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Tribological performance of micro structured surfaces generated by micro milling

Florian Böhmermann and Oltmann Riemer

LFM Laboratory for Precision Machining, University of Bremen, Badgasteiner Str. 2, 28359 Bremen, Germany

boehmermann@lfm.uni-bremen.de

Abstract
Industry has an ever increasing demand for metallic micro components. This, for example, can be related to increased complexity and the functional integration in modern consumer electronics. A cost effective manufacture of metallic micro components through micro metal forming appears to be the method of choice to fulfil industrial needs; however, a simple downscaling of well-known manufacturing processes does not lead to the desired results. This is mainly due to size effects, e.g. surface to volume ratio of formed parts. Current research addresses the controllability of such size effects to gain a robust design of forming processes as well as the development of dry forming processes. One approach is the tribological adaption of micro metal forming tools through micro structuring of the tool's surfaces. In this work the tribological performance of micro structured surfaces of hardened tool steel samples is investigated. Structures were manufactured by raster micro milling with different width of cut. The structures were characterised by means of areal roughness parameters Sa, Spk, Sk, and Svk according to ISO 25178 standard. Friction measurements were carried out with a micro tribometer with linear alternating motion. Brass balls with a diameter of 5 mm were used for frictional testing. The coefficient of friction derived from the measured normal and frictional force was correlated with the areal roughness parameters

Keywords: micro milling, tribology, micro forming

1. Introduction

Micro milling is a flexible technology for the manufacture of small deep drawing tools made from hardened tool steels. It meets the high requirements of geometric accuracy and surface finish even in smallest dimensions, what is crucial for a reliable micro deep drawing process [1, 2]. When applying micro raster milling, a distinct micro structure on the machined surfaces can be generated. This is assigned to plastic deformations of the work piece material due to low undeformed chip thickness and depending on the process parameters width of cut, the feed as well as on the material hardness [3]. Brinksmeier et al. showed the tribological effectiveness of such micro structures generated by micro milling in strip drawing tests under dry conditions, where a reduction of the coefficient about 0.05 was achieved for surfaces with an average roughness Sa of 200 nm to 400 nm compared to a polished surface [4]. The transfer of such structures can help to develop micro deep drawing tools exhibiting surfaces with well-defined tribological properties especially for dry metal forming. To further understand the tribological effectiveness and to avoid time-consuming testing by using a strip drawing test, tribological investigations of micro milled surfaces were carried out using a micro tribometer with linear alternating motion and a hardened steel ball [5]. The findings partially underlined the earlier results. However, the correlation in between the areal roughness parameter according to ISO 25178 standard and the frictional properties so far is not fully understood. In this paper a subsequent study is shown aiming on the correlation of areal roughness parameter and tribological performance of surfaces. Hardened tool steel samples were micro structured by micro milling varying the width of cut and investigated by an optical profilometer. Tribological investigations were carried out on a micro tribometer with a brass ball and the frictional properties were compared with the roughness parameters.

2. Experimental section

Eight micro structured samples were manufactured from 1.2379 (X153CrMoV12) hardened tool steel with a hardness of 60 HRC ± 0.6 HRC. The machining was carried out on a *DMG Sauer US 20 linear* micro milling machine tool under the use of cooling fluid. Each micro structured area was a square of 5 mm x 5 mm. Tungsten carbide ball-end mills of two different diameters (2.0 mm and 1.5 mm) were applied. The cutting strategy was down-milling. The tools were aligned normal to the machined surfaces. The feed velocity and the depth of cut were kept constant at v_f = 600 mm/min and a_p = 60 µm. The width of cut a_e was varied. Furthermore, one polished reference sample R has been manufactured. An overview on the samples and the process parameters is given in Table 1.

Table 1 Sample numbers and cutting parameters..

Sample No.	Diameter of mill d	Rotaional speed n	Width of cut a_e
1	2.0 mm	19 000 min^{-1}	100 µm
2			40 µm
3			20 µm
4			4 µm
5	1.5 mm	25 500 min^{-1}	75 µm
6			30 µm
7			15µm
8			3µm
R	-	-	-

3. Surface topography

A *Sensofar PLu 2300* optical profilometer with a lateral and vertical resolution of 100 nm and 2 nm respectively was used to measure the machined surfaces and the raw data was evaluated according to DIN EN ISO 25178 standard and the areal roughness parameters arithmetical mean height Sa, reduced summit height Spk, core roughness depth Sk, and reduced valley depth Svk. The results are given in Table 2

Table 2 Results of roughness measurements.

Sample No.	Roughness parameter (all in nm)			
	Sa	Spk	Sk	Svk
1	195	209	555	325
2	75	105	221	143
3	128	164	409	146
4	85	123	279	104
5	217	285	704	236
6	156	195	500	203
7	117	132	373	155
8	66	85	213	78
R	17	24	50	26

4. Tribological investigation

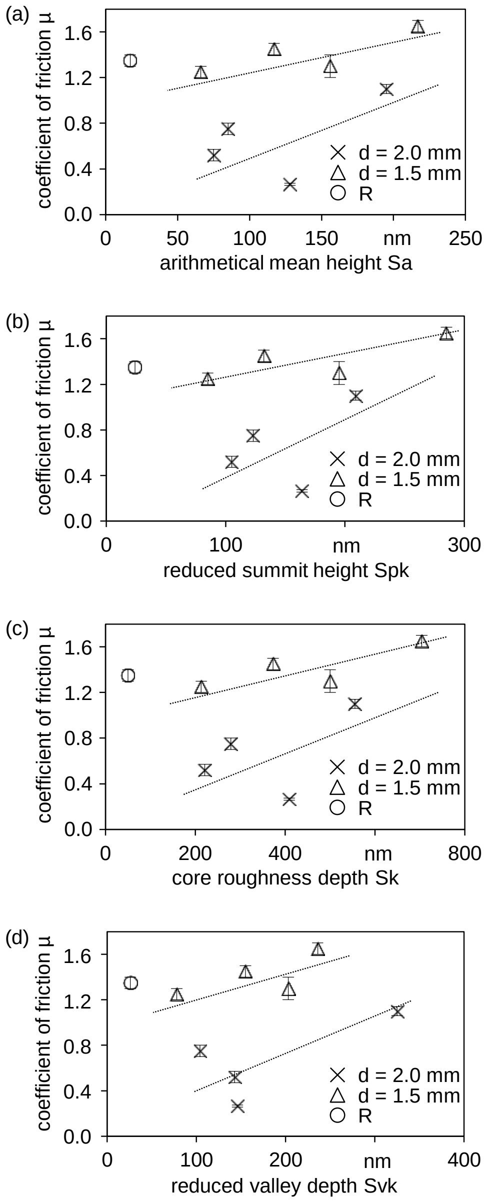

Figure 1. Measured coefficient of friction µ in dependence on areal roughness parameters Sa (a), Spk (b), Sk (c), and Svk (d).

The evaluation of the coefficient of friction was carried out on a *Tetra Basalt MUST* micro tribometer with linear motion. A new MS63 brass ball (d = 5 mm) was used for every experiment. The stroke length was 4 mm, the test velocity 5 mm/s, test direction was in feed direction of the milling process, and a normal force F_N of 100 mN was applied. The frictional force F_R was recorded for 100 cycles of forward and backward motion. The coefficient of friction was calculated from the forces subsequently. For all experiments the coefficient of friction increased with the first 30 cycles. The average coefficient of friction after the 30th cycles for each surface under test is in dependence on the measured areal surface roughness parameters is displayed in Figure 1.

5. Results and Discussion

All measured coefficients of friction are of relatively high values and spread over a range from µ = 0.27 to 1.65. This can be explained by a stronger impact of the adhesion on the samples in tribological contact in the micro regime. The polished reference surface exhibits a coefficient of friction of 1.35 what can be related to the predominant adhesion. Lower friction was observed for samples with an average roughness Sa in between 85 nm and 128 nm, although the sample No. 7 (Sa = 117 nm) has a considerably higher coefficient of friction. The minimum coefficient of friction was measured for the sample surface No. 3 with Sa of 128 nm. The sample with the highest roughness Sa also exhibits the highest coefficient of friction µ. In general the coefficient of friction increases with higher roughness, that can be explained with a ploughing of the sample's surface asperities in the surface of the comparably soft brass ball. A significant correlation of the tool used for surface generation and the frictional properties can be observed. Surfaces manufactured by a 2.0 mm diameter ball-end mill generally exhibit lower coefficients of friction µ. This effect could be associated with the material removing mechanisms depending on the micro geometry of the main cutting edge.

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