Investigation on tool properties for the production of components with micro textured surfaces

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Abstract. Defined surface microtextures offer potential for the friction reduction in elastohydrodynamic contacts and can thus increase the energy efficiency of technical systems. The production of prostheses, where microtextured surfaces can provide anti-bacterial effects is another application area. To manufacture these components economically in large quantities, forming processes are to be aimed at. Since lightweight parts are crucial in most application areas, the forming of sheet metal is the subject of current research. A major aspect of the presented investigation is the behavior of tool materials for the production of such microtextured sheet metal parts. Applying microtextures of varying geometries to the tools is a key challenge. Limitations in the accuracy of electrical discharge machining processes for the fabrication of micro cylinders, prisms and cuboids are therefore analyzed on the high-speed steels 1.3343 and 1.3244. In addition, the tool surfaces are characterized regarding their friction properties with case hardening steel as a contact partner. In this paper, the tool friction is analyzed for the steel 1.7131 (16MnCr5) with an initial sheet thickness of $t_0 = 2.4$ mm, which is often utilized for high-wear applications due to its high strength and toughness. In this context, the friction behavior of the wax-containing lubricant Beruforge 150 DL made for bulk forming processes is compared with zinc-free high-performance lubricants Raziol CLF 65-400 of varying viscosity.

1. Introduction
Applying defined microscopic structures on metal surfaces have the potential to reduce friction between highly loaded lubricated components under relative motion [1]. In bioengineering, microtextured surfaces can be implemented to provide antibacterial effects [2]. Recent investigation approaches for the single stage fabrication of micro textured metal components are based on a cup backward extrusion process in combination with micro coining [3]. In this process, the high lateral material flow of the specimen impedes a precise imprint of the micro textured coining punch onto the semi-finished material [3]. A promising method for overcoming this process limitation is the combination of sheet-bulk metal forming processes with micro coining. In sheet-bulk metal forming, which is characterized by the application of bulk forming operations on sheet metal semi-finished parts [4], the global adaption of the tribological conditions enables a targeted material flow control. Besides the use of tailored tool and workpiece surfaces [5], the lubricant influences the tribological system and therefore the friction. The lubricants are mostly designed for their specific application, either in sheet metal forming or bulk metal forming. Their properties are thus adapted to long sliding path for sheet metal forming or high contact normal stresses for bulk metal forming [5]. Due to the appearance of both described load cases in sheet-bulk metal forming, the suitability of lubricants for sheet-bulk metal forming is to be investigated.
2. Methodology and experimental setup

Different zinc-free sheet metal forming lubricants are investigated and compared to a bulk metal forming lubricant. In drawing processes, the lubricant viscosity is a major factor to adapt the friction system. This can be explained by the velocity dependant friction conditions between the forming tool and the sheet blank [6]. The examined lubricants are therefore chosen according to its varying viscosity. In case of the Raziol CLF lubricants, the corresponding viscosities at 40°C are 65 mm²/s, 100 mm²/s and 400 mm²/s, whereby an increasing viscosity positively influences the load capacity of the lubricant [7]. Common application fields are drawing, forming and coining processes of construction steel, stainless steel and aluminum [7]. Due to the addition of extreme pressure additives, a high pressure absorption capacity and a good tool wear protection is reached [7]. The behaviour is furthermore compared to the bulk forming lubricant Beruforge 150 DL, which is a wax-containing and water-miscible oil [8]. Since it was identified in [9] as suitable for the use in sheet-bulk metal forming, it is used as reference lubricant. In accordance with [9], the pin-extrusion and the ring-compression test are applied to characterize the friction conditions for sheet-bulk metal forming processes. Figure 1 shows the tool setup of both processes.

Due to its frequent application in high-wear applications, the steel 1.7131 (16MnCr5) is used as blank material. The tests are conducted with tools from the high-speed steel 1.3343. In order to ensure universally applicable results, the tests are conducted on polished tools without microtextures. Cutting of the specimens in the desired geometry is realized using a CO₂ laser, which are subsequently processed in a hydraulic press Lasco 100SO. During the pin-extrusion test, the initial sheet thickness of 2.4 mm is reduced by 50 %, causing a radial material flow as well as a flow into the die cavity. The forming can be described as a combination of forward extrusion and upsetting and is therefore especially suitable for the friction characterization for loads comparable to those in bulk forming processes. With higher friction between the tools and the specimen, more material flows into the cavity and induces a larger pin height $h_s$. For processes with lower contact normal stresses, the ring-compression test can be applied [9], where a sheet metal ring is upset between two parallel tools. Under higher friction, the outward oriented radial material flow is hindered which results in inward oriented material flow of the material. As proposed in [10], the inner diameter $d_1$ is selected as the decisive factor for the characterization of the tribological conditions. Numerical models for both processes are furthermore developed to quantify the corresponding friction factor $m$. Since the finite element method is a common approach to numerically investigate forming processes [11], the forming software Simufact.forming 16.0 is chosen. Recommendations of [12] are moreover used to prove the validity of the numerical models.

Since the final aim of this investigation is to evaluate the suitability of the two high-speed steels 1.3343 and 1.3244 for micro texturization, they are analysed regarding their behaviour in the fabrication of microtextures, using the electronic discharge machining (EDM). For the production of high precision
products of elevated hardness, the production via EDM is a usual strategy [13]. The suitability is classified by the analysis of the form accuracy of the texture elements. Cuboids, prisms and cylinders with a height of 15µm and varying lateral dimensions are therefore eroded on the tool surface. Table 1 gives an overview of the analysed microstructure elements in the scope of this research.

| Cuboid / Prism | Cylinder |
|----------------|----------|
| [h] µm | [l] µm | [h] µm | [Ø] µm |
| 15 | 15 | 15 | 20 |
| 25 | 15 | 25 | 30 |

3. Results and discussion

The friction factors are determined by the combination of experimental results from the pin-extrusion and the ring-compression test with numerical results from the simulation models. On the one hand, the process force from the simulation and the experiment are compared to provide a process-related validation. The tested sheet metal of 16MnCr5 is modeled using an experimentally determined initial yield stress of 508 MPa. On the other hand, the experimentally obtained microhardness is compared to the calculated true strain distribution. Using the Fischerscope HM2000 from the Helmut Fischer GmbH, the hardness distribution is obtained in accordance with ISO 14577-1 at a testing load of 500 mN. The comparison of numerical and experimental results is given in Figure 2.

For the process forces, only small deviations are visible. The force curves show good compliance for the linear elastic forming at initiation of the process as well as in the phase of plastic material deformation. The ability of the simulation model to realistically predict the material’s mechanical properties is proven by correlating the degree of deformation $\phi$ with the hardness values. These two parameters are connected due to an increased hardness induced by a high degree of deformation, which causes strain hardening [12]. Both simulation models predict the strain hardening behaviour of the material in a precise way. In conclusion, the good concordance of numerically calculated values with experimentally measured parameters enables the use of both simulations models for the determination of the friction factors.

In the experimental procedure for pin-extrusion and ring-compression, the four lubricants are applied onto the specimen surface in a quantity of 10 g/m². Figure 3a shows the height of the specimen $h_s$ after the pin-extrusion test with $n = 4$ experiment replications, distinguishing between four applied lubricants.
A lubrication system using Beruforge 150DL results in the lowest height with 2.13 ± 0.002 mm. For all Raziol lubricants, the specimen and therefore the extruded pin is higher than for Beruforge 150DL. With rising viscosity, the height rises from 2.26 ± 0.003 mm to 2.48 ± 0.004 mm.

Figure 3: Inner specimen diameters (a) and corresponding friction factors (b) in the pin-extrusion test.

The larger specimen heights and therefore higher friction factors in Figure 3b of all Raziol lubricants in comparison to Beruforge 150DL is justified by the additive substances. At elevated surface pressure, the wax particles, included in Beruforge 150CL, lead to a friction reduction in the pin-extrusion test. Since all three Raziol lubricants are designed for sheet metal forming at low surface pressure, the oil is pressed out of the forming zone during testing. The increased friction is therefore caused by a direct contact between the tools and the specimen, resulting in friction factors of up to 0.13.

For the characterization of the friction system of 16MnCr5 specimens under lower contact pressure, the ring-compression test is used. The boundary conditions regarding lubricant types, amount of oil applied and testing speed are chosen in accordance with the pin-extrusion test to ensure the comparability of the results. Figure 4a shows the measured inner diameters of the ring-compression specimens after the upsetting process whereas Figure 4b presents the corresponding friction factors, which are identified using the numerical model.

Figure 4: Specimen diameters (a) and corresponding friction factors (b) in the ring-compression test.

For the ring-compression test with the Beruforge 150DL lubricant, an inner diameter of 10.69 ± 0.09 mm can be observed. The use of Raziol lubricants leads to smaller inner diameters with its minimum at 9.63 ± 0.06 mm for Raziol CLF 400E. A friction reduction with the use of wax containing lubricants is detected. This is similar to the ring-compression test, however the resulting friction factors are higher in the ring-compression test. The ring-compression test enables a free material flow in two directions, whereas in the pin-extrusion test, only a defined material flow into the die cavity is induced [9]. At an equal thickness reduction of 50% in both test variants, the contact normal stresses are consequently lower in the ring-compression test [9], leading to higher friction factors.
Besides its friction system, the suitability of the tool material 1.3343 for the fabrication of micro texturized punches is analysed. In the design of micro textured surfaces for the use in friction reduction applications of highly loaded lubricated body contacts, the height is a decisive parameter to influence the hydrodynamic pressure and therefore the lubricant’s film thickness [1]. The heights of cuboid textures, fabricated by EDM, are accordingly analysed for the high speed tool materials 1.3323 and 1.3244. As can be seen in Figure 5, the aimed height of each texture element is 15 µm while the target edge length varies between 15 µm and 30 µm.

It can be observed for both materials, that a higher edge length has a beneficial influence on the height accuracy. This is due to a larger top surface, when fabricating textures with a larger edge length, which is not affected by unintentional detaching of particles in direct contact to the carbide electrode. For textures with a smaller edge length, the electrode is closer to the top surface centre and therefore negatively affects the overall height accuracy more than for textures with a higher edge length. Nevertheless, the height accuracy reaches saturation at an edge length of 20 µm. Furthermore, a material-dependent difference in the height accuracy is visible. The absolute height deviation for 1.3343 results in range between 1.7 µm and 3.8 µm whereas the range for 1.3244 is found between 0.8 µm and 2.3 µm. The use of powder metallurgical steels like 1.3244 can thus be a potential approach to enhance the height accuracy in the fabrication of micro textured forming tools. A comprehensive analysis of the manufacturing limits demands the investigation of additional structural variants. For this purpose, the heights of three texture variants are compared in Figure 6. Besides the cuboid structures, cylinders and prisms with concurring target edge length and diameter are selected.

Figure 5: Heights of cuboid textures of the tool materials 1.3343 and 1.3244 fabricated by EDM

Figure 6: Heights of cuboid, cylinder and prism textures of 1.3244 fabricated by EDM
All four size variants show a form-dependent height accuracy behaviour. Cuboid structures fit the target height of 15 µm best, followed by cylinder elements. In all size variants, the lowest height accuracy is detected for prism texture elements. This is due to the larger separation of the carbide electrode from the element’s top surface when performing the layered contour erosion. Structures with a target edge length respectively diameter of 15 µm are furthermore found to be influenced most by production inaccuracies, regardless of the geometrical form. This is in line with the findings for Figure 5. Regarding the element height, the selection of elements with a minimum edge length or diameter of 20 µm is therefore beneficial to narrow the manufacturing deviations.

4. Summary and outlook

The investigation has shown a methodology for the qualification of tool materials for the production of components with micro structured surfaces. To characterize the friction system of the high-speed steel 1.3343, the pin-extrusion test and the ring-compression test were used. In the combined experimental and numerical approach, the friction factors with four lubricant variants were identified. In both tests, the application of the bulk forming lubricant Beruforge 150DL leads the lowest friction factors, in comparison to the tested sheet metal forming lubricants from Raziol. Furthermore, the tool materials 1.3342 and 1.3343 were examined, regarding the suitability for the fabrication of microscopic texture elements by electrical discharge machining. In general, the powder metallurgical steel 1.3244 meets the target dimension better than 1.3343. A minimum edge length for cuboids and prisms and a diameter of 20 µm has a beneficial influence on the structure accuracy. In further investigations, measures to enhance the overall accuracy of the process are to be developed. In this context, an overcompensation of the target value as well as an adjustment of the electrode diameter is conceivable.

5. References

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