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Evolution of residual stress and damage in coated hard metal milling inserts over the complete tool life

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ABSTRACT

In coated hard metal milling inserts the main damage mechanisms are thermal fatigue induced by interrupted tool–workpiece contact and wear. Dependent on the magnitudes of thermal and mechanical loads in two applied test setups, either wear or thermal fatigue in the form of combcracks is induced. The evolution of residual stress and damage in the used milling inserts was documented over their complete lifetime. In a region of interest on the tool rake face a significant buildup of tensile residual stress was observed via a synchrotron based technique. A special preparation technique enabled position resolved measurements in this area by in-house X-ray diffraction facilities to study the evolution of residual stress over the entire tool lifetime. The onset of cracking was observed to happen in this region of interest by means of focused ion beam milling and scanning electron microscopy. The residual stress levels observed are comparable in used inserts at early stages of application, independent of the different cutting conditions and the applied characterization technique. At the end of tool life wear damage dominated inserts showed tensile residual stress, whereas thermal fatigue as the dominant damage mechanism resulted in compressive residual stresses.

Introduction

The dominant damage mechanisms in milling processes are wear and thermal fatigue [1], with the latter inducing characteristic cracks that will be referred to as combcracks throughout this paper. Wear damage is generally induced by two mechanisms: One is adhesive wear, in which workpiece material sticks to the tool's rake and flank face during cutting and the other one is abrasive wear, where material is removed from the tool surface [2,3]. Abrasive wear kinetics are highly increased when debris in the form of hard metal and coating fragments are introduced by the shattering of exposed surface features such as combcrack flanks [1].

Combcracks appear in cutting tools after a certain number of load cycles with propagation planes perpendicular to the cutting edge of a milling insert. Some authors postulated that the temperature difference between heating upon cutting and cooling upon the idle period in a cutting cycle is the key factor influencing damage [1,5]. They assumed that the cyclic thermo-shock fosters combcrack formation. During idle time, when high cooling rates are effective, tensile residual stresses are created upon surface material contraction [1,5]. Opitz and Lehewald [1] expected that these residual stresses are oriented parallel to the cutting edge and foster crack growth. Yellowley and Barrow [6] determined plastic deformation during cutting which is localized close to the cutting edge — this initiates nucleation and growth of combcracks [2]. Local plastic deformation at the tool edge is introduced by thermal stress amplitudes induced by frictional heating [6]. A combination of these thermal stresses and the sufficiently high load stresses can surpass the flow stress of a tool material at the present temperature. Upon cooling, these loads can trigger the buildup of tensile residual stress in the cutting edge of milling inserts. Cyclic mechanical loads in the form of cyclic contact pressure between chip and tool may also introduce local plastic deformation close to the cutting edge [6]. Bathia et al. [7] described a combination of process parameters under which no tool failure induced by combcracks occurs in intermittent turning of mild steel plates due to subcritical thermal or mechanical tool loading. For this situation to occur, the feed rate and the cutting speed have to be lower than 0.1 mm/revolution and 1.5 m/s, respectively. The parameter intervals for the described process field of tool failure caused by cracks are also dependent on the radius of the tool's cutting edge. A milling insert with a large cutting edge radius widens the process parameter field in which wear rather than fracture determines tool life [7].

Cyclic thermal shocks in coated steel discs and the resulting residual stresses were investigated by Kirchlechner et al. [8]. The position resolved measurements with high lateral resolution were enabled by using synchrotron based X-ray diffraction [9]. Teppernegg et al. [4]

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found a significant tensile residual stress buildup on the rake face of a used milling insert in a region of approximately 0.3 × 1.6 mm^2. In Fig. 1 the surface of a milling insert's rake face is shown. The dashed frame indicates the area of the position resolved residual stress measurements and the black frame represents the position of the mentioned region of tensile residual stress buildup. This region will be referred to as region of interest (ROI). The centre of this ROI was located about 0.4 mm from the cutting edge [4]. In previous work, tensile residual stress with a value of about 1000 MPa was detected in the WC phase of a used milling insert in a direction parallel to the horizontal and straight part of the cutting edge (see Fig. 1) [4].

Currently, no data on the evolution of residual stresses in milling tools during the complete tool life is available in the open literature. In the present work, the evolution of residual stress in used milling inserts is compared during the complete tool life for two different test setups. In addition, the resulting damage states are compared. In one setup the main influence on tool lifetime is combcrack formation, in the other one wear damage is dominant. The results shall illustrate the interaction of residual stress and damage for the investigated milling test setup.

Experimental

Fig. 2 shows two different test setups for the milling experiments. In Fig. 2a test setup A is shown, Fig. 2b illustrates test setup B, also used in [4] and [10]. The following test setup parameters were the same in both test setups.

- Milling insert geometry
- Single edge synchronous milling arrangement
- Cut workpiece material
- Cutting speed of 220 m/min
- Depth of cut of 4 mm
- No use of cooling agents such as lubricants or cold air
- Milling tool holder referred to as “miller” in Fig. 2 with a diameter of 125 mm

All investigated milling inserts were made of WC–8 wt.% Co hard metal with an average WC grain size of 1 μm. They were coated with a TiAlN-based film having a thickness of 8 μm, deposited by cathodic arc evaporation. The insert dimensions were 6.35 × 11.4 × 10 mm^3, and cutting edges were chamfered. The workpiece material was a 42CrMo4 steel in a normalized state with an upper yield strength of 400 N/mm^2, workpiece dimensions were 800 × 96 × 200 mm^3. The milling tests in test setup A were stopped after an accumulated tool–workpiece contact length (aTWCL) of 2.5, 36, 407.8, and 611.7 m and at end of lifetime after 2854.7 m. In test setup B the machining experiments were stopped after 10, 50, 500, 1000, 5600, 9600, 13,100, 17,700, 23,400, 26,200 and 37,400 tool–workpiece contacts. This corresponds to aTWCLs of 0.51, 2.57, 25.72, 51.44, 288.06, 493.82, 673.86, 910.49, 1203.7, 1347.73 and 1923.86 m, more details regarding test setup B are given in [10].

The differences between test setups A and B are the start and end positions of the milling tool (see Fig. 2), the cut segment length, and the feed rate per tooth. The cut segment length in test setup A was 96 mm and the applied feed rate was 0.5 mm/tooth. In test setup B the cut segment length of 800 mm and a feed rate of 0.4 mm/tooth were used. Due to the differences in the start and end positions of the milling tool, the milling inserts in test setup A experienced non-constant tool–workpiece contact lengths at the beginning and at the end of each cut segment. With increasing number of contacts, the tool–workpiece contact length (TWCL) increased from 0.47 mm at the first cut within one cut segment length to 51.44 mm after 92 cuts. Until TWCL reaches a constant value of 51.44 mm after 92 cuts, the insert cuts an aTWCL of 2.5 m under non-constant cutting conditions. The milling inserts used in test setup B cut the entire cut segment lengths under constant cutting conditions with a constant TWCL because the beginning and the end of the segment are removed by a dummy tool.

The residual stress state in the ROI (see Fig. 1a) was determined in the direction parallel to the straight portion of the cutting edge in the WC phase of the hard metal. The values of residual stress were acquired in a depth region ranging from the interface between coating and WC–Co substrate and about 5 μm below this interface. The residual stress states of all milling inserts were measured by a D8 Discover X-ray diffractometer (Bruker AXS, Germany) in parallel beam geometry (40 kV, 35 mA, Cu Kα radiation). The diffractometer was equipped with a Sol-X energy dispersive detector, an open (90°) Eulerian cradle and a polycapillary collimator. The areas outside of the ROI were covered with a brass foil, see Fig. 3. The diffraction maximum (211) of the hexagonal WC phase at 117.3° 2θ was selected for the subsequent stress determination [11]. Brass was chosen as a cover material to avoid the overlap of the diffraction peak (211) originating from the WC phase in the sample and the cover material.

Preliminary experiments showed that for the determination of the stress component parallel to the straight portion of the milling insert's cutting edge it is favourable to choose a diffraction geometry with incident and diffracted beam parallel to this direction. These beams penetrate the WC phase parallel to the long axis of the uncovered ROI to minimize shadowing effects caused by the covering brass foil. Otherwise, the shadowed fraction of the rectangular ROI with a long axis a and a short axis b would be larger by a factor of five at the same incidence angle θ if symmetric incident and diffracted beam are assumed and no sample tilt is considered ($\psi = 0$). The effect would be larger at tilted samples ($\psi > 0$). Consequently, for the determination of the stress component parallel to the straight portion of the cutting edge, the ω-method was selected [12]. For the stress determination, diffraction intensity was recorded in a diffraction angle range 2θ from 114.6 to 119.1° and sample tilt angle ψ up to 35°. For the determination of the

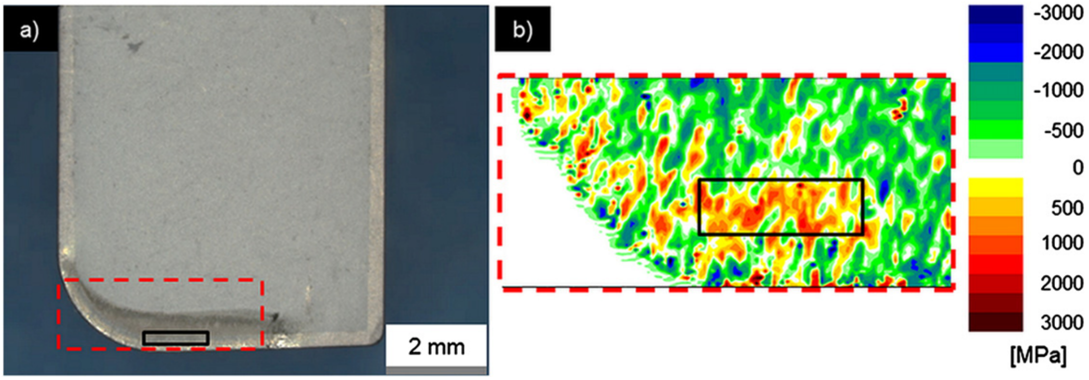

Fig. 1. Results of stress measurements via synchrotron X-ray radiation taken from [4]. Top view of the rake face of a used milling insert with 1000 tool–workpiece contacts. Dashed frame in a) indicates the area of residual stress measurement shown in b) that represents a position resolved map of residual stress acting in horizontal direction in the WC phase. Solid frame in b) indicates the area with detected significant tensile residual stress buildup [4].