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Tribological Performance of Textured Micro Forming Dies

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Abstract

Aim of this work is the tribological investigation of micro structured surfaces generated by micro milling and the performance testing of a micro structured micro deep drawing die. Three samples exhibiting different micro structured surfaces with arithmetical mean heights Sa in a range of 148 nm to 741 nm were manufactured by micro milling. The surface texture is determined by the process parameters of the micro milling operation. Tribological properties of the micro structured surfaces were investigated by means of a ball-on-plate micro tribometer and compared to those of a polished reference sample (Sa = 24 nm), a clear dependence of the frictional properties on the surface roughness was found. Lowest friction μ =0.26 was achieved for the sample with a roughness Sa = 148 nm. Surfaces with higher or lower roughness provoked increased friction in tribological testing being associated with an interlocking of surface's asperities or dominant adhesion, respectively. Subsequently, micro structures were machined into the surface of a micro deep drawing die for drawing of rectangular micro cups. The performance of this die was tested in deep drawing experiments against a polished reference die by means of achievable drawing ratio. At this stage the full advantage of the micro structuring of die surfaces was not achieved, yet. Still particular challenges within the micro regime, e.g. alignment of punch and die as well as blank positioning, have to be improved.

Keywords: Micro deep drawing, tribology, textured surfaces

1 Introduction

Innovative micro replication techniques such as micro metal forming allow the economic mass manufacture of smallest parts fulfilling mechanical functions, and, thus, to cover new market demands. However, miniaturized processes have to deal with size effects. In micro deep drawing adhesion forces between forming dies and work pieces become more dominant and affect the achievable drawing ratio [1]. Microstructured forming die surfaces can support the forming process by controlling the frictional behavior, especially under dry conditions. Brinksmeier et al. demonstrated the tribological function of micro structured surfaces generated by raster micro milling with ball-endmills in strip drawing tests under dry conditions [2]. A reduction of the coefficient of friction down to 0.21 was observed for surfaces exhibiting an arithmetical mean height Sa of 200 nm to 400 nm, compared to a polished reference sample (Sa = 30 nm) with a coefficient of friction of 0.26. The design of such "quasi-deterministic" surface textures generated by micro milling is primarily determined by the properties of the machined material, the cutting strategy (up- or down-milling), and the machining parameters width of cut a_e and feed per tooth f_z [3]. The transfer of micro structured surfaces to tribologically adapted forming dies is highly desirable, especially for dry forming tasks. Main advantage is the potential to manufacture the forming die's geometry and the tribological active micro structured surfaces in a single process step. The identification of most suitable micro structured surfaces characterized by areal roughness parameters according to ISO 25178 standard still remains a research topic. Even though strip drawing tests are suitably for necessary tribological investigations they suffer from time consuming preparation for each single test. The application of a micro tribometer instead can significantly reduce the testing time. This paper presents two consecutive steps towards the investigation and application of micro structured surfaces generated by micro milling: extended tribological investigations carried out on a micro tribometer and the transfer of micro structures to the surface of a micro deep drawing die and the investigation in deep drawing experiments.

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2 Tribological investigation of micro structured surfaces

2.1 Samples

Hardened 1.2379 (X153CrMoV12) tool steel with a hardness of 60 HRC ± 0.6 HRC was used as sample material for tribological investigations. This material is suitable for micro forming tools and is characterized by a fine grained micro structure. Three different micro structured samples (#1 – #3) were manufactured. The manufacture of the micro structured surfaces was carried out on a DMG Sauer US 20 linear micro milling machine tool under dry conditions. Tungsten carbide ball-endmills of 1.5 mm diameter were applied and the tool was aligned normal to the machined surface to enforce the generation of quasi-deterministic surface textures. The spindle speed n and the cutting depth a_p were kept constant at $n = 40{,}000\ \text{min}^{-1}$ and $a_p = 0.025$ mm for all three samples, whilst the width of cut a_e and the feed velocity v_f and the cutting strategy (up- and down-milling) were varied. Here, the selection of process parameter is derived from preliminary studies with the aim to provide a spectrum of micro structured surfaces relevant for the application to tribologically adapted forming dies. Besides the micro structured samples a reference sample (R) was manufactured by polishing. An overview of samples and machining parameter is given in Table 1.

Tab. 1: Samples, cutting parameter, and results of roughness measurements.

sample No.	width of cut	feed velocity	feed per tooth	cutting strategy	roughness
	a_e	v_f	f_z	-	Sa
	[mm]	[mm/min]	[µm]	-	[nm]
R	-	-	-	-	24
#1	0.045	1000	12.5	down-milling	148
#2	0.090	2000	25.0	up-milling	470
#3	0.045	5000	65.2	down-milling	741

The machined surfaces were measured by an optical profilometer (Sensofar PLu 2300). Plots of the polished reference sample surface and the three micro structured sample surfaces are given in Figure 1. The raw data were processed by an image processor (Scanning Probe Image Processor, SPIP™) to derive areal roughness parameters according to ISO 25178 standard (cut-off $\lambda_s = 0.25$ µm, cut-off $\lambda_c = 0.08$ mm). The results of the roughness evaluation are also given in Table 1.

2.2 Tribological investigation

The determination of the friction coefficients µ of the micro structured surfaces was carried out using a micro tribometer (Tetra BASALT MUST) with alternating linear motion. A 5 mm diameter Al99.9 ball was used for frictional testing. An overview of the test setup is given in Figure 2.

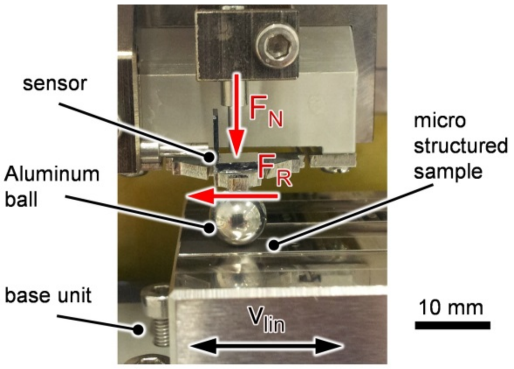

Fig. 2: Ball-on-plate setup for frictional testing on Tetra BASALT MUST micro tribometer.

A normal force F_N of 100 mN was applied for testing. All experiments were carried out under dry conditions The testing direction with respect to the micro structured surface was always parallel to the feed direction of the micro milling process. The stroke length of the linear motion was 4 mm and the test velocity v_{lin} was 4 mm/s. One test procedure included 10 cycles of forward and backward motion. During the movement of the sample the applied normal force F_N and the resulting friction force F_R were recorded. 100 data points were collected for each forward and backward motion. The average values of the coefficient of friction µ as well as the maximum and minimum deviation were calculated for each forward and backward motion from the measured normal and friction forces. All measurements were repeated four times.

2.3 Results of tribological investigation

An exemplary development of the coefficient of friction as a function of the number of cycles of the experiment and the direction of motion is given in Figure 3 for the polished reference sample. The error bars indicate the minimum and maximum values measured for each single cycle. The variance of the coefficient of friction during one single motion can be explained by the occurrence of stick-slip. Similar distinctiveness of stick-slip was found for all the surfaces under test.

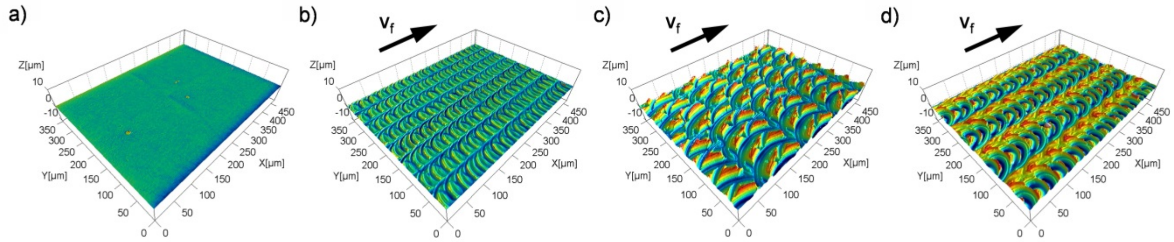

Fig. 1: Surface plots of samples applied in tribological testing: a) polished reference sample R (Sa = 24 nm), b) sample #1 (Sa = 148 nm), c) sample #2 (Sa = 470 nm), and d) sample #3 (Sa = 741 nm).

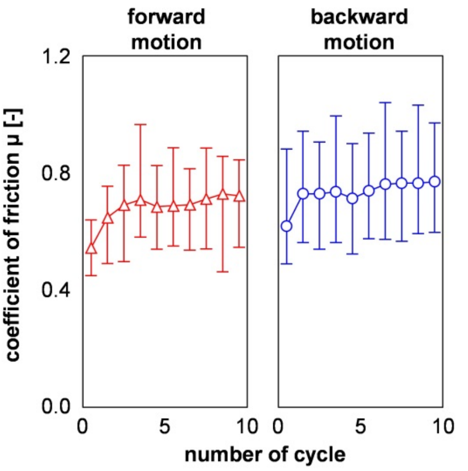

Fig. 3: Coefficient of friction μ for the reference sample as a function of the number of cycle and the direction of motion.

The mean values of the coefficient of friction for every micro structured sample and the polished reference sample were calculated from the four repeated experiments for both, forward and backward motion. The results are given in Table 2. A clear dependence of the frictional properties on the surface roughness was found. The highest friction was observed for the polished reference sample with a mean value of the coefficient of friction up to μ = 0.85. The minimum average coefficient of friction μ = 0.26 was derived for sample surface #1 with an arithmetical mean height Sa = 148 nm. The coefficient of friction again increases for the samples #2 and #3 exhibiting rougher surfaces. Contrary to expectations, the sample surface #2 with an arithmetical mean height Sa of 470 nm provoked higher friction (average coefficient of friction up to μ = 0.53) than the roughest samples surface #3 with a roughness Sa = 741 nm. For this sample surface an average coefficient of friction μ = 0.44 for both directions of motion was obtained. A dependence of the coefficient of friction μ on the direction of motion was not observed for any of the surfaces under test; mean values for forward and backward motion remained almost identical for every experiment.

Tab. 2: Samples, cutting parameter, and results of roughness measurement.

sample No.	roughness	coefficient of friction forward motion	coefficient of friction backward motion
	Sa	μ	μ
	[nm]	[-]	[-]
R	24	0.85	0.73
#1	148	0.32	0.26
#2	470	0.51	0.53
#3	741	0.44	0.44

3 Manufacture and testing of micro structured forming die

3.1 Micro deep drawing die manufacture

Hardened tool steel 1.2379 (X153CrMoV12, 60 HRC ± 0.6 HRC) was also chosen for the manufacture of micro deep drawing dies, Figure 4. Two dies were manufactured, both showing the same geometry of the drawing cavity as given in Figure 4 b). The cavity was generated by EDM and subsequently the finishing process of the die's surfaces was carried out by polishing or micro milling. The polished die was manufactured to serve as a reference. The polished surface can be described as smooth with a nondirectional structure with an average arithmetical mean height of Sa = 20 nm. The second die was micro structured by a milling process with a 1.5 mm diameter ball-endmill according to [2]; the cutting strategy was down milling. The feed velocity v_f, the rotational speed n, the cutting depth a_p and the width of cut a_e were set at v_f = 600 mm/min, n = 25,500 min^{-1}, a_p = 0.060 mm and a_e = 0.030 mm, respectively. Figure 4 c) shows the resulting quasi-deterministic texture with an orientation of about 45° relative to the feed direction and a roughness of Sa = 295 nm. The feed direction was selected to achieve an orientation of the microstructures perpendicular to the sheet material flow direction at the angle bisector of the cavity corner as displayed in Figure 4 c). Along this line the highest shear stress in the sheet material is expected during the deep drawing process [4]. At last, the drawing edge radius of 0.12 mm was manufactured by micro milling using a 0.3 mm diameter ball-endmill.

3.2 Deep drawing experiments

Aluminum A99.5 foil with a thickness of 15 µm was applied as blank material. The geometry of the blanks is shown in Figure 5 and was derived by FEM simulation according to [5]. The length l, the width w, and the radius required for different drawing ratios β_0 are given in Table 3.

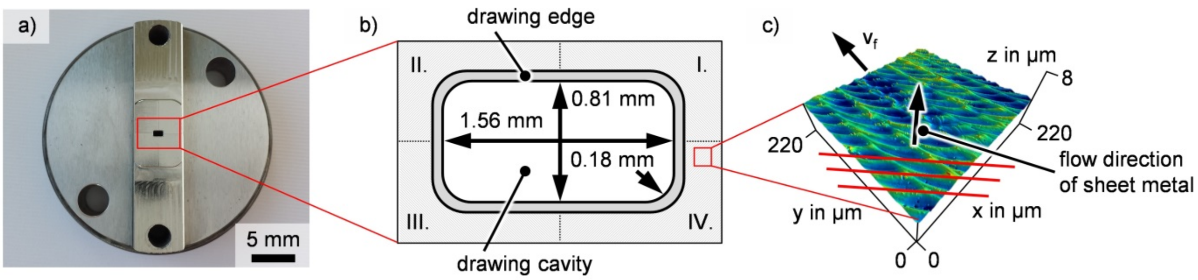

Fig. 4: Micro structured micro deep drawing die a), design of drawing cavity b), and topography of micro structured area c).

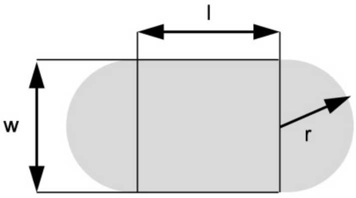

Fig. 5: Design of blanks for micro deep drawing of rectangular cups.

Tab. 3: Blank geometry for different drawing ratios.

drawing ratio β_0 [-]	radius r [mm]	length l [mm]	width w [mm]
1.3	0.616	0.576	1.232
1.4	0.663	0.620	1.327
1.5	0.711	0.664	1.421
1.6	0.758	0.709	1.516
1.7	0.805	0.753	1.611

The experiments were carried out on a two-axes micro forming press. The blank holder (polished surface) is driven by the lower axis. An integrated force measurement allows for the precise setting of the blank holder force. The blank holder pressure p_{bh} (pressure per unit area) applied to the blank before the actual drawing sequence is calculated in dependence on the clamped area of the blanks and the blank holder force. The blank holder pressure p_{bh} was varied at 0.5 and 1.0 N/mm^2. Generally, higher blank holder pressures are favorable to avoid wrinkles on drawn parts but also increase the probability of cup's base fractures. The drawing speed was kept constant for all experiments at 10 mm/s, Renoform HBO 947/11 oil was used as lubricant. The blanks were positioned manually on the drawing die for every experiment. After the drawing process the micro cups were investigated with an optical microscope. Parts exhibiting drawing defects such as base and wall fractures, or wrinkles were refused; compare Figure 6.

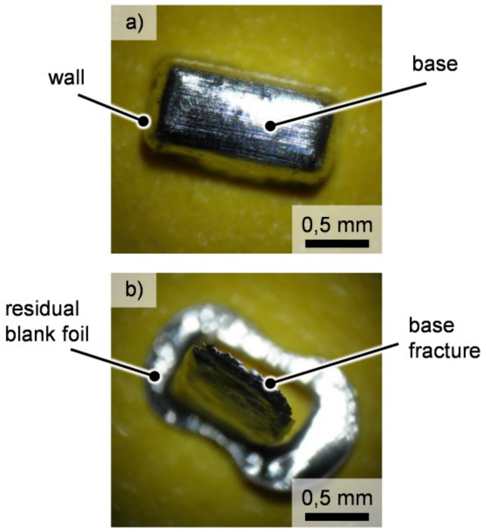

Fig. 6: a) Accepted part: rectangular micro cup with no drawing defects, and b) refused part: drawn rectangular micro cup with fracture of cup's base.

3.3 Drawing experiments results

Figures 7 a) and b) show the distribution of accepted and refused micro cups for the polished and the structured die, respectively. Refused parts could not be avoided by any of the combinations of blank holder pressure p_{bh} and drawing ratio β_0. Best results for the structured die were found for a blank holder pressure $p_{bh} = 0.5$ MPa and a drawing ratio $\beta_0 = 1.5$. However, no accepted parts were obtained at a blank holder pressure of 1.0 MPa. Additional experiments with a p_{bh} of 0.25 MPa and a drawing ratio β_0 of 1.6 allowed drawing only one accepted part out of ten.

4 Summary and conclusion

The tribological properties of structured surfaces generated by micro milling under dry conditions were investigated by means of a micro tribometer. A clear correlation of the coefficient of friction and the sample

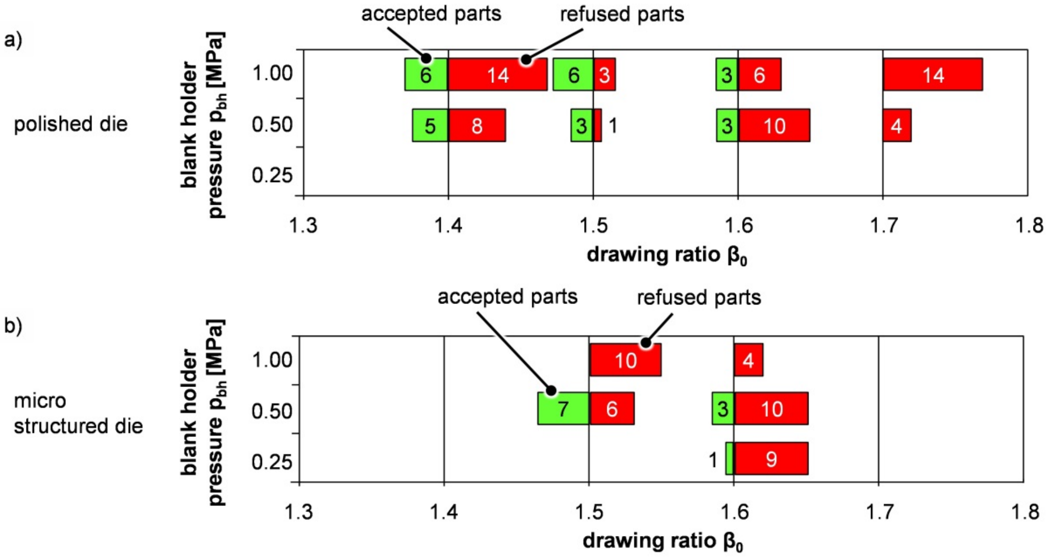

Fig. 7: Distribution of accepted and refused micro cups as a function of drawing ratios β_0 and blank holder pressure p_{bh} for the polished die a) and the micro structured die b).

surface's roughness was observed. The results of the tribological testing are summarized in Figure 8. To support clarity, no error bars are displayed in the diagram.

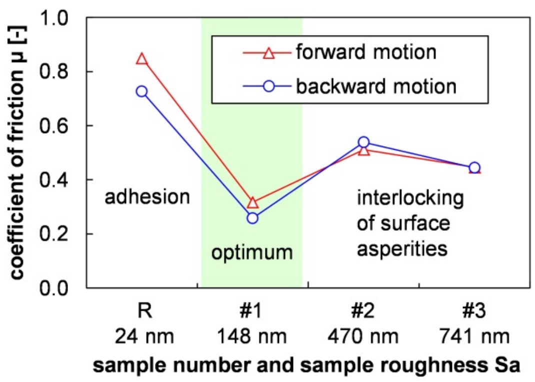

Fig. 8: Average coefficients of friction for forward and backward motion as a function of the sample number and the associated arithmetical mean height Sa.

The highest average coefficient of friction was measured for the polished reference surface with μ up to 0.85. This is drawn back to predominant adhesion due to an increased area of effective contact between the sample surface and the Aluminum ball. The lowest value of μ was obtained for sample surface #1 with an arithmetical mean height Sa = 148 nm. The two samples with rougher surfaces provoked increased friction. However, the sample #3 exhibiting the roughest surface (Sa = 741 nm) exhibited slightly lower friction compared to sample #2 (Sa = 470 nm).

Generally it can be concluded, that the presence of a certain roughness can reduce the frictional properties of a surface in dry sliding contact. For the presented material combination, hardened tool steel and Aluminum Al99.9, the steel surfaces ideally should exhibit an arithmetical mean height Sa of about 150 nm to achieve minimum friction. Surface roughness lower than this value lead to an increased adhesion, roughness greater than 150 nm promote interlocking of surface's asperities, both associated with higher friction. Future work should comprise the correlation of the frictional properties of micro structured surfaces generated by micro milling with additional roughness parameters derived from ISO 25178 standard to allow an in depth understanding of the impact of roughness on the tribological performance of a surface under dry conditions.

Deep drawing tests of rectangular micro cups were carried out with a micro structured deep drawing die and a polish reference die. So far, a clear difference in the performance of the micro structured and the polished die was not observed. The micro structured die did not allowed to increase the achievable drawing ratio. A wide distribution of acceptable and refused parts could be observed for both dies. This is drawn back to the inaccuracy of the machining process for micro forming die manufacture and inaccurate punch and die alignment. Furthermore, the manual positioning of the blanks over the drawing cavity is expected to have a major influence on the deep drawing results. Before conducting further deep drawing tests to evaluate the tribological performance of micro structured surfaces, it is necessary to provide a more accurate setup that allows for deep drawing of acceptable rectangular micro cups.

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References

[1] U. Engel: U (2006) Tribology in microforming. Wear 260 3 (2006) 265-273.

[2] E. Brinksmeier, O. Riemer, S. Twardy: Tribological behavior of micro structured surfaces for micro forming tools. International Journal of Machine Tools and Manufacture 50 4 (2010) 425-430.

[3] E. Brinksmeier, O. Riemer, S. Twardy: Surface Analysis of Micro Ball End Milled Cold Work Tool Steels. Proceedings of the International Conference on Nanomanufacturing. 2 (2010) 173-177.

[4] E. Daxin, T. Mizuno, Z. Li: Stress analysis of rectangular cup drawing. Journal of materials processing technology 205 (2008) 469-476.

[5] Z. Hu: Realisation and application of size dependent FEM-simulation for deep drawing of rectangular work pieces. CIRP Journal of Manufacturing Science and Technology 4 1 (2011) 90-95.