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PVD COATING AND UP-TO-DATE WEAR TEST OF HOT-FORMING TOOLS

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Recently, the requirements for decreasing the tool costs have been increased in forging technologies. These costs could be decreased by increasing the lifetime of the tools. In hot-forming there is a new possibility to increase the lifetime, namely: Physical Vapour Deposition (PVD) coating of the tools. Participants in testing the effects of coating were the employees of the Universtiy Széchenyi István, Rába Axle Ltd., Fraunhofer Institut für Schicht- und Oberflächentechnik Braunschweig and Westsächsische Hochschule Zwickau. Lately, pre-upsetting used in production lines served by robots – as upsetting made between parallel pressure plates used frequently in die-forging – was used to make wear tests. In the wear tests, the friction work according to the energetic model was calculated by applying a kinematically admissible velocity field, which takes into account the friction coefficient and the local displacements. Expectable friction coefficient – using the results of previous researches – has been determined based on geometrical data of the pre-upset work-piece.

Keywords: PVD coating, tool, upsetting, mathematical modeling of material flow, wear

Introduction

The first experiments with Physical Vapour Deposition (PVD) coated tools were made in the Forging Plant of *Rába Axle Ltd.* when hot-extrusion tools were coated in 2008. These extrusion tools were made to produce spindle in large series *(Figure 1).*

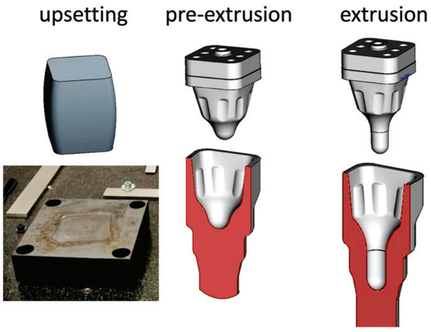

Figure 1: Steps and tools in forming the spindle

Before the experiments, it has been determined what data and methods are required (1) to fix the starting condition of the tools and the technological parameters, (2) to provide consistency of hot-extrusion conditions, and (3) to judge that the test tools cannot be used anymore. It has been determined, furthermore, what methods, measurements, and observations are needed to detect wear-out of the tools.

Experimental production lasted until surface errors appeared on the tools, which inevitably required intervention. At the first intervention point, the experiment was finished. After the extrusion tools were reground, production was continued.

Two pre-extrusion and two extrusion tools were coated in the institute of *Fraunhofer Institut für Schicht- und Oberflächentechnik Umformwerkzeuge* in Braunschweig (PVD: chrome-vanadium-nitride-layer in ~5 µm thickness) [1] *(Figure 2).*

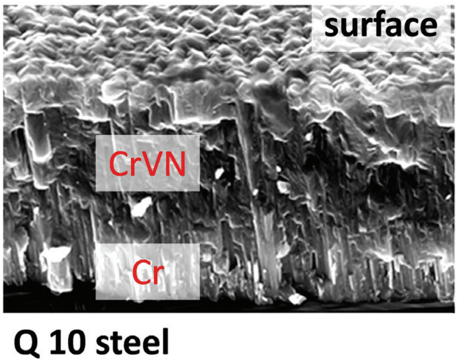

Figure 2: Photo taken by electron microscope on CrVN coating

Conditions of the extrusion tools before and after the experiments were compared in optical digitalization. In the geometrical change, some wear and some residual deformation – upsetting – could be detected *(Figure 3).*

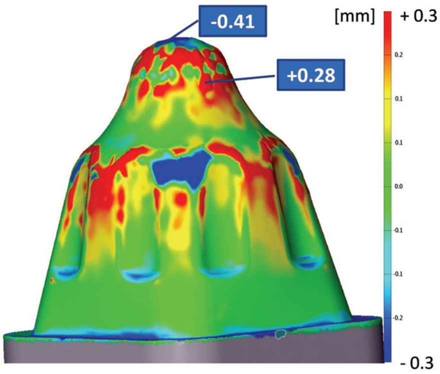

Figure 3: Change in geometry of the coated extrusion tool

Coating made regrinding of the tools unnecessary and clearly increased lifetime of the tools. Increase in lifetime was nearly four times of the lifetime without coating [1]. Then, a new research target was set: how the coating will change the friction conditions, the material flow, and optimal shape of the extrusion tool – where are the force or performance required to forming minimal. When friction conditions were investigated, there was no difference in composition of PVD coatings as preparation of the surface necessary for applying the coating was considered to be determinant [2, 5, 11].

Comparison test of friction conditions

It seemed to be simpler to inspect the change of friction conditions during pre-upsetting. According to the current technology, during pre-upsetting between parallel pressure plates the work-piece is taken and moved to the next workplace by a robot. Due to the good position-taking accuracy of the robot, the work-piece was always placed onto the same location on the pressure plates, so it was simple to inspect wear of the pressure plate. Test was carried out after 26.000 pre-upsetting were made on pressure plates coated and without coating [3]. Wear cavities are readily detectable on the pressure plates coated and without coating *(Figure 4).*

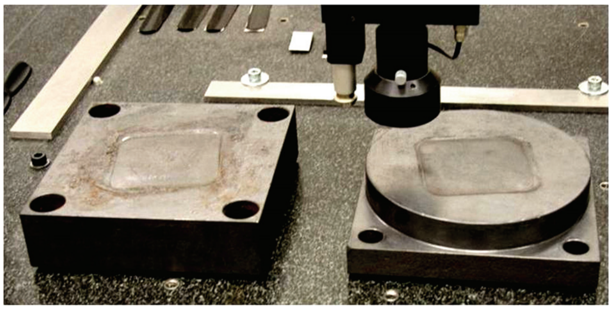

Figure 4: Wear mark of pressure plates coated and without coating after 26.000 pre-upsetting cycles were completed on each [5]

The nACRo® nano-composite platit PVD coating, which is AlCrN coating embedded in 5–6 µm thick α-Si_3N_4 matrix was prepared at the plant of *Pannon Platit* in Hungary. Boundary line of the wear cavity is located between the boundary line without friction and the starting boundary line *(Figure 5).*

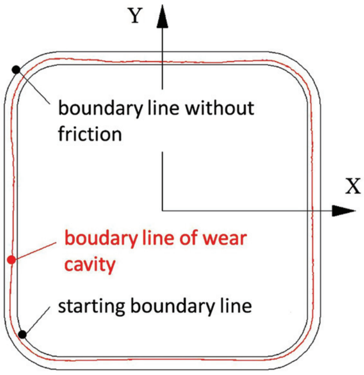

Figure 5: Illustration of boundary line of wear cavity and of theoretical boundaries

Geometry of the boundary line was interpreted proportionally with area, according to this volume consistency. When the two pressure plates were compared, we could establish that on the coated plate the boundary line of the cavity covered larger area. This implies lower friction, as the lower the friction coefficient is, the less the work-piece is getting barreled during upsetting and the larger the contact surface of the work-piece to the pressure plate will become [11]. According to this logic, different projection values of the wear cavity can lead to to differences in friction conditions. If coordinates of the points in the boundary line are as closely defined as necessary, by means of CAD software – with a spline curve on these points – the closed projection curve can easily be drawn and the area bounded by the curve can be measured.

Area of the projection, which is closed by boundary line of the wear cavity presented in the Fig. 5 is 10225.8 mm^2.

Such a measurement (estimation) can produce numeric data about different friction conditions.

Of course, it does not mean that the friction coefficient is known. *Figure 6* shows wear curves of the pressure plates shown in *Fig. 4*, in perpendicular direction to the billet plate.

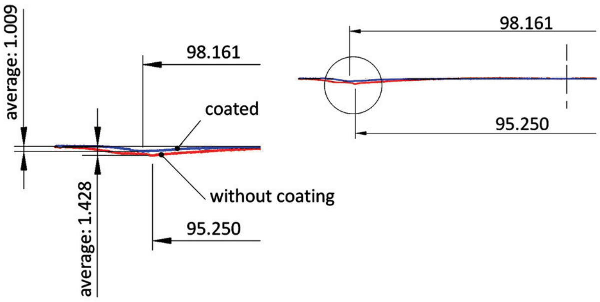

Figure 6: Wear mark of the pressure plates coated and without coating after 26.000 pre-upsetting cycles were completed on each [5]

A conclusion can be drawn on different friction conditions if there is no wear cavity occurring, as during upsetting the hot work-piece causes discoloration on the newly machined surface of the pressure plate [2]. The discolored area (mark) can be determined as described above.

Based on the wear curves, the effect of coating can be judged to a certain extent [2, 3, 11]. In order to get more exact knowledge, an actual forming has been chosen where the starting material is a cut cylindrical rod. During upsetting the cylindrical work-piece between parallel pressure plates, deformation was mathematically modeled. On the basis of the largest diameter of the barreling work-piece, the approximating value of friction coefficient was determined and wear depth was numerically calculated.

Experimental determination of friction coefficient

During actual forming, in *Rába's* forging plant, under production conditions 10 cylindrical specimens were upset between newly machined parallel pressure plates with surface roughness of Ra = 0.25. Experimental specimens are presented in *Figure 7.*

Figure 7: Forgings made in experimental upsetting

Typical parameters and geometrical data at room temperature:

- cut mass: m' = 12.48 ± 0.2 kg,
- cut length: $H_0 = 167$ mm,
- heating temperature: $T_{heating} = 1213–1226°C \rightarrow T_{(average)} = 1219°C$,
- starting diameter: $D_0 = 110 \pm 0.2$ mm,
- upset height: $h_{n(cold\ dim.)} = 142.32–142.91$ mm $\rightarrow h_{n(average)} = 142.6$ mm,
- upset upper diameter: $D_{1(upper-cold\ dim.)} = 114.2–114.5$ mm $\rightarrow D_{1(average)} = 114.3$ mm,
- upset lower diameter: $D_{2(lower-cold\ dim.)} = 112.4–113.7$ mm $\rightarrow D_{2(average)} = 113.0$ mm,
- upset largest diameter: $D_{k(cold\ dim.)} = 121.6–122.3$ mm $\rightarrow D_{k(average)} = 122.1$ mm,
- lubrication: less lube,
- forming machine: 10 MN LASCO hydraulic press,
- hardness of tool surfaces: 48 ± 2 HRC,
- measured surface temperature of tools: $T_{lower-max} = 302°C$; $T_{upper-max.} = 239°C$.

Temperature conditions during upsetting are special. At the contact area of the work-piece to the pressure plate – with some simplification – temperature of the work-piece is 1100°C. The temperature of the pressure plate is 300°C. At the same time, the measured values are mainly at room temperature. Dimensions were recalculated, as necessary, according to the law of linear heat expansion.

In numerical calculations, a kinematically admissible material flow model was used [7, 9]. By means of the applied material flow model, the approximate value of the *Kudo* friction coefficient was determined at the same time [9], so when the wear depth was numerically calculated, the work-piece got barreled according to the given friction coefficient.

The applied material flow velocity field for the cylindrical work-piece – with some simplification – can be specified with two components:

Axial velocity component:

$$w_z(z) = \frac{z\begin{pmatrix} -2z^2(1-m)v_0 + 2z^2 v_0 + \\ 3z(1-m)v_0 h - 3zv_0 h - (1-m)v_0 h^2 \end{pmatrix}}{h^3}, \qquad (1)$$

Radial velocity component:

$$w_r(r,z) = -\frac{1}{2}\frac{r\begin{pmatrix} -6z^2(1-m)v_0 + 6z^2 v_0 + \\ 6z(1-m)v_0 h - 6zv_0 h - (1-m)v_0 h^2 \end{pmatrix}}{h^3}, \qquad (2)$$

where:

$w_z(z)$ – velocity component in height direction[ms^{-1}],
$w_r(r,z)$ – velocity component in radial direction [ms^{-1}],
m – *Kudo* friction coefficient [-],
v_0 – velocity of the upper pressure plate [ms^{-1}],
h – instantaneous height of the upset work-piece [mm].

If we want to expand the relations (1, 2) to the total pre-upsetting, the forming process should be divided into superposed stages. Within a stage, the upper pressure plate moves $\Delta h = v_0 \Delta t = 0.1$ mm and in each stage the calculation should be made with a new height *h.* The actual height is obtained if the value Δh is deducted from the previous height [3].

After upsetting is simulated in the superposed stages, upset shape and velocity field of a work-piece can be studied in the *Figure 8*.

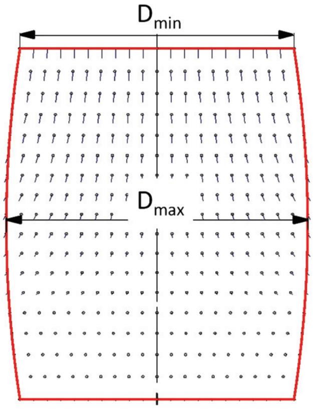

Figure 8: Instantaneous geometry and velocity field of the upset work-piece ($m = 0.8$)

When simulations are made with dimensions converted to the forming temperature of nominal geometrical data of the experimental parts, changes in the largest and the smallest diameters (radii) can be detected.

Average of the largest upset diameters is $D_{\mathrm{k(average)}} = 122.1$ mm. Taking the forming temperature into account, the largest radius is $R_{\max(1100)} = 61.86$ mm. When this value is used, the approximate value of the *Kudo* friction coefficient is $m = 0.7$ on the basis of *Figure 9*.

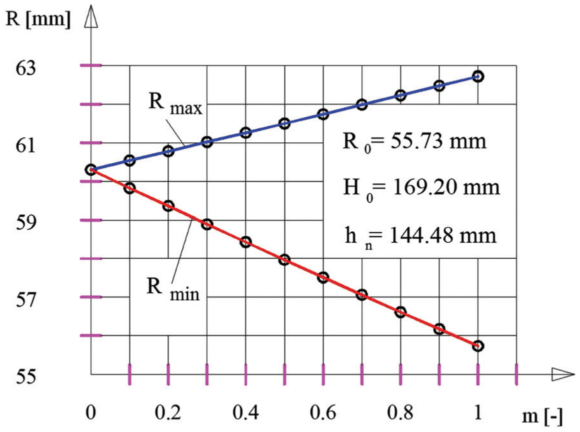

Figure 9: Changes in the values of $R_{\min}$ and $R_{\max}$ as a function of the Kudo friction coefficient at forming temperature

Earlier, the expectable range of the friction coefficient was determined with the *Burgdorf* ring upsetting. A new set of curves had to be applied to the geometry proper to hot forming [9] *(Figure 10)*.

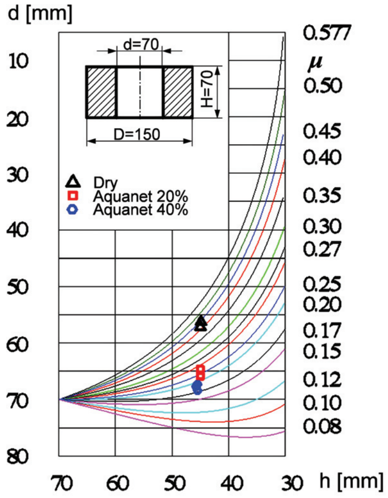

Figure 10: Determination of expectable friction coefficient with Burgdorf ring upsetting

Based on the measurements, in the case of dry friction, the *Coulomb* friction coefficient is actually $\mu \approx (0.4\text{–}0.45)$. Converted to *Kudo* friction coefficient, it is $m \approx (0.7\text{–}0.8)$. It conforms to the previous value. In numerical calculation of the wear depth, the work-piece gets barreled according to the specified friction coefficient.

The friction coefficient defines the field of displacement of the work-piece on the pressure plate.

Determination of wear depth by using an energetic wear model based on a kinematically admissible displacement field

From the point of view of forging, determination of the expectable highest wear depth is important as the wear cavity has sensible effect on material flow. It is a potential hazard point to the surface folds occurring on the work-piece.

In the wear test, at the contact of the pressure plate to the upset work-piece – at the location $z = 0$ – only the radial velocity (displacement) should be taken into account, which is as follows based on the relation (2):

$$u_r(r,0) = w_r(r,0)\Delta t = \frac{1}{2}\frac{r(1-m)\Delta h}{h}\,. \tag{3}$$

The *Archard* model, in extreme cases – when friction coefficient is zero or when the displacement is zero typically to whole sticking – has produced some results, which will have to be clarified yet. That's why the relation between the friction coefficient and the wear depth is investigated by applying the energetic wear model.

The *energetic wear model* assumes proportionality between the volume of the worn material and the friction work causing the wear [4].

Based on the energetic wear model, wear depth can be defined as [4]

$$z = C\sum_{i=1}^{M}\tau_s(r,t)v(r,t)\Delta t\,, \tag{4}$$

where:

z – wear depth [mm],
C – constant typical to material combination [$\mathrm{mm^3J^{-1}}$],
M – number of discretized time increments [-],
τ_S – friction stress [Pa],
v – relative sliding speed between friction surfaces [$\mathrm{mms^{-1}}$],
Δt – time increment [s].

Using the simplification frequently used in plastic forming, namely

$$\tau_s = \mu\sigma_N \cong \mu k_f = m\frac{k_f}{\sqrt{3}}\,. \tag{5}$$

In the *Kudo* friction the friction stress τ_S can be interpreted as proportional to the direct shear yield point m.

In the frictionless condition $m = 0$, in sticking $m = 1$. In hot forming, the deformation strength k_f of the material can be considered constant during upsetting, so local distribution of the wear is determined by the superposed radial (3) displacements defined at the contact of the pressure plate to the upset work-piece.

From the point of view of wear, the displacements in each stage should be added. Taking the above into account, the wear depth is as follows:

$$z = C\sum_{i=1}^{n} m\frac{k_f}{\sqrt{3}}\frac{1}{2}\frac{r(1-m)\Delta h}{h}, \tag{6}$$

where:

n – number of superposed stages [piece].

Using the relation (5), taking the temperature conditions and initial surface hardness of the tool into account [6, 10, 12], a MathCAD program was prepared [3] to define the wear depth.

Using the friction coefficient m obtained from the experiment, the approximate value of the energetic wear factor C was determined on the basis of literature references [3, 8, 10].

While the wear factor was constant, the depth of wear was inspected to a single upset cycle as a function of the work-piece radius R and the friction coefficient m *(Figure 11)*.

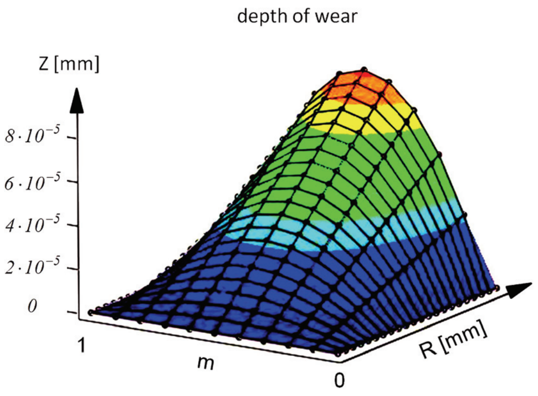

Figure 11: Change in depth of wear as a function of the work-piece radius and the friction coefficient

Fig. 11 illustrates that wear is zero at the location $R = 0$, it is continuously increasing within the constant contact range along the radius, and it is zero again at the largest radius of the upset work-piece.

The constant contact range is up to initial radius R_0 of the work-piece [3]. During upsetting the contact surface of the work-piece to the pressure plate is increasing. The radial displacement size of the new surface and, thus, the wear are influenced by the friction coefficient too.

In the frictionless case ($m = 0$), the radial displacements are the largest, however, the tool does not wear.

In total sticking ($m = 1$), the surface of the work-piece does not change at the tool contact. There is no displacement, that's why the tool does not wear. As per the applied model, at the highest wear the *Kudo* friction coefficient is 0.5.

Besides the expectable values of friction coefficient ($m = 0.7$–0.8), the wear curve was taken separately, too *(Figure 12)*.

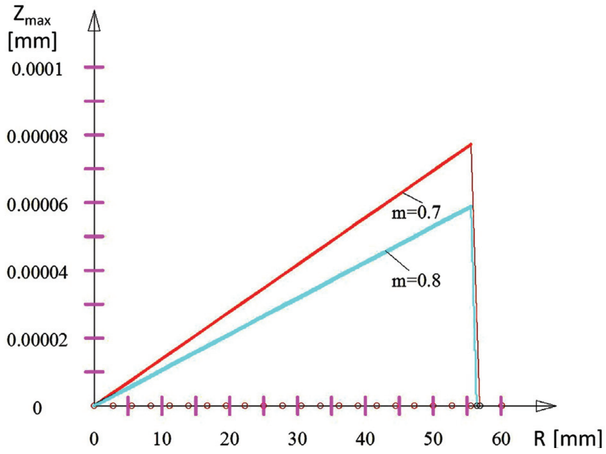

Figure 12: Wear curves in a single upset cycle at various friction coefficients

Change of wear along the radius is similar to the actual wear shown in *Fig. 6*.

We wanted to determine the energetic wear factor C with an experiment. In the experiment, the wear of the pressure plates was inspected after 10 cylindrical work-pieces were pre-upset *(Fig. 7)*. Due to some reasons of measuring technique, the experiment has not produced clear results yet. It can be explained by that after 10 upsetting cycles the average surface roughness of the test tools did not decrease below the value, which is critical for an occurring wear cavity.

Similar results are obtained on the basis of the friction work occurring on a surface within the constant contact range. During pre-upsetting, friction work occurring on the surface A is as follows:

$$w_s = \int_A m\frac{k_f}{\sqrt{3}}\left|u_{rel}\right| dA, \tag{7}$$

$$w_s = \frac{4\pi\sqrt{3}\,R^3 k_f\, m(1-m)\Delta h}{9h}. \tag{8}$$

The above friction work is zero if $m = 0$ and $m = 1$, so the extreme cases mentioned previously are properly described by the selected model. The highest friction work occurs if $m = 0.5$.

In calculating both the depth of wear and the wear work, the simplified relation (5) was used. It certainly affects the results, however, in our opinion, based on the work performed it can be declared that during upsetting there is a friction coefficient at which the friction work and the maximal depth of wear are the highest.

Summary, conclusions

Based on our experiments, it has been detected that coating has decreased the friction coefficient, the depth of wear and thus the lifetime of the tool have clearly improved.

Reduction of friction coefficient could be measured from numerical data with projection area of the wear cavities.

By using the energetic wear model, we have supported our opinion that during upsetting, in the limits of *Kudo* friction coefficient /m = 0 and m = 1/ there is a friction coefficient at which the wear is maximal.

A task for the future could be more exact determination of energetic wear factor *C* based on a larger experimental sample.

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