Impact of liquid lubricant on the flattening behaviour of single asperities

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Abstract

Scaled friction tests show that in micro forming applications friction is increasing significantly when forming processes are scaled down. This phenomenon can be explained by the model of open and closed lubricant pockets characterising the surface topography: the forming load is transmitted from the tool to a lubricated workpiece by three different bearing ratios. These are the real contact area (RCA) as well as open (OLP) and closed lubricant pockets (CLP). The developing hydrostatic pressure which is built up in CLPs takes a part of the external forming load, thus reducing the normal pressure on the asperities leading to a decrease in friction.

With miniaturisation in micro forming applications, the ratio of CLPs is reduced drastically as the surface topographies are mainly invariant to scaling. Thus, the forming load is mainly transmitted by the remaining RCA leading to an increase in friction. Hence, the interface between tool and RCA has to be investigated in more detail for the characterisation of the tribological conditions in microforming. In contrast to the macroscopic approach, where the RCA is assumed to be flattened completely, in microforming submicron effects within the RCA have to be considered.

In order to investigate the contact state in the RCA a novel, high-resolution experimental set-up has been developed which enables the measurement of the force-displacement characteristics during flattening the surface topography, and simultaneously, the in-situ observation of the developing real contact area by using a translucent tool. Thus, the deformation behaviour of idealised asperities represented by pyramids with a base area of 120 x 120 µm² and a height of 32 µm can be examined. In-process measurement is complemented by post-process topography analysis.

The present paper will present recent results and experiences obtained by the investigations described above. The detailed knowledge about the evolution of surface topography is relevant in particular to microforming but also for an improved understanding of tribological phenomena in general.

Keywords: microforming, tribology, surface characterisation, asperities

1. Introduction

Due to the ongoing trend towards higher integrated functional density and miniaturisation of electronic and micromechanical components the demand for metallic parts with dimensions in the sub-millimetre range increases steadily [1]. For an economic production of these parts in large quantities and with high accuracy, forming technology seems to be a suitable manufacturing method. However, the knowledge from metal forming in conventional length scale cannot be simply transferred to the micro world as so-called size effects appear. One of these effects consists of a significant increase in friction when scaling down forming processes to micro dimensions [2, 3]. This size effect in friction has been investigated by scaled ring compression tests for the first time revealing an increase in friction with miniaturisation. A more detailed study [4] using a double-cup-extrusion (DCE) test, which reproduces the conditions appearing in cold forging processes very well, confirms these findings and suggests a theoretical approach based on the mechanical-rheological model [5] to understand and describe this size effect.

The mechanical-rheological model assumes that the forming load is transmitted from a forging tool to a lubricated workpiece by three different bearing ratios. These are the real contact area (RCA), open (OLP) and closed lubricant pockets (CLP). As CLPs have no connection to the edge of the workpiece (fig. 1a), the entrapped lubricant is pressurised while the forming load is applied. The developing hydrostatic pressure takes a part of the external forming load, thus reducing the normal pressure on the asperities leading to a decrease in friction. In case of lubricant pockets with a connection to the edge of the surface, the lubricant cannot be pressurised and is squeezed out with increasing normal pressure. These OLPs transmit only a negligible part of the forming load. It can be summarised that CLPs reduce friction in contrast to OLPs.
Miniaturising the forming process, thus the nominal contact area, things become quite different [3]: due to the invariance of topography to scaling, the ratio of CLPs is reduced drastically and forces will be transmitted more and more by the RCA which consequently will increase causing an increase in friction (fig. 1b). Hence, the interface state between tool and RCA gets predominant for the tribological conditions in micro forming applications. Thus, a long-standing question again gains in importance: are there still asperities on a flattened asperity, or in other words, is it justified to assume real contact within the RCA? The existence of a contact- or nano-topography emerging within these solid contact areas on top of flattened asperities has already been proposed by [6].

The aim of this project is the detailed characterisation of the flattening behaviour of single asperities and of the evolution of the contacting topography in order to improve the understanding of tribological phenomena in microforming.

2. Experiments

2.1. Experimental set-up

A high-resolution experimental set-up has been developed which enables the measurement of the force-displacement characteristics during flattening the surface topography, and simultaneously, the in-situ observation of the developing real contact area by applying a translucent tool. A principle drawing is shown in fig. 2. The test rig consists of a piezoelectric actuator with an integrated position sensor for the vertical movement of the specimens in 10 nm steps. The required force for flattening the asperities is measured by a load cell with high sensitivity. The translucent upper tool is designed as a frustrum with a diameter in the nominal contact area of 1.2 mm and is made of quartz glass. With a telecentric objective and a CCD camera the surface flattening of the specimens can be observed in-situ as illustrated in fig. 3 within an image area of 1.2 x 0.9 mm² and a resolution of approx. 2 µm.

2.2. Specimens and methods

Technical surfaces which are produced by turning or grinding for example, are not very well suited for basic investigations due to poor reproducibility of the results. Instead, pyramids with a base area of 120 x120 µm² and a height of 32 µm are used as idealised asperities (fig. 3a). Additionally, frustrums of a pyramid with a height of 20 µm, which are produced by pre-flattening of the above mentioned pyramids are examined (fig. 3b). Besides good reproducibility, interactions between adjoining asperities are avoided as they are located in an array with a distance of 1 mm between each element. The specimens are made of OFHC (Oxygen-Free High-Conductivity) copper at the Laboratory for Precision Machining at the University of Bremen. The upsetting experiments are carried out with and without liquid lubricant in order to evaluate its influence on the flattening behaviour. For lubrication a mineral oil mixed with a dye has been used for enhancing the contrast. In-process measurement is complemented by post-process analysing the topography by means of confocal microscopy, scanning electron microscopy (SEM) and scanning probe microscopy (SPM).

3. Results and discussion

3.1. Force-displacement characteristics

Fig. 4a shows the average force-displacement-curves in case of specimen type 1 (no pre-flattening) for performing the upsetting tests with and without lubricant. The required force for flattening the pyramid increases steadily due to the increasing contact area. The complete flattening of the pyramid is indicated by the intense increase of the required force at a punch position of approx. 30 µm. At this point the whole specimen contacts the upper tool, leading to a strong increase of contact area and force. Thus, the maximum force for flattening pyramids is approx. 3 N.

The use of lubricant is supposed to decrease the friction in the contact area between tool and pyramid, resulting in lower frictional forces. Thus, the required force for flattening the pyramid should decrease when lubricant is used. As fig. 4a shows there is no significant difference between the force-displacement-characteristics of the lubricated and the non-lubricated case.
With respect to the force-displacement-curves of specimen type 2 (31 % pre-flattening) illustrated in fig. 4b, there is a slight tendency to reduced forces when lubricant is used. This is an indicator for the change of friction conditions in the contact area which can be attributed to the formation of smallest CLPs in the contact area.

3.2 Evaluation of contact area

Fig. 5 presents images of the contact area which have been taken through the translucent tool at a forming force of 2.5 N. The contact area is represented by white and grey tinted pixels while the non-contacting flanks of the pyramids are visible as black regions. Due to the small film thicknesses, lubricant is translucent and not directly visible. Regarding frustrums of a pyramid (left column), various topography features like dimples and valleys are visible in the contact area when lubricant is used. After unloading, these topography elements have a depth up to 120 nm (measured by confocal microscopy). In contrast to the lubricated case, there are hardly any pits or valleys observable when no mineral oil is used for upsetting. Due to the different topography evolution, it is assumed that so-called nano-CLPs emerge within the real contact regions when frustrums of a pyramid are upset. Regarding the topography evolution of the pyramid (right column), there is no significant difference between the lubricated and the non-lubricated case. Obviously, the lubricant is squeezed out of the contact area due to the geometrical conditions.

In case of frustrums of a pyramid, the nominal contact area is significantly higher for the lubricated case compared to the non-lubricated case indicating less resistance against lateral material flow, thus less friction in the contact area. Hence, the lubricant has an impact on the friction conditions under certain geometrical conditions of the specimens which could be attributed to the formation of nano-CLPs within the real contact area.

4. Summary and outlook

In microforming applications the contact state between the tool and workpiece is characterised by the existence of only a few asperities and hardly any closed lubricant pockets leading to an increasing influence of single asperities on the frictional behaviour. Thus, the nanotopography emerging on top of flattened asperities has to be taken into account for friction modelling in the surface pressure calculated from the force-displacement curves of the flattening experiments. The light-coloured areas indicate contact between tool and workpiece. It can be clearly seen that the surface is not completely flattened even though the contact pressure is over-estimated. This can be taken as an evidence that a nanotopography exists on top of single idealised asperities, where submicron lubrication effects can occur.

In order to determine the influence of the nanotopography on the friction conditions, the nominal contact area is measured through the translucent tool at different load stages for both specimen types (fig. 7a). For flattening the pyramid there are no significant differences detectable between the lubricated and the non-lubricated case. Obviously, the lubricant is squeezed out of the contact area due to the geometrical conditions.

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microforming processes. For a detailed analysis of the flattening behaviour of single asperities and the interactions between nano-topography and liquid lubricant, upsetting tests have been performed with idealised asperities represented by pyramids with a base area of 120 x 120 µm² and a height of 32 µm. Additionally, the flattening behaviour of frustrums of pyramids with a base area of 120 x 120 µm² and a height of 20 µm has been investigated.

The results show that under certain geometrical conditions a nanotopography can occur within the real contact area which has an influence on the friction conditions. The existence of this nanotopography has been proven by in-situ observation of the contact area and by simulation based indirect measurement of the contact area.

The influence of liquid lubricant on the forming behaviour is closely linked to the initial shape of the asperity. Regarding the force-displacement-characteristics, a slight tendency towards lower forces for upsetting with lubricated specimens is only visible for frustrums of pyramids. This could be explained by lower friction forces as a result of lubricant being entrapped in the contact area between tool and specimen. These findings point out that within this nano-topography, closed lubricant pockets emerge leading to a reduction of friction forces. If regularly shaped pyramids are flattened, no difference in the force-displacement characteristics is noticeable. It could be assumed that due to the geometrical conditions the major part of lubricant is squeezed out of the contact area. Thus, there is no impact of the lubricant on the forming process. These findings are confirmed by the analysis of the evolving contact area: When frustrums of pyramids are flattened the contact area is larger at defined load stages in the lubricated case. Furthermore, this effect indicates a reduction of friction forces in the contact area due to lubricant, thus the evolution of a sub-topography in the contact area with nano-CLPs. The evolution of dimples is also noticeable in the CCD-camera image of the specimen surface contacting the tool.

Further investigations have to resolve in detail the geometrical condition that such a nanotopography can emerge. Additionally, the influence of the microstructure of the workpiece material on the formation of the nanotopography has to be investigated in detail. The detailed knowledge about evolution of surface topography is essential in particular for characterising the workpiece surface concerning its frictional behaviour in microforming applications but also for an improved understanding of tribological phenomena in general.

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References