Based on the results obtained by the FEM analysis, calibration curves for the specified tool geometries were established for various reduction in areas, e=0.36, e=0.49, and e=0.64, as shown in Figures 2 to 4.

It is clearly seen that the height of the upper cup h_1 is always larger than that of the lower cup h_2 in case of m>0 and that the ratio h_1/h_2 increases with increasing friction factor. This is due to the earlier mentioned influence of container friction on flow. The curves for h_1/h_2 versus the reduction in height for various friction factors show distinct differences even for small variations in friction. The trend of all curves is almost identical in the three sets of curves as shown in Figures 2 to 4, except for the curve B (m=0.3 and e=0.64).

During extrusion the container/cup contact length increases with increasing upper punch stroke. After the material flows to pass the punch land the radial pressure on the container becomes approximately zero. Thus, the friction stress between the cup wall and the container, beyond the punch land, is insignificant and can be neglected.

However, in FEM simulations, a surface "roughness", is generated by the computation along the inner cup surface, as seen in Figures 5, 6(a) & 6(b). This causes an unrealistic contact condition between the punch/cup and the container/cup interfaces. In order to avoid this problem the container wall has to be continuously varied (or the punch shank diameter reduced), allowing tool/workpiece contact only in the region between the upper and lower punches. This is a time consuming procedure to carry out in the FEM analysis because the simulation has to be interrupted and the die shape adjusted at short steps of the stroke. A simpler procedure would be to assume a contact length equal to the initial height of the billet by "tilting" the container wall a few degrees just behind the upper and lower punch lands. This has been done for the simulation results shown in Figure 6(c) and 7. The corresponding calibration curve A (m=0.30, e=0.64) is shown in Figure 4.

In Figure 4, the differences between the dotted curves and the solid curves are significant only for m=0.30. When examined in detail, Figure 8 (m=0.08, e=0.64) shows that the inner cup wall is very smooth and does not touch the punch shank surface. For lower reductions in area (e=0.36 and 0.49) the cup height error caused by the surface "roughness" was insignificant. Therefore, the calibration curves shown in Figure 2 and 3 were generated without modification of the straight container wall.

5-2. Comparison of predictions with experimental data

From Figures 2 and 3 it is seen that the calibration curves agree well with the experimental results for the different lubricant systems investigated. Thus, the assumption of constant friction factor seems to be correct. This is reasonable since a solid film lubricant system was employed in every case.

For larger reductions in area, however, the agreement is worse and this goes for low friction (zincstearate) as well as high friction (MoS_2). For zincstearate coatings with the reduction in area e=0.64, Figure 4, the friction factor increases with the reduction in height unlike the results obtained for low reductions in area as shown in Figures 2 and 3. This may be due to the effect of thinning of the lubricant film in both upper and lower cups. The same trend is not observed in case of MoS_2 but with both lubricant systems the friction factor estimated for e=0.64 is larger than that estimated for e=0.36 and e=0.46 (compare Figure 4 with Figures 2 and 3). Thus, the theory predicts higher values of the friction factor for larger reductions in area. This may be explained either by the deterioration of the coating due to higher interface pressure and larger surface expansion at higher reductions in area or by the influence of the normal pressure on the shear strength of the lubricant film.

For very small reductions in height, deviation of the experimental results from the calibration curves occurs for all three reductions in area investigated, Figures 2-4. This may be explained by inaccuracies in measurement of the cup heights. Due to their small size in this initial phase errors in measurements will have a large influence on the estimated cup height ratio.

5-3. Variables affecting performance of the double cup extrusion friction test

The simulations, given in Figures 5 and 8, (using a straight container wall, e=0.64, n=0.223, m=0.30 & 0.08) show that as the friction value m increases, the material rises faster in the upper cup portion, particularly in the early and intermediate punch strokes. As the process proceeds, the rate of flow into the lower cup becomes larger. This is probably due to: (a) the increase of forces due to the current surface friction on the material in the upper cup and (b) the high strain hardening experienced in the upper cup. Both these effects retard the material movement into the lower cup direction. The effective stress distributions, Figure 7, show that the magnitude of stresses in the bottom corner of the upper cup is growing faster compared with the same region of the lower cup. This seems to indicate that due to growing resistance against flow into the upper cup, metal flows easily downward into the lower cup. This phenomenon, however, needs further investigation so that a definite conclusion can be made.

The comparison of Figures 6 (a) and (b) shows that the upper cup rises rapidly compared to the lower cup for the imaginary material with very low strain hardening index (n=0.001). This again, seems to support the observation made above.

Figure 9 illustrates that the ratio h_1/h_2 is very sensitive to reduction in area, e, [10] for e<0.50. However, smaller reductions in area, less than 0.25, may cause bending or failure of the punch. Furthermore, the radial pressure on the container wall would be very small, thereby making the test unsuitable as a friction test for cold forging. It is clearly seen in Figure 10 that the punch pressure decreases as the reduction in area increases up to about 0.55. In order to minimize the stresses in the punch a reduction in area of this range would be beneficial.

6. SUMMARY AND RECOMMENDATIONS

In this paper, an analysis of the double cup extrusion test has been conducted, using the FEM based program DEFORM. The effect of different friction factors and reductions in area upon the ratio of upper and lower cup heights, h_1/h_2, have been studied. Comparisons with experimental results demonstrated the capability of the established technique for evaluating friction conditions qualitatively as well as quantitatively. Three sets of calibration curves for evaluating friction conditions have been established for three different reductions in area.

Reasonable agreement was obtained between the predictions and experimental results. However, significant deviations between FEM simulations and experimental data were observed for the high reduction in area, e=0.64, with larger friction factors (m=0.3). The main cause of this error was the assumed unrealistic contact condition between the cup walls and the tooling, especially for the cases with higher friction values and higher reductions in area.

The solid curves in Figure 4 illustrate that calibration curves can be improved by assuming a tapered container wall or a smaller punch shank diameter in FEM simulations. Even with a straight container wall and unrealistic interface conditions the curves show reasonable trends for higher reductions in area with low m values or for lower reductions in area with high m values.

The strain hardening of the material appears to be another factor that influences metal flow in this test because the strains increase at the corners of the upper punch area more than they increase at the corresponding areas close to the lower punch. This observation, however, needs a more detailed study.

This work helped to determine the useful range of reductions in area (corresponding to the maximum sensitivity to friction) for the practical range of friction (m=0.08 to 0.3). However, further investigations should be conducted to evaluate the punch geometry in order to optimize its design with respect to the metal flow behavior and punch load. Furthermore, the evaluation of the process conditions by computer simulations would be more accurate if the variation of friction during the test could be considered.

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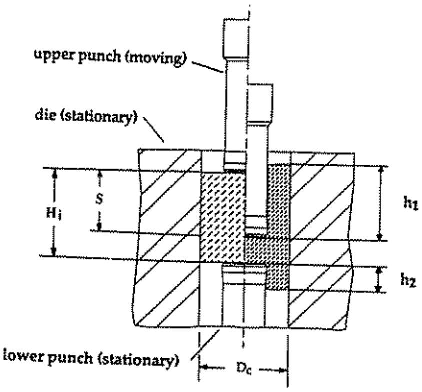

Fig. 1 (a) Double cup extrusion

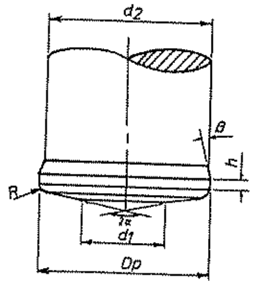

Fig. 1 (b) Punch geometry details

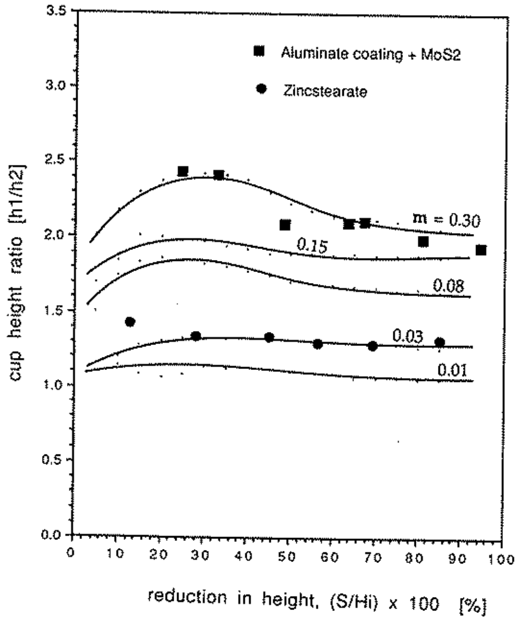

Fig.2 Comparison between predicted and measured cup height ratios h_1/h_2 vs reduction in height (reduction in area e=0.36; initial billet size=20 mm dia. x 20 mm high; billet material: Al 99.5%)-A straight container wall was assumed in FEM simulations.

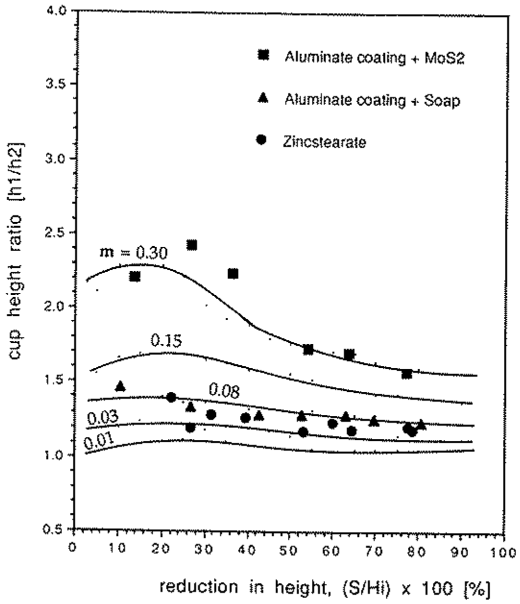

Fig.3 Comparison between predicted and measured cup height ratios h_1/h_2 vs reduction in height (reduction in area e=0.49; initial billet size=20 mm dia. x 20 mm high; billet material: Al 99.5%)-A straight container wall was assumed in FEM simulations.

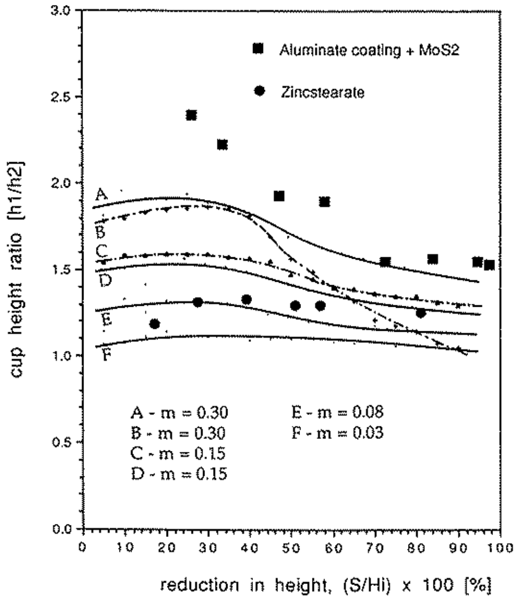

Fig.4 Comparison between predicted and measured cup height ratios h_1/h_2 vs reduction in height (reduction in area e=0.64; initial billet size=20 mm dia. x 20 mm high; billet material: Al 99.5%)-A tapered container wall was assumed for curves A, D, E, F and a straight wall was assumed for curves B & C.

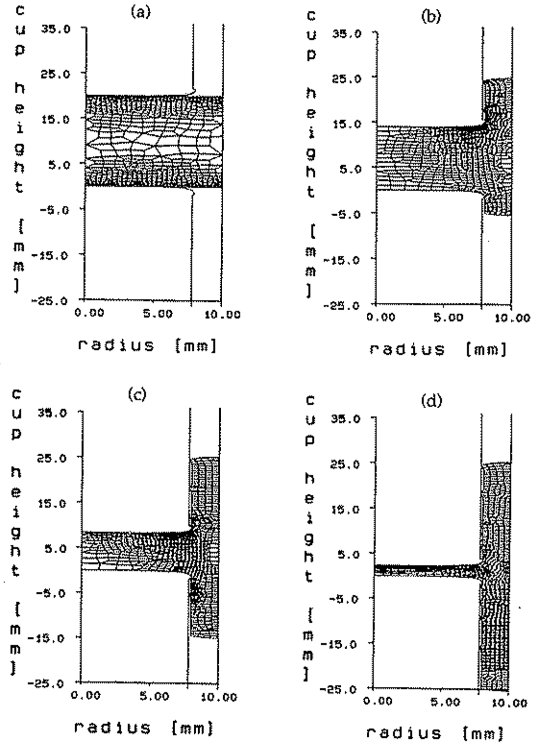

Fig.5 FEM simulations for various reductions in height: (a) 0 %; (b) 30 %; (c) 60 %; (d) 90 % (reduction in area e=0.64; friction factor m=0.30; initial billet size=20 mm dia. x 20 mm high; straight container wall)

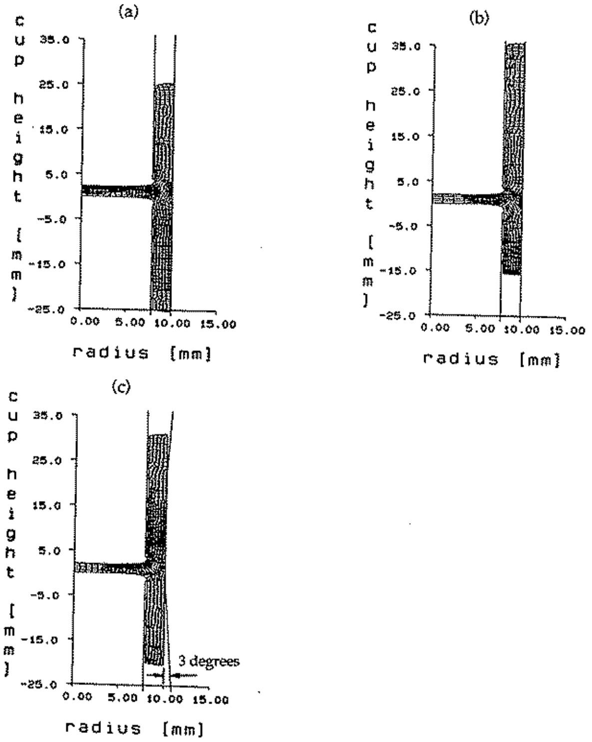

Fig.6 FEM simulations for materials with different strain hardening coefficients n ($\bar{\sigma}=k\,\bar{\varepsilon}^n$): (a) n=0.223; (b) n=0.001; (c) n=0.223 with tapered container wall (reduction in height 90 %; reduction in area e=0.64; friction factor m=0.30)

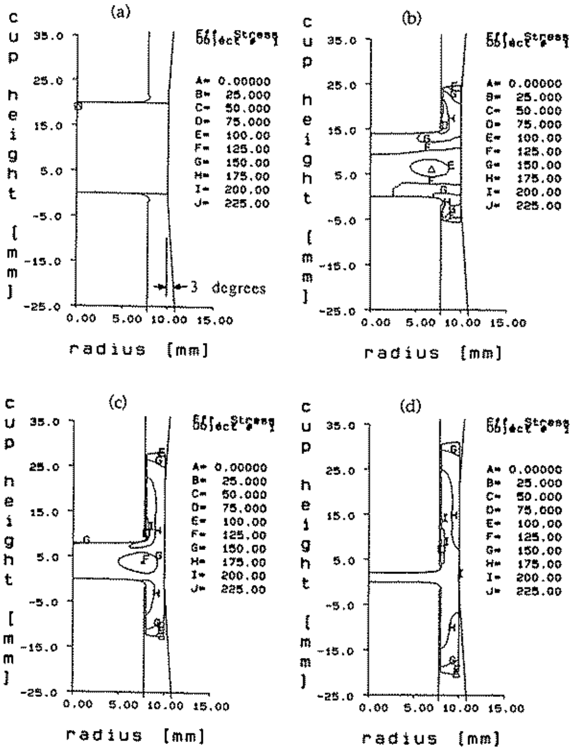

Fig.7 Effective stress distributions for various reductions in height: (a) 0 %; (b) 30 %; (c) 60 %; (d) 90 % (reduction in area e=0.64; friction value m=0.30; tapered container wall)

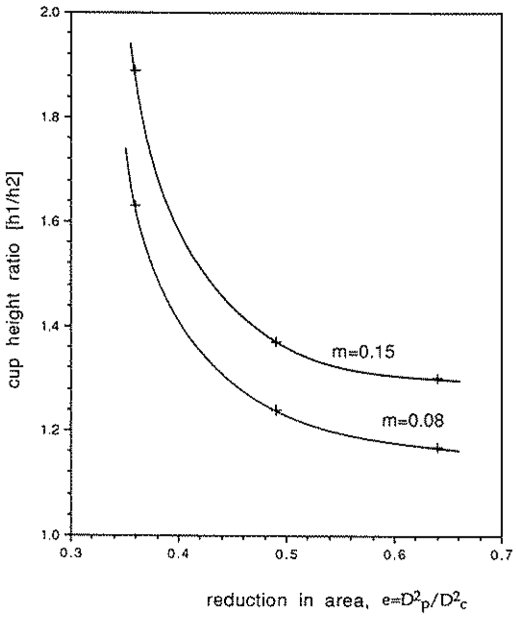

Fig.9 Relationship between cup height ratio and reduction in area for 90% reduction in height

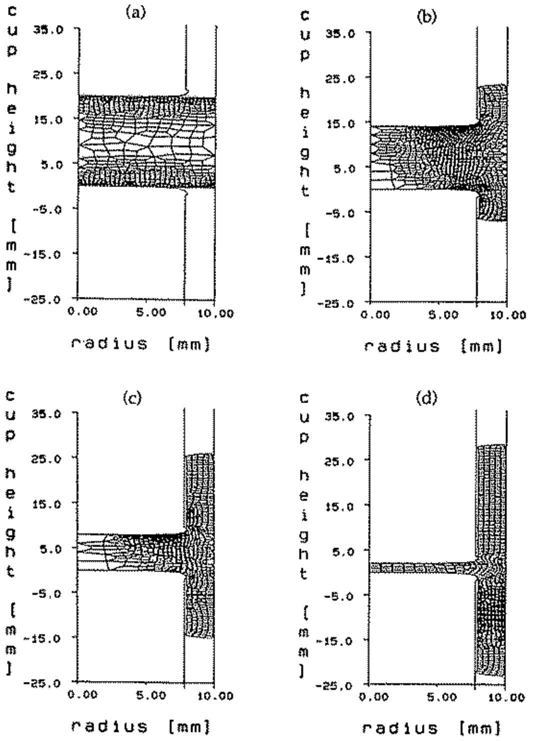

Fig.8 FEM simulations for various reductions in height: (a) 0 %; (b) 30 %; (c) 60 %; (d) 90 % (reduction in area e=0.64; friction factor m=0.08; initial billet size=20 mm dia. x 20 mm high; straight container wall; curve E in Figure 4)

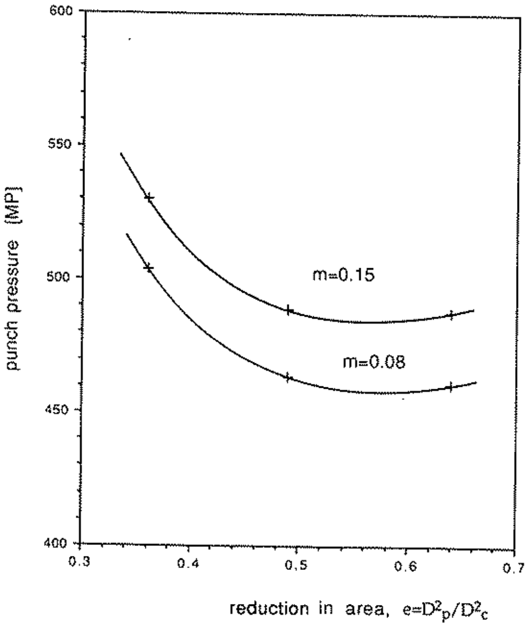

Fig.10 Relationship between punch pressure and reduction in area for 90% reduction in height