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Material removal mechanisms and deformation analysis by flycutting tests with round and polygon shaped tools on AISI4140 steel

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Abstract
Results from flycutting tests on a workpiece made of 42CrMo4 steel (AISI4140) are presented. To obtain information about the deformation without material removal as it applies e.g. during deep rolling and the deformation superimposed by material removal as it occurs in material removal processes like turning or precision grinding, specific single-contact tools with different shapes were used. One of them had a small deep rolling ball on the tip and the others single cBN grains normally used in grinding wheels. The cBN grains had a diameter of approximately 0.6 mm, which is comparatively big for a grinding grain, and the used ball a diameter of approximately 1.2 mm is comparatively small for a deep rolling tool in order to generate comparable contact sizes. A variation of cutting depth a_e was applied to identify the correlation of this parameter and the material modification. As modifications, the relative chip volume (f_{ab}-value) was evaluated to describe the surface properties. Nevertheless, all tools cause scratch shapes giving insights regarding the amount of deformation and material removal and correlations of the process parameters and loads. The results contribute to an understanding of the material deformation and removal mechanisms close to minimum chip thickness which occur in multiple mechanical manufacturing processes in precision engineering.

Flycutting, material deformation mechanisms, material removal mechanisms, deep rolling, grinding, steel

1. Introduction

For improving surface quality in finishing processes, mechanical surface treatments like grinding and deep rolling are often used. The grinding process is characterized by chip removal based on effects like micro-ploughing, micro-grooving and micro-chipping. In contrast, deep rolling is a forming process inducing plastic deformation of roughness peaks. In both processes, the obtained surface quality is a result of the interaction of the tool and the workpiece under consideration of the internal load within the contact area. Klocke [1] describes three phases of surface generation mechanisms: elastic and elasto-plastic deformation and the chip removal. However, the exact mechanisms are hard to observe in a grinding and deep rolling process.

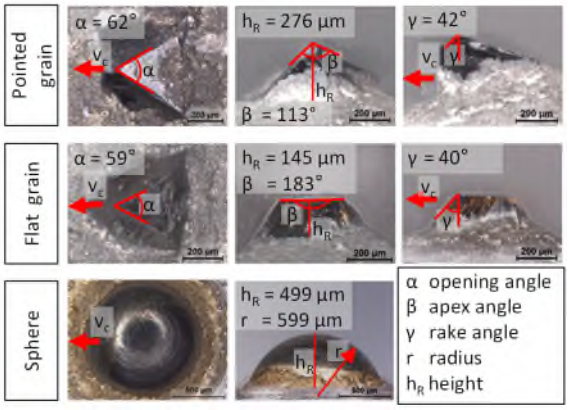

Figure 1. Flycutting tools and orientation of angles

Flycuting experiments enable the possibility of analysing single tool contacts in the material and the resulting topography. Rasim et al. investigated the influence of different tool shapes of CBN grains on the beginning of plastic deformation in single grain scratch test [2], while Anderson et al. use a spherical tool to analyse the transitions between elastic to elasto-plastic deformation to plastic cutting [3]. In the presented work, flycutting is applied to generate single separated scratches using tool geometries comparable to grinding and deep rolling. Hence, the variation of contact conditions was selected widely from a spherical tool tip shape, similar to deep rolling, to sharp polygonal and flat grains typically for grinding processes. The tool geometry was varied in a way which aimed at deducing a better knowledge regarding the deformation and material removal mechanisms in grinding and deep rolling processes.

2. Experimental Setup

For the characterisation of the influence of contact conditions, flycutting tests with spherical and polygonal tools were performed. In order to achieve a comparable mechanical impact, the tools were designed in a similar diameter range with a grain diameter of approx. d_g = 600 µm and diameter of the sphere of d_s = 1198 µm. The tools are shown in figure 1. The two grains differ in the size of the opening angle α, while they show a comparable orientation in the direction of tool speed, so that a pointed and a flat tool contact surface result. For the experimental investigations, workpieces made of AISI4140 with a ferritic-perlitic microstructure and surface hardness of 257 HV1 were used. The surface was pre-polished to a roughness of Ra = 0.074 µm.

To quantify the material removal and deformation, single contact scratches were induced using an air bearing spindle combined with a controlled radial feed axis. By the rotation of the spindle with a cutting speed v_c of 1 m/s the tool performs a circular motion resulting in a curved contact with the

workpiece surface with varied cutting depths (a_e = 0.5 µm to 10.0 µm) under dry conditions. A translatory feed motion of v_f = 0.7 mm/s ensures sperated scratches. Simultaneous force measurements enable the analysis of normal and tangential forces.

3. Results

The topography after flycutting is investigated using a white-light interferometer to describe surface modification depending on the mechanism during mechanical impact of single contacts with varied tool geometry. Figure 2 shows exemplarily the topography of single scratches for the three tools for a cutting depth of a_e = 4 µm. All tools have the same height of the tool tip, ensuring a constant contact length independent of the tool. Transversal cross-sections in the middle of the calculated contact length enable an analysis of the scratch geometry and the maximum scratch depth $z_{s,max}$. For the pointed grain and the spherical tool, the tool shape reflects the resulting topography of the scratch. The pointed grain leads to a sharp profile of the scratch, characterised by a scratch depth $z_{s,max}$ comparable to the cutting depth a_e and low height of pile-ups. This is assumed to be a typical scratch shape for grinding process contacts dominated by micro-chipping and micro-ploughing. Wheareas the spherical tool leads to a reduced scratch depth $z_{s,max}$ while the pile-ups are significant, as assumed in deep rolling processes. This indicates a higher elastic as well as a plastic material deformation caused by the large apex angle β of the sphere leading to a lateral flow of the material. In contrast, the flat grain shows an asymmetric profile and significantly higher maximum depth of the scratch $z_{s,max}$ compared to the cutting depth a_e. In addition to the chip cutting, a pit formation can be observed. In contrast to the constant contact length, the scratch length varies in dependence of the tool geometry, whereby the spherical and the pointed tool show a similar length, while scratch length of the flat grain is significantly higher. This enables conclusions regarding the dominating elastic deformation at the onset of the contact.

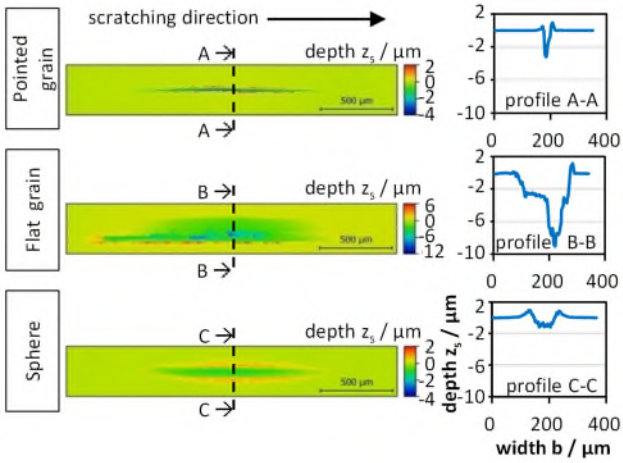

Figure 2. White-light interferometer measurement of scratches for varied tool geometry

To describe the removal mechanism in dependence of the contact conditions and the resulting scratch geometry, the relative chip volume f_{ab} applied by Brinksmeier et al. [3] was used. The relative chip volume f_{ab} describes the relation between the area of the cross-section of the scratch to the area of the piled up material, whereby the $f_{ab} = 0$ describes a dominating deformation and $f_{ab} = 1$ characterises ideal cutting. For this, cross-sections transversely to the scratching direction at the middle of calculated contact length were generated allowing the analysis of the max. scratch depth $z_{s,max}$ of this cross-section (see fig. 2). Figure 3 shows the development of the relative chip volume f_{ab} over an increasing maximum scratch depth $z_{s,max}$ for the different tools applying different depths of cut a_e. The plotted graphs of each tool are the result of single scratches with varied depth of cut a_e from 0.5 to 10.0 µm. Three replicates of each experimental condition are presented to analyse the divergence of measurement. Depending on the tool shape and the resulting contact area, the relative chip volume f_{ab} covers nearly the whole range from deformation to cutting. For low cutting depth a_e, the spherical tool is characterised by almost pure deformation, whereas an exponential growth of relative chip volume f_{ab} occurs for increasing cutting depth a_e. With increasing cutting depth a_e of the pointed grain, the relative chip volume f_{ab} shows a slight increase, whereby the dominating mechanism changes from micro-ploughing to micro-cutting ($f_{ab} > 0.5$). The dominating mechanism for the flat grain is cutting as shown by the high f_{ab}-values. In contrast to the other tools, the experimental investigations of the flat grain were reduced to a cutting depth a_e of 4 µm caused by the high nomal forces of F_n = 54.2 N. Nonetheless, the maximum scratch depth $z_{s,max}$ of the flat grain register the highest values despite the reduced cutting depth a_e and are characterised by a divergence in the measurement values.

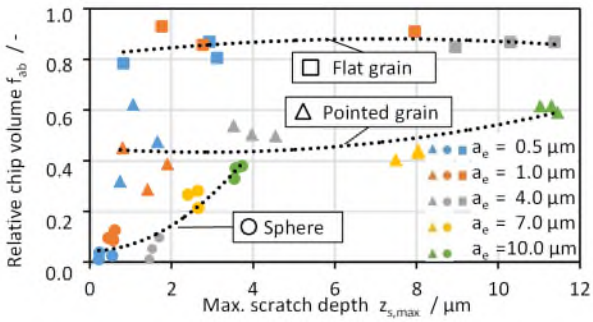

Figure 3. Relative chip volume as a function of the cutting depth in dependence of the tool geometry

4. Conclusion

The presented results show the influence of the contact geometry on the material removal and deformation mechanism in single-contact flycutting. It can be confirmed that the geometry of the tool strongly influences the dominating material removal and deformation mechanism. In a range from elastic deformation induced by low cutting depth a_e and a spherical tool over a ploughing of the pointed tool independent of the cutting depth a_e to resulting pits induced by a flat, polygonal tool the topography can be affected. Additionally, the ratio of removed to plastically deformed material increases with a spherical single contact tool to a pointed grain tool. Nevertheless, the intensity of the surface modification is depending on the process load. The flattened grain provokes a high mechanical load on the material surface which causes plastic deformations but it also resulted in pits.

Acknowledgment

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