Influence of surface integrity on the tribological performance of cold forging tools

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Abstract

In forming industry the tool is fundamental for the profitability, as it determines efficiency of cold forging process. In this regard, the tool surface has a distinctive influence on the tribological conditions and thus on the occurring tool stresses. The present study investigates the influence of different fine machining strategies on the tribological performance of cold forging tools made of WC-Co cemented carbide by applying the double cup extrusion test. The results reveal that a peened surface causes higher friction in the forming process compared to polished tool surfaces up to 100%. For polishing a minimum in friction is found for the diamond grit D 6 μm with a friction factor of m = 0.03.

1. Introduction

Cold forging enables mass production of high loadable and accurate steel based components [1]. The tribological conditions during cold forging have a fundamental influence on the process, as they determine the material flow, the quality of formed parts, the required energy amount of the forming process as well as the tool wear [2]. Friction is the result of interaction of the components of the tribological system: the workpiece, the tool, the applied lubricant as well as the ambient medium [3]. Negative impacts of high friction are among others energy dissipative effects, an increased energy consumption and a reduced tool life due to increased wear and forming forces. The tribological conditions during the forming process are determined by the contact normal stresses and the relative velocity between workpiece and tool, the surface enlargement of the workpiece, the process temperature and the lubrication system [4]. In addition, the friction is influenced by the surface integrity of the forming tool. Since the tool has a fundamental influence on the profitability of the forming process, there is ongoing demand for improvement of tool quality. Due to high loads during cold forging high loadable tool materials in terms of hardness and compressive strength are required. If there are special requests concerning wear resistance cemented carbides represent the standard as tool material in cold forging industry [5]. Due to high hardness of the composite complex tool geometries are often hard machined by electrical discharge machining (EDM) [6]. The heat flux of EDM causes a thermal influenced surface layer [7], the so called white layer. If the influenced top layer is not fully removed by subsequent fine machining steps, remaining craters and micro-cracks can reduce tool life [8]. In tool making a variety of fine machining technologies is available. It is expected, that the resulting surface topographies have a distinctive impact on the tribological conditions in cold forging. Standard in tool finishing is manual polishing [9]. Within polishing surface roughness is determined by the grain size of the applied abrasives. However, quantitative investigations which surface topography is
favorable for tribological conditions within cold forging are missing so far. Since manual polishing is cost intensive, there is a great demand for reduction of polishing effort or even substitution by other fine machining technologies. Nevertheless, other finishing techniques will only be attractive if they gain an equal or even better tool performance. In this context, the present study contrasts polishing by a peening process. Peening enables removing of thermally influenced layer and compresses the surface. Detailed comparisons of these both fine machining technologies in terms of their tribological impact are unknown up to now. Against this background, the scope of the present paper is the investigation and description of the interactions of fine machining of tools, resulting surface integrity and the corresponding tribological performance of forming tools. For the quantification of the tribological tool behavior the double cup extrusion test (DCET) was carried out.

2. Friction determination in the DCET

For quantitative characterization of friction the friction factor model is applied, as the underlying correlation (1) between the frictional shear stress $\tau_f$ and the flow stress $k$ of the formed workpiece material represents the conditions in cold forging in good approximation.

$$\tau_f = m \cdot k$$  (1)

The friction factor $m$ is determined within the DCET. The model test under laboratory conditions is appropriate for quantification of friction as the DCET realistically mirrors the conditions of industrial cold forging, especially in terms of contact normal stresses and surface enlargement [10]. For determination of friction as a function of fine machining process different machined dies made of the cemented carbide grade G55 of the company Kennametal are investigated. Within the study a peened tool surface is contrasted by conventional polished dies. In order to gain information about favorable tribological conditions several diamond grits with different grain sizes were used as abrasives for the final polishing step.

2.1. Experimental setup

The experimental setup of the DCET consists of a movable upper and a stationary lower punch, the prestressed die as well as the billet which is positioned in the die between the both punches (Fig. 1 a). The cold forging process leads to extrusion of two cups. While the upper cup is formed by backward cup extrusion, the lower cup results from forward cup extrusion.

![Fig. 1. DCET (a) test set-up, (b) principle](image)

In the presence of friction, the height of the lower cup $h_2$ is smaller than the height of the upper cup $h_1$. The DCET uses the effect that the cup height ratio $h_1/h_2$ increases with increasing friction factor due to different relative velocities between the punches and the die. If there is no friction ($m = 0$), the cup heights are equal resulting in a ratio $h_1/h_2 = 1$ (Fig. 1 b). In the other edge case of static friction ($m = 1$), only the upper cup is formed. As could be shown by Schrader et al. [11], the punch friction has no effect on the cup height ratio, as long as there are identical tribological conditions at both punches. Consequently, the $h_1/h_2$-ratio reflects the tribological conditions between workpiece surface and die cavity. As the investigation of topographical influences requires high sensitivity to small changes in friction, the ratio of billet height $h_{\text{billet}}$ to billet diameter $d_{\text{billet}}$ was chosen to 1.5 (with $d_{\text{billet}} = 11$ mm), since sensitivity of the DCET increases with raising $h_{\text{billet}}/d_{\text{billet}}$-ratio [12]. In addition, the extrusion ratio $e = d_{\text{punch}}^2/d_{\text{billet}}^2$ determines sensitivity of the DCET [13]. Since small ratios result in high $h_1/h_2$-ratios, $e$ was chosen to 0.2.

2.2. Tribological system

The investigated tribological system in the present study consists of the G55-die, the 30MnB4-workpiece and the lubrication system. G55 represents the established cemented carbide standard for tool application and is often used for active tool components such as dies or punches [14]. The tungsten carbide (WC) – cobalt (Co) – compound contains 27.0 % Co. As workpiece material the heat treatable steel 30MnB4 (1.5526) with a yield strength of 400 MPa was applied. Components made of 30MnB4 are often used for connection technologies. In order to mirror the conditions in industrial cold forging, the workpieces were coated with zinc phosphate. The applied lubrication system includes the polymer Chemetall “Gardomer L6328” which is deposited on the cylindrical billets, the wire drawing lubricant Bechem “Fimitol ZT 305” as well as a cold forging oil. For quantification of the
influence of the lubricant the DCETs were carried out for the two oils KFP 148 neu (KFP 148) and KFP 80 neu (KFP 80), both of the company Bechem. While KFP 80 is used for forming operations of medium complexity, KFP 148 is recommended by the manufacturer for challenging cold forging operations. The properties of the oils are given in Table 1. Both oils are mineral based oils including additives. KFP 148 has a distinctive higher viscosity compared to KFP 80.

Table 1. Properties of applied cold forging oils [15, 16]

<table>
<thead>
<tr>
<th>Cold forging oil</th>
<th>KFP 148 neu</th>
<th>KFP 80 neu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>Mineral oil</td>
<td>Mineral oil</td>
</tr>
<tr>
<td>Density at 20°C [g/cm³]</td>
<td>0.92</td>
<td>0.91</td>
</tr>
<tr>
<td>Viscosity at 40°C [mm²/s]</td>
<td>99 - 121</td>
<td>60 - 65</td>
</tr>
<tr>
<td>Burning point [°C]</td>
<td>&gt;200</td>
<td>&gt;186</td>
</tr>
</tbody>
</table>

3. Tool manufacturing

Within the investigations the influence of the process chains “EDM – peening” and “EDM – polishing” on the friction factor \( m \) was determined.

3.1. Electrical discharge machining (EDM)

The die cavity was hard machined by sinking EDM. EDM was done on a Zimmer and Kreim “Genius 602”. The sequence of different roughing and finishing steps was chosen according to established industrial standard. The parameter settings are given in Table 2. As final EDM strategy the VDI step 12 with an Ra target value of 0.4 \( \mu \)m was chosen. This last machining step defines the resulting topography.

Table 2. Parameters of applied EDM steps

<table>
<thead>
<tr>
<th>Step (VDI)</th>
<th>Peak current [A]</th>
<th>Discharge voltage [V]</th>
<th>Pulse duration [( \mu )s]</th>
<th>Pulse interval [( \mu )s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>2</td>
<td>270</td>
<td>50</td>
<td>450</td>
</tr>
<tr>
<td>27</td>
<td>2</td>
<td>270</td>
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<td>2</td>
<td>180</td>
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<td>2</td>
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<td>150</td>
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<td>12</td>
<td>1</td>
<td>150</td>
<td>12</td>
<td>18</td>
</tr>
</tbody>
</table>

3.2. Fine machining

Within the present paper the thermal influenced top layer caused by EDM is comparatively removed by peening and polishing. Shot peening is a common method for improving the surface integrity of components [17]. Within the machining experiments a two-step peening process was applied. In a first abrasive step, shot blasting with aluminium (Al) oxide grains (diameter 10 – 20 \( \mu \)m) cracks and removes the white layer. In a further compressive step, shot peening with ceramic balls made of zirconium oxide (diameter 30 – 70 \( \mu \)m) smooths the surface. Peening was done on an Iepco peening machine “Peenmatic Micro 620s”. For both steps the working distance was chosen to 45 mm with an angle of incidence between 80 and 90°. The peening pressure was chosen as 0.17 MPa for abrasive peening and 0.15 MPa for the compressive step.

Polishing aims to reduce surface roughness resulting from previous machining steps. Within the experiments, the die rotates on a polishing bench. An arbour made of wood brings the diamond grit in contact with the surface of the die cavity. The tool surfaces are polished by a sequence of different grain sizes. In order to quantify the influence of polishing process on the tribological conditions, the diamond grits D 15 \( \mu \)m (D15), D 9 \( \mu \)m (D9), D 6 \( \mu \)m (D6) and D 1 \( \mu \)m (D1) were comparatively applied for the final polishing step. The tool surfaces were polished by each grit until saturation for the roughness value is reached.

4. Analysis of surface integrity

The surface properties after the final machining step are analyzed in terms of surface topography and roughness. The surface topography is fundamental for the tribological performance of a cold forging tool as friction and material flow are directly influenced. In this regard, the machined surfaces were analysed by confocal microscopy on a NanoFocus “\( \mu \)Surf” microscope. The topographies and the corresponding profile depth after the final machining step are given in Fig. 2. The two step peening process leads to a scarred surface structure without a preferential direction. This appearance is related to abrasive effects. The Al-oxide abrasives crack and remove the brittle white layer while compressive peening smooths the surface. The corresponding profile depth Rt, which is the sum of the height of the highest profile peak and the depth of the lowest profile valley within the roughness profile, amounts 3.55 \( \pm \) 1.12 \( \mu \)m. In contrast, polishing leads to a regular structure with a characteristic low profile depth. The induced preferential direction is the result of rotational movement of the polished surface. The abrasive grains cause local plastic deformations. Once the maximum deformation capacity of the material is reached, the grains chip the material in tangential direction, resulting in the typical polishing grooves. Theses grooves have a strong influence on the tribological conditions. Furrows perpendicular to the material flow impede extrusion process and can initiate tool wear in terms of galling. Moreover, the required higher forming forces can lead to tool life reducing.
stress peaks. On the contrary, grooves may function as reservoir for lubricant which is favorable for the formation of an oil film. This film separates tool and workpiece and therefore reduces the occurrence of galling. While the D15 polished surface reveals distinctive furrows, D9 polishing leads to a surface improvement. Not only the profile depth is halved from \( Rt = 0.38 \pm 0.01 \, \mu m \) to \( 0.19 \pm 0.02 \, \mu m \), but also the polishing grooves are less distinctive. Polishing with D6 causes a uniform surface with a profile depth of \( Rt = 0.15 \pm 0.01 \, \mu m \). However, polishing grooves are still detectable. Only D1 polishing totally removes the furrow structure, resulting in a mirror-like surface. The corresponding Rt value amounts \( 0.10 \pm 0.01 \, \mu m \).

Confocal microscopy gives a good overview of topographical specifics. However, the pure topographies are not sufficient for quantitative correlations of surface integrity and tool performance [18]. In this context, the reduced peak height Rpk, the core roughness depth Rk and the reduced valley depth Rvk are measured. Regarding cold forging tools, Rpk is relevant for the wear and run-in behavior of a tool, since peaks in the roughness profile impede the material flow. Rk represents the roughness profile which is stressed by the occurring loads after run-in. Rvk is a measure for valleys extending below the core profile and relevant for evaluation of local surface defects and grooves. Besides, Rvk is an indicator for the oil-retaining capacity of a tool surface and therefore essential for the tribological tool behavior. The roughness measurements were carried out on a Mahr “Mar Surf GD 120”. For roughness determination five measurements were performed. The peened surface reveals highest roughness values with a mean Rk value of 1.39 \( \mu m \). Especially the distinctive peak height with an Rpk value of 0.46 \( \mu m \) can hinder the material flow within cold forging process. In contrast, the polished surfaces lead to lower roughness values. The core roughness Rk decreases with decreasing grit size of diamond abrasives from 0.15 \( \mu m \) (D15) to 0.061 \( \mu m \) (D9) to 0.056 \( \mu m \) (D6) to 0.041 \( \mu m \) (D1). The Rpk value amounts 0.049 \( \mu m \) for D15 polishing, while for the other grits this value is distinctive low with values below 0.02 \( \mu m \).

Thus, the peaks in the roughness profile remaining from previous machining steps are removed to a great extent by the finer diamond grits. Regarding the valley depth, Rvk decreases from 0.070 \( \mu m \) (D15) to 0.020 \( \mu m \) (D1). Since Rvk is closely linked to the tribological conditions within cold forging, this parameter is used for the evaluation of the following DCETs.

5. Results of the DCET

A direct determination of the friction factor m is not possible by the DCET. Therefore, the principle of numerical identification is used. In this regard, a model of the DCET with rigid tool components and the deformable 30MnB4-billet was implemented in simufact.forming 11.0. The cup height ratios \( h_1/h_2 \) of the formed parts function as indicators for the occurring friction. In this regard, several friction factors were simulated. This enables the determination of the cup height ratios as a function of the friction factor. The corresponding calibration curve for the applied minimal punch distance of 8.5 mm is shown in Fig. 4. By comparison of the experimentally determined and the simulated cup height ratios the friction factors m are determined.

![Fig. 2. Topographies after final machining step](image2)

![Fig. 3. Surface Roughness after final machining step](image3)
The DCETs were carried out on a universal testing machine Schenck Trebel 400. The velocity of the upper punch was chosen to 6 mm/min. In order to provide steady conditions regarding the distribution of lubricant in the interaction zone of tool and workpiece, three specimens were used for run-in for each test series. After run-in of dies five specimens were extruded for determination of the friction factor. A significant change in roughness values of the tool surfaces before and after the test series could not be detected. Consequently the roughness values can be considered as constant. The m values for the different machined die cavities and extrusion oils are given in Fig. 5. As can be seen, both the surface integrity of the tool as well as the applied extrusion oil have an effect on the tribological conditions within the forming process. The friction factors vary between 0.03 and 0.08. Regardless of the surface integrity lubrication of forming process by KFP 148 leads to lower m values in contrast to KFP 80. As low friction values are favorable for the quality of formed part, the energy consumption of the forming process as well as the tool life due to reduced forming forces and tool wear, KFP 148 should be preferred in cold forging.

In terms of surface integrity of the tools the peened die bores result in highest m values of \( m = 0.068 \pm 0.001 \) (KFP 148) and \( m = 0.075 \pm 0.003 \) (KFP 80). In contrast, the D15 polished surface reduces the friction factor of about 40% (KFP 148) and 27% (KFP 80) to values of \( m = 0.041 \pm 0.005 \) (KFP 148) and \( m = 0.055 \pm 0.015 \) (KFP 80). This effect is related to the reduced profile depth and peak height which is favorable for the material flow. Polishing of die bore by D9 grit leads to an additional decrease of mean friction factor of 13% (KFP 148) and 8% (KFP 80) to friction factors of \( m = 0.036 \pm 0.001 \) (KFP 148) and \( m = 0.051 \pm 0.001 \) (KFP 80). While for the D6 polished surfaces a slight improvement of frictional conditions is observable with friction factors of \( m = 0.034 \pm 0.004 \) (KFP 148) and \( m = 0.048 \pm 0.006 \) (KFP 80), the application of the D1 grit does not improve the tribological conditions leading to friction values of \( m = 0.036 \pm 0.004 \) (KFP 148) and \( m = 0.050 \pm 0.004 \) (KFP 80). The results reveal that the applied fine machining process and the corresponding surface integrity of the tool have a fundamental influence on the tribological performance of a tool. As can be shown, the applied peening process does not lead to favorable frictional conditions in contrast to polished tool surfaces. As a consequence, tool surfaces should always be polished in order to gain optimal tribological conditions. Within polishing a reduction of friction could be detected from D15 to D9 to D6, while D1 polishing does not contribute to an additional improvement of the tribological conditions.

The correlation of the reduced valley depth \( R_{vk} \) and the friction factor \( m \) gives an explanation for the observed results (Fig. 6). In general, high roughness values, like in terms of a peened surface, lead to high friction as distinctive asperities impede the material flow.

Regarding the polished tool surfaces, the remaining grooves are decisive for the tribological tool behavior. Due to polishing process the polishing grooves are orientated perpendicular to the material flow. Deeper furrows, like for instance after D15 polishing, hinder the extrusion process resulting in a higher friction factor. An additional roughness reduction by the application of finer polishing grits D9 and D6 leads to a reduced oil-retaining capacity which would lead to an increase in...
friction. This effect seems to be overcompensated by reduction of sliding resistance resulting in an overall lower friction factor. By polishing with the D1 grit the effect caused by the reduced oil-retaining capacity is predominant. The consequence is a slight increase in mean friction factor. This result is in good correlation with the topographical analysis. The D1 polished mirror-like surface does not reveal any grooves. Therefore, the formation of lubricant pockets is not possible to a sufficient extent.

6. Summary and outlook

Within this paper the influence of different fine machining strategies on the tribological tool performance are investigated. The surface integrities of the different machined die surfaces is analyzed in terms of topography and surface roughness. The results show that peening and polishing lead to specific surface topographies. While peening results in a scarred structure with a distinctive profile depth, polishing leads to smooth surfaces characterized by polishing grooves. For the different machined surfaces the DCET was carried out. The chosen test parameters and the corresponding high sensitivity of the DCET have enabled the investigation of the tribological influences of applied lubricant and surface integrity of the tool. The results reveal favorable tribological conditions for the oil KFP 148 in contrast to KFP 80. In addition, it can be shown that a peened surface causes higher friction in the forming process compared to polished tool surfaces. As a consequence, peening is not sufficient for replacing polishing process regarding tribologically challenging tasks. Within polishing the diamond grit D6 leads to lowest friction values. Consequently, an additional polishing with D1 is obsolete. This process chain reduction has the potential to reduce tooling costs whereas the tribological tool performance remains equal. All in all the results reveal that optimization of tribological conditions within cold forging requires consideration of both the lubrication system as well as the surface integrity of the forming tool.

In further DCETs the influence of tool coatings on the tribological conditions will be investigated. Coatings are often applied in a post machining step for improvement of the wear behavior of cold forging tools. However, these top layers change the tribological system and therefore influence the tribological behavior of a forming tool. Beside the tribological conditions also the tool performance in terms of the fatigue strength will be evaluated in additional experiments since a great influence of the surface integrity on the tool life is expected. In this regard, the fatigue behavior of the different machined tool surfaces will be investigated under laboratory conditions as well as in serial production tests. The overall results will enable the derivation of recommendations for an optimized tool production in terms of tribological performance and fatigue behavior of forming tools.

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