EXPLORING EFFICIENCY OF TOOL COATING VIA DEEP DRAWING OF CYLINDRICAL CUPS

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Abstract

The present investigation was set up to examine both predicted and experimental values of forces, power, press work and friction in drawing cups from low carbon steel blanks using the same die set but in different uncoated and TiN coated conditions. The results showed a good agreement between predicted and experimental values. In addition, the findings demonstrated that the TiN coated tools reduced the friction at a tool – blank – die – interface (by about 5%), which in turn reduced the forces, power and work (by about 7%) and improved the final product quality, when compared to the performance of uncoated tools..

Keywords:

Deep drawing, cylindrical cups, tool geometry, tool surface treatment, steel blanks, forces, work, power, friction, product quality

1. Introduction

Drawing is a metal forming operation successful in production of cylindrical hollow cups from blanks. It involves a circular blank that is formed, simultaneously, over a punch and a die profile radius by stretching and drawing [Audy 2003]. A stress ring is used to apply some pressure to the blank in order to prevent it from wrinkling and buckling. This requires an extra attention to detail. It is because if the pressure is too high the reductions in blank thickness are excessive and the material may tear. When insufficient pressure is applied, the material enters the die cavity too fast. It is not stretched enough and when it reaches the die cavity there is not enough clearance between the punch and the die. Because of this, the thickness of material is reduced by ironing when dragging it against the side of the die as component travels in the direction of the punch. As a result the drawing forces increase, the component quality is poor, and the die life is reduced due to scratching, micro-welding and localised heating effects at the die cavity – work piece material – and punch interfaces. In seeking improved deep drawing performance, researchers and manufacturers have made significant advances through the modification of die-punch geometry and advanced coatings. The selection of compromise geometrical features for die-sets and punches has resulted in setting up the limits to the radii of punch corners, radii of die entries, depth of draw and reductions in blank diameters achievable, if tearing of the material is to be avoided [Maj 1997 and 2000]. With respect to coatings previous empirical studies on metal drawing [Audy 2003] and metal forming [Lemon 1999] have shown that TiN coated forming tools were more efficient than uncoated tools [Audy 2003] and hard chrome plated tools [Lemon 1999]. Audy [2002] studied the influence of hard coatings on the performance of industrial tools employed in practical machining and forming operations. His work suggested that the hardness and chemical stability of coatings have been identified among the most desirable properties, since this would lead to reduced tool wear and increased tool life. With respect to metal forming operations, the TiN coated tools were reported [Lemon 1999] to provide about 70% tool life increase for about 14% cost increase compared to uncoated tools. Most recently market offers a large variety of single and multi-layer surface coatings, each claiming to significantly improve the technological performance measures such as increased tool-life, and reduced forces and power. Much of the reported information appears to be descriptive and qualitative, leaving the many 'hard decisions' to the users and customers. Further research aimed at providing reliable quantitative evidence of improvements in forming performance for each and every coating available in the market is clearly required.

Consequently, this study involved investigations of efficiency of TiN coated tools in deep drawing cylindrical cups from steel blanks. It looked at predicted and experimentally measured technological performance measures such as forces, power and press work. Uncoated die-set and punch were also included in the study for comparison.

2. Experimental Details

A type Ruwolt – 50 tonnes – hydraulic press was employed to carry out the experimental investigations. It was equipped with a die-tool set specially designed for deep drawing operations. Relevant drawing tooling set up showing the position of tools and work piece blank materials including photographs of the actual stress ring and the die are shown in Figure 1.

The deep drawing experimental set up (i.e. the actual experimental arrangement) for the force, power and work tests is shown in Figure 2. The press was equipped with a load cell for force measurements and a linear voltage displacement transducer (LVDT) for stroke measurements. A computer was used to record and plot the out put data. The intended blank diameter, D and the thickness, t, values were 60 mm and 1 mm, respectively. The actual value of the blank diameter was $59.99^{\pm 0.005}$ mm. The work-piece material flow stress data were: K=716 MPa; n=0.22; $R_m=\sigma_t=824$ MPa. The relevant values of actual experimental die set / tool geometrical features are shown in Table 1.

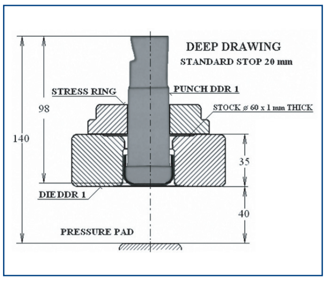

Figure 1. *The experimental cup forming set-up showing the actual position of drawing tools and blank material*

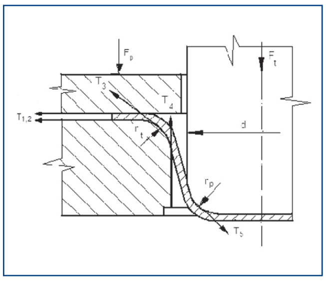

Figure 3. *A sketch showing friction forces in conventional deep drawing process*

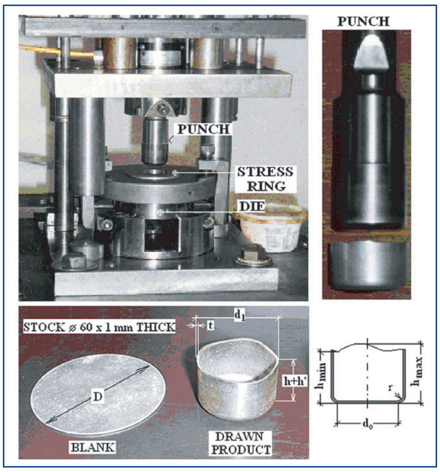

Figure 2. *General experimental arrangement for cup forming tests showing the die-set with tools; drawing punch and drawn product; including both the blank and the drawn product with their key dimensional features.*

Table 1. Geometrical data of tools employed in the deep drawing experiments				
Punch diameter [mm]	Punch corner radius [mm]	Mid-corner radius [mm]	Die entry radius [mm]	Angle of radial stress at die entry, α [°]
32.88	5	5.5	3	90

In order to prevent the blank from tearing the actual dimension of the drawn cups was chosen in a way that the experimental drawing ratio *m* (= punch diameter divided by the blank diameter) were higher than the minimum allowed limiting ratio for ductile materials [Maj 1997 and 2000]. In this experiment the initial ratio of blank thickness to blank diameter was 1.67 (=100*t*/*D* or 100/60). It was lower that 2 and higher than 1.5 *i.e.* it fit nicely into the range for which the literature sources [Maj 1997 and 2000] recommended the minimum allowed limit of 0.48 for the punch diameter versus blank diameter drawing ratio, *m*. The actual limit, *m*, was 0.55 (*i.e.* 32.88/59.99) which confirmed that the blank would be able to sustain drawing forces and pressure without tearing.

The tools were tested firstly in uncoated conditions and then in TiN coated conditions. The coating was deposited by a physical vapour cathodic arc system. With reference to source [Audy 2003] the base pressure in the coating chamber was $5x10^{-3}$ Pa; the tool substrate material was argon ion etched at a pressure of 5Pa and a bias voltage of -1kV; the metal ion etching was conducted at a bias voltage of -800V; the actual TiN was deposited as a single layer (up to a thickness of ~1μm) using a substrate bias voltage of –100 V and a chamber pressure of $5x10^{-1}$ Pa.

3. Results and Discussion

Predicted Values

Prior conducting the actual experimental test it was decided to calculate (predict) the height of the cup, and various performance measures such as stresses, forces, the friction coefficient. Conservation of volume was assumed in this experiment, and the examples of calculations are shown in Equations 1 to 8, below.

Area of blanks:

$$A = \frac{\pi.(D)^2}{4} = \frac{\pi.59.99^2}{4} = 2826mm^2 \quad (1)$$

Area of cup:

$$A = \pi.d(h+h') + 2\pi r^2 + \frac{\pi^2.r.d_o}{2} + \frac{\pi.(d_o^2)}{4}$$
$$A = \pi.34.04(21.63) + 2\pi(5^2) + \frac{\pi^2(5).(33.72)}{2} + \frac{\pi.(33.72^2)}{4} = 4334.8mm^2 \quad (2)$$

Base diameter of cup:

$$d_o = d_1 - 2.(r_{mid.corner}) = 34.04 - 2(5.5) = 23.04mm \quad (3)$$

Height of cup:

$$h + h' = \frac{D^2 - 8r^2 - 2\pi.r.d_o - d_o^2}{4d} =$$
$$h + h' = \frac{59.99^2 - 8.(5.5^2) - 2\pi.(5.5)(23.04) - (23.04^2)}{4.(34.04)} = 19.69mm \quad (4)$$

After 10% trim *h* = 17.72 mm

Strain:

$$\varepsilon = \frac{1}{2}\ln\left(\frac{D}{d_1}\right) = \frac{1}{2}\ln\left(\frac{59.99}{34.04}\right) = 0.2833 \quad (5)$$

Flow stress:

$$\sigma_f = k\varepsilon^n = 716.(0.2833)^{0.22} = 542MPa \quad (6)$$

Estimated applied force:

$$F_{applied} = \pi.d_1.t.\sigma_f.\ln\left(\frac{D}{d_1}\right).\sin\alpha$$
$$F_{applied} = \pi.(34.04).(1).(542).\ln\left(\frac{59.99}{34.04}\right).\sin 90 = 32.8kN \quad (7)$$

Estimated Work:

$$W = Forcexstroke = 32.8kN.x9.69mm. = 647kNm \quad (8)$$

The literature source [Streefland 2000] suggests calculating the friction coefficient from experimental – cup test – results using Equation 9.

$$f = \frac{F_{tc2,ref} - F_{tc1,ref}}{2(F_{p2\cdot ref} - F_{p1\cdot ref})} \quad (9)$$

Where $F_{tc2,ref}$ is the drawing force with respect to the holding force F_{p2} and the reference materials of both the die and the blank. The $F_{t1,ref}$ represents the drawing force associated with the holding force F_{p1} including the reference material of both the punch and the blank. It needs to be noted that $F_{p1ref} < F_{p2ref.}$ This mutual relationship is dictated by simplified assumtions that do not include friction along the die. Hrivnak and Evin [Hrivnak 2000] developed Equation 10 for calculating the friction coefficient from the total drawing force. The latter contains following components, see Figure 3 [Hrivnak 2000].

$$F_{t\max} = (F_{i\max} + T_1 + T_2 + T_3 + T_4 + F_O).\sin\vartheta \quad (10)$$

Where F_{imax} represents a component of the drawing force required for deforming the blank *i.e.* the deformation resistance of the blank material. The symbols T_1 and T_2 represent friction forces between the blank, the blank holder and the die. The T_3 is the friction force at the die radius. The T_4 is the friction force inside the die cavity, while T_0 is the bending force and υ is the angle (for radial stress) at the die entry, α=90°.

The force components required to deal with the friction at the blank – die – punch – blank holder interfaces, Figure 3, can be calculated using Equation 11.

$$(T_1 + T_2) = T_{12} = (f_1 + f_2).F_p = 2.f_{12}.F_p \quad (11)$$

It needs to be noted that under optimum drawing conditions the holding force (k_p ≈ 0,1 ÷ 0,2). The friction coefficients of the actual drawing force are responsible for about 5 percentages of the total drawing force. The friction force component T_3 is needed for overcaming the friction along the die radius, and it can be calculated using Equation 12.

$$T_3 = (F_t - F) = F.(e^{\vartheta.f_3} - 1) \quad (12)$$

Generally, in the deep drawing process the friction coefficient $f = f_1 = f_2 = f_3$. The angle for radial stress υ, at the maximum drawing force, is equal to υ ≅ π/2 and T_4 ≅ 0 and, when considering a reasonable large drawing distance . Consequently, the maximum drawing force can be calculated using Equation 13.

$$F_{t\max} = (F_{id\max} + T_{12}) + (F_{id\max} - T_{12}).(e^{f.\pi/2} - 1) + F_o = F_{id\max}.(1 + 2.k_p.f)e^{f.\frac{\pi}{2}} + F_o \quad (13)$$

The friction coefficent can then be calculated from the drawing force components, F_{tc2} and F_{tc1}, see Equation 14.

$$F_{tc2} - F_{tc1} = \Delta T = (F_{id} + 2.f_{12}.q_p.F_{p1} - F_{id} - 2f_{12}.F_{p1})e^{\vartheta f3} \quad (14)$$

Consequently, for υ =90° and , it is possible to carry out further modifications, see Equation 15.

$$f.e^{1,57.f} = \frac{F_{tc2} - F_{tc1}}{2(F_{p2} - F_{p1})} \quad (15)$$

Figure 4 shows a plot of $f.e^{1,57.f}$ against friction force f calculated by both Fourier transformation and regression analyses.

From analyses in Figure 4 it appears that if one emplys the Fourier transformation for unfolding the $e^{1,57.f}$ on the left side of Equation 15 in the following way ... $e^{1,57.f}$ =1+1,16.f, then, for the friction values f_3 ≤ 0,1, the differences between $e^{\alpha.f_3}$ and $1+1,16.f_3$ are

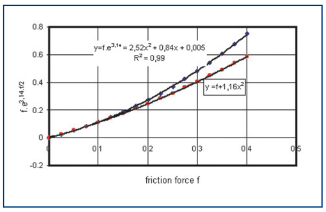

Figure 4. *shows a plot of* $f.e^{1,57.f}$ *against friction force f calculated by both Fourier transformation and regression analyses.*

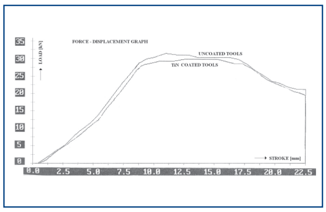

Figure 5. *An example of experimental load/stroke out puts showing 'qualitative' comparison for forces and work generated by the same tool set employed, in both uncoated and TiN coated conditions, in drawing a Type 1010 steel blank work-piece materials.*

negligible. However, for the friction values $f_3 > 0,1$ these differences are quite large – ranging from about 5 % to about 20 %. In order to achieve better correlation and to simplify the equations involved in calculations of the friction coefficient it was decided to solve the $f_1 e^{\nu.f_3}$, on the left side of Equation 15, using regresion analysis, shown in Equation 16.

$$y = 2{,}523.x^2 + 0{,}8399.x + 0{,}0047 \qquad (16)$$

The results of Equation 16 are roots x_{12}, in Equation 17.

$$x_{12} = \frac{-b \pm \sqrt{D}}{2a} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \qquad (17)$$

Subtitution of these results into Equation 15 for the die and blank reference materials will yield the following Equation 18.

$$y = 2{,}523.f^2 + 0{,}8399.f + 0{,}0047 - \frac{F_{tc2,ref.} - F_{tc1,ref.}}{2(F_{p2,ref} - F_{p1,ref})} \qquad (18)$$

Consequently, the friction coefficient can be calculated using Equation 19.

$$f = \frac{-0{,}8399 \pm \sqrt{0{,}8399^2 - 4.2{,}523.\left(0{,}0047 - \frac{F_{tc2,ref} - F_{tc1,ref}}{2(F_{p2,ref} - F_{p1,ref})}\right)}}{2.2{,}523} \qquad (19)$$

Table 2 shows the values of friction coefficients (calculated from Equations 9 and 19) for five different holding forces of 2, 5, 10, 20 and 30 kN, and a Type DC 04; DX 54 D; and DIN 1.4301 – CrNi reference tool materials in uncoated conditions.

Table 2. Experimental forces and calculated friction coefficents for different tool materials

Reference materials	FERROCOAT						
	Holding force F_N [kN]	2	5	10	20	30	Average value
DC 04	Drawing Force Ft [kN]	20.08	20,65	21,60	23,50	25,40	NA
	Friction coefficient, from Eq. (9), f(9)		0,095	0,095	0,095	0,095	0,095
	Friction coefficient, from Eq. (19), f(19)		0,085	0,085	0,085	0,085	0,085
DX 54 D	Ft [kN]	19.72	20,48	21,74	24,26	26,78	NA
	Friction coefficient, from Eq.(9), f(9)		0,126	0,126	0,126	0,126	0,126
	Friction coefficient, from Eq (19), f(19)		0,109	0,109	0,109	0,109	1,108
DIN 1.4301 CrNi	Ft [kN]	34.56	35,59	37,40	41,22	45,54	NA
	Friction coefficient, from Eq (9), f(9)		0,171	0,177	0,185	0,196	0.182
	Friction coefficient, from Eq (19), f(19)		0,139	0,143	0,148	0,155	0.146

Experimental Values: Evaluation and Data Processing

The experimental outputs recorded the press stroke and force for each produced cup, see an example shown in Figure 5.

The press work was calculated as the area under the force-stroke curve. In addition, the as produced cups were measured in order to quantify the changes in the work material thickness and the cup height, and their surfaces were visually inspected for scratches and defects. These experiments were conducted by Audy at Melbourne University.

From Figure 5 it is evident that the die set and tools employed in these deep drawing tests produced qualitatively similar pattern in both uncoated and coated conditions. However, from the quantitative point of view, the uncoated tools produced greater forces, and hence greater press work than the coated tools. The mean values of forces and press work for 15 measurements were statistically different at 95 % and higher confidence level (C.L.) for both the uncoated and coated tools. The same was found for the variances – they were different at 95 % C.L and greater for the uncoated tools. This allowed to use the grand mean values for quantifying the overall benefit of coated tools against uncoated tools, see Table 3.

Table 3. Comparison of experimental data for uncoated and coated tools, predicted values, and differences between measures produced by the coated and uncoated tools. After Audy *et al* [Audy 2003]

Feature	Uncoated tools (UT)	Coated Tools (CT)	Predictions	CT versus UT Difference [%]
Cup Height [mm]	20.1	19.8	19.69	-1.5
Force [kN]	$32.18^{\pm 0.94}$	$30.2^{\pm 0.65}$	32.8	-6.2
Work [kNmm]	$524.17^{\pm 2.86}$	$485.58^{\pm 0.82}$	647	-7.4

The following experiments were conducted independently by Evin at Technical University in Kosice city in Slovakia [Evin 2003]. Figure 6 shows the out puts from extensive computer simulations for uncoated and coated tools employed in drawing a Type 1010 (DC1) steel blanks. Figure 7 shows a distribution pattern of strains along the drawn cup. The main focus was on stresses, strains and forces in the initial and maximum drawing stage.

It needs to be noted that the drawing forces have to be lower than the maximum force (or ultimate tensile strength) of blank material. The use of TiN coated tools was found to reduce the friction coefficient by about 4 % which improved material flow and reduced drawing work, forces and power needed in drawing cups from a Type DC 04 steel material. The overall reduction in forces (due to improve friction) was estimated to be about 3.5 %. Similar improvements are expected in drawing products from *eg* CrNi – austenitic steel used in automotive industry.

Comparison of computer assisted predictions in Figure 6 with experimental trends in Figure 5 showed strong similarities in patterns / trends, and a reasonable good agreement from qualitative and quantitative point of view. This agreement was for the force-stroke displacement at different stroke lengths ranging from 0 mm to 12 mm. At strokes greater than 12 mm the differences between experimental trends and simulations became more distinctive. It is because in the experimental tests the drawing clearance was similar to the blank thickness. This caused some increasing of the cup thickness at the top of the product, and hence reducing its wall thickness during deep drawing. Consequently, the range/duration of maximum drawing forces (of ~30 kN 'on average'), see Figure 5, was quite long. It occurred at the stroke lengths ranging from ~10mm to ~17mm. In contrast, when looking at Figure 6 (simulations) for the maximum drawing forces this range / duration was much shorter. In this case it occurred at strokes ranging from ~10 mm to ~12 mm. This happened because in simulations the drawing clearance was 1.2 times greater than the blank thickness. Because of this, no wall thickness reduction was involved and the values of forces, friction and power were slightly lower than those obtained from the actual experiments on drawing caps by wall reduction.

Evin *et al* [Hrivnak 2000] and [Evin 2003] suggested that the accuracy of results obtained by simulations depends on (a) material model, (b) software configuration, (c) friction model, (d) drawing speed,

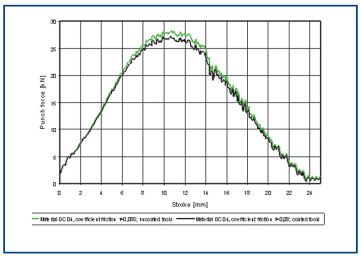

Figure 6. *Predicted load/stroke out puts for uncoated and TiN coated tools employed in drawing a Type 1010 steel blank.*

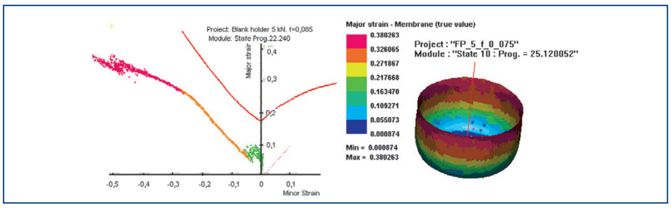

Figure 7. *Key features of major strain distributions along the drawn product.*

and (e) deformation model. The software package Type PAM-STAMP 2G used in the simulations outlined in this paper (Table 2, Figure 6 and 7) enabled to generate/predict satisfactory outputs for qualitative and quantitative comparison of predicted trends with experimental out puts. It indicated that the knowledge obtained from computer assisted predictions and computer assisted modelling approach on different reference tool materials can be applied for comparison of individual measures between two or more different processes. This is because of geometrical and mechanical similarities between the processes. Referring to the material similarities, Hrivnak and Evin [Hrivnak 2000] suggested rewriting the earlier Equation 19 in the following way.

$$f = \frac{-0{,}8399 \pm \sqrt{0{,}8399^2 - 4.2{,}523\left(0{,}0047 - \frac{F_{tc2,ref} - F_{tc1,ref}}{2(F_{p2,ref} - F_{p1,ref})} \cdot \frac{F_{ti}}{F_{tref}}\right)}}{2.2{,}523} \qquad (20)$$

Where F_{ti} = 27.21 *kN*, and F_{tref} =28.2 *kN* were calculated by using a Type FEM mathematical simulation, and they represent the drawing forces acting on the tools in coated and uncoated conditions, respectively. The values of friction coefficient, calculated from Equation 20, for the uncoated and coated tools were 0.085 and 0.081, respectively. Consequently, the benefit of coated tools in reduced friction and drawing forces (in simulations involving the drawing of cups without wall thinning) represented 'on average' about 5%, and 3.5% respectively.

In contrast, the efficiency of tool surface coating in reducing the forces and press work (due to reduced / improved friction) became more evident in deep drawing of cups with wall thinning. This has been documented well by data in Table 3 which showed that the coated tools reduced the press force and press work by about 6.2 and 7.4 percent, respectively. Comparison of predicted data with experimental data indicated a reasonable good comparison for the forces and the cup heights. Empirical rules for predicting press work provided only rough approximation. Visual observations of the cup surfaces indicated more scratches and surface defects hence occurrence of some ironing in drawing with uncoated tools.

4. Conclusions

The experimental deep drawing tests conducted in the present study have shown that the pattern of forces verus stroke produced by the uncoated and the coated tools were qualitatively similar and quantitatively different at 95 % and higher confidence level. The coated tools reduced the force by 6.2 %, work by 7.4 %, and improved the friction coefficient by about 5 % when drawing cups with wall thinning. The cup height values were very similar *i.e.* 20.1 mm for those produced by the uncoated tools, and 19.8 mm for those produced by the coated tools. The main differences were in earring (wavy pattern around the top of the cup) and scratches due to ironing close to the earring which were greater for drawing tools in uncoated conditions than in the coated conditions. Predictions were reasonable good for both the forces and the cup height values, but not so good for the work values. It has also been noticed that there is very limited theoretical knowledge about understanding (and modelling from a mathematical point of view) of the friction behaviour of different materials in sliding. Consequently, the open literature sources offer a wide variety of friction coefficients obtained from empirical testing of different couple materials in mutual contact. In addition, there are mathematical models and methods for calculating the friction coefficients from forces, or the forces from friction coefficients in metal forming operations. However, the accuracy of such predictions appears to vary in a range from ~5 % to about 15 % [Evin 2003]. During simulations that involved drawing cups without the wall thinning the coating reduced the drawing forces by about 3.5 % and improved the friction by about 5% compared to the data generated by the uncoated tools. Finally, it needs to be noted that in order to fully acknowledge the overall benefit of coating for different tool-work-piece material combinations there is a need to establish more reliable predictive equations for coated tools.

Acknowledgments

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