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Detailed analysis of microstructure of intentionally formed built-up edges for improving wear behaviour in dry metal cutting process of steel[☆]

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ABSTRACT

Tool wear is a very important factor determining tool life and surface quality of a machined workpiece surface. In the range of small cutting geometries the cutting depth can be in the range of the cutting edge radius, hence, it promotes the development of built-up edges (BUE). A systematic and comprehensive examination of built-up edge formation and associated microstructural features is still lacking. In the present study a targeted examination of microstructural features of the built-up edge was carried out with uncoated WC/Co as cutting tool and SAE 1045 steel as workpiece material. The process parameters were chosen so that the built-up edge formation was provoked.

The dimensions of the built-up edge were assessed by light-optical microscopy (LOM) and scanning electron microscopy (SEM). The microstructure of the adhering built-up edge was revealed using new nonconventional metallographic methods. The nanocrystalline grain structure of the built-up edges was analysed by means of focused ion beam (FIB) inspection and preparation as well as transmission electron microscopy (TEM) in combination with energy-filtered TEM (EFTEM). The investigated built-up edges showed a highly deformed microstructure and a possible protecting effect could be concluded with respect to the cutting tool for certain cutting speed regimes. The built-up edge can be considered as a protecting surface layer formed in-situ during the metal cutting process with different microstructural states of ferrite and cementite. The developed microstructures show similar properties as microstructures produced by severe plastic deformation processes.

In addition to built-up edge and wear examinations, the resulting surface layer states in the machined workpiece were determined using a stylus instrument for surface roughness measurement and by means of X-ray diffraction for residual stress analysis.

1. Introduction

Comprehensive knowledge about the contact-zone behaviour between the cutting tool and the workpiece and about the chip-forming process is essential to evaluate and optimise the machining of metals. This importance arises due to the fact that the surface integrity of the machined workpiece is influenced by the chip formation zone and the tool wear is highly affected by the contact conditions between cutting tool rake face and chip, respectively, and by the cutting tool flank face and the workpiece [1]. For further improvement in the knowledge of wear behaviour of cutting tools, the surface layer states of the worn tools are important to distinguish different wear mechanisms acting in the cutting zone. In some application as micromachining and metal cutting of ductile materials the built-up edge phenomenon is an issue of particular importance. These layers consist of highly deformed material of the workpiece material, which is bonded on the rake face and cutting edge of the cutting tool [2], [3]. The affected zones are also known as dead zones, where metal remains as a stagnant layer in a region between cutting tool, chip, and workpiece [4]. The layers′ microstructure of different workpiece materials was examined by Wallbank [5]. Here, built-up edges from quick-stop tests were investigated by classical

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metallography and TEM-analysis. These examinations revealed a very fine grain structure (grains in the range of some hundreds of nanometres) and deformation structure comparable to structures found in drawn wires. The observed microstructure for low carbon steels consists of ferrite cells and pearlite colonies. The effect of wear-protecting properties and wear-promoting properties of built-up edges are often discussed in a controversial manner in literature e.g. [6,7]. Opitz and Gappisch [6] concluded that with increasing height of the built-up edge the flank wear is increasing but a protection against crater wear can be seen.

In the present study a more detailed view on the interface between built-up edge and cutting tool was performed to gain a deeper understanding on the built-up edge formation and about the bonding mechanisms. We expect the potential of protecting properties of the BUE, hence, the wear-acting mechanisms (adhesion wear) will be examined on the rake face and flank face of the cutting tool using elaborate and sophisticated analysis techniques. Complementary to conventional metallographic examinations using light optical microscopy (LOM) and scanning electron microscopy (SEM), target-preparation using FIB was used to extract TEM-lamellae. Via conventional and energy-filtered TEM the microstructure of the BUE layers and also of the interface between the cutting tool and built-up edge was systematically examined in detail.

Due to different cutting speeds used in the experiments the strain rates and temperatures varied such that the resulting microstructure is influenced by the cutting speed, where either wear-protecting or wear-accelerating properties are to be expected. Furthermore, the influence of tool wear and built-up edge formation on the surface layers of the workpiece were examined using a stylus instrument to reveal the surface roughness and by means of X-ray diffraction to analyse the local residual stress state induced by machining.

2. Experimental setup

Plain carbon steel SAE 1045 in a normalised state was chosen with an initial grain size of $\approx 16\,\mu m$ as workpiece material. The chemical composition is given in Table 1.

Cylinders with lengths of 50 mm or 100 mm, respectively, and with an initial diameter of 58 mm were produced as workpieces. Dry plain turning was performed using a machining centre Heller MC 16. The cutting tool (manufacturer: Walter AG) used for the experiments was industrial fine-grained cemented carbide (grade K10) with a composition of 94 vol% WC and 6 vol% Co in an uncoated state, which promotes built-up edge formation due to adhesion tendency to the chosen workpiece material. The designation of the tool is SNMA 120408 according to the standard DIN ISO 1832 as a simple geometry. The cutting parameters are summarized in Table 2. A negative rake angle was chosen since it supports the formation of a built-up edge [8].

For the detailed analysis of the microstructure of built-up edges, the cutting of cylindrical workpieces was always done with a new unworn cutting tool to avoid wear-related variations from the initial cutting tool geometry (cutting edge radius, flank wear, crater wear, notch wear, radius wear, etc.) and therefore changes in the formation of built-up edges. After small cutting lengths (in the range of 80–180 m) these cutting inserts were removed to get the possibility to examine the generated built-up edges via LOM and SEM on the cutting tool. Due to the statistical built-up and breaking off the cutting tool of the formed built-up edge only those cutting edges were considered, where the BUE was adhering on the tool. When adhering to the chip, the built-up edge height was not measured. Hereby the height is measured on four measurement lengths as indicated by the orange lines in Fig. 3(b) and the area is determined using the back scatter electron (BSE) detector in the SEM, where the materials contrast (atomic number) was used to distinguish between the cemented carbide structure and the seized built-up edge (steel). For the determination of the area of the BUE the BSE-image was colour-coded (see Fig. 3(d)) for unique phase separation. Nine different built-up edges seized on the cutting tool were considered for the measurement of height and the area covered by the built-up edge (Figs. 4–7).

Table 1
Measured chemical composition of workpiece material (SAE 1045) in weight-% obtained by emission-spectroscopy.

C	Si	Mn	P	S	Cr	Ni	Mo
0.420	0.285	0.663	0.021	0.035	0.153	0.107	0.021

Table 2
Cutting parameters used in the experiments for provoked built-up edge formation and conservation of built-up edge on the cutting tool.

Cutting speed v_c [m/min]	50–150
Feed rate f [mm/rev]	0.05
Cutting depth a_p [mm]	1.0
Rake angle γ [°]	−8
Clearance angle α [°]	8
Wedge angle β [°]	90
Corner radius r_ε [mm]	0.8
Initial cutting edge radius r_β [µm]	30
Entering angle κ_r [°]	45

After the examination of built-up edges on the unworn cutting tool various wear tests were carried out to reveal the influence of built-up edges on the wear state of the cutting tool. The parametric study of the machining was carried out by dry plain turning of the cylindrical workpieces (initial diameter=58 mm) down to a diameter of 24 mm. The cutting tools were examined after different cutting lengths, where the built-up edge, the flank wear, and the radius wear were documented by means of LOM and SEM. The measurement of flank wear was performed by measuring the flank wear land width (VB) with four measurement lengths and the radius wear with one measuring length as indicated by the coloured lines in Fig. 9. The average values of wear sizes were recorded after defined cutting lengths to reveal the wear evolution.

For further detailed microstructural examination the cutting tools were first sectioned in the cutting zone by using a diamond wire saw and then metallographically prepared. For the metallographic preparation the specimens were coated electrolessly by a nickel-coating to avoid edge rounding and to be able to obtain a seamless fitting to the embedding resin. These metallographic sections were etched by Beraha I etching agent, which appears to be nonconventional for the material forming the BUE, and furthermore FIB examinations were carried out. The Beraha I etching agent was used because it results in a higher contrast for developing a low-carbon steel microstructure than using traditional black-white etching agents (Nital). As an example, Beraha I etching agent is also successfully applied for friction weld characterisation between SAE 1045 steel and high-speed steels [9], where similar microstructural changes due to plastic deformation are expected as in the case of built-up edge microstructures. For the determination of hardness variations in the built-up edges produced at different conditions Martens hardness measurements were performed according to ISO EN 14577 using an instrumented micro hardness testing system type Fischerscope H100. The applied load for micro hardness measurements was in the range between 30 mN and 150 mN .

In three different zones of the built-up edge the grain structure was revealed (region next to the “new” cutting edge of the built-up edge, region inside built-up edge, and interfacial area between built-up edge and cemented carbide). Especially for the interfacial region between built-up edge and cemented carbide, TEM-lamellae (see