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Coated tools' performance in up and down milling stainless steel, explained by film mechanical and fatigue properties

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ABSTRACT

The knowledge of coated tool wear mechanisms in milling is crucial for explaining film failure and adjusting appropriately the cutting conditions. In the described research, coated cemented carbide inserts were applied in up- and down-milling stainless steel for monitoring the tool wear at repetitive cutting loads of various magnitudes and durations. The variable stress, strain and strain-rate fields developed in the tool during milling affect the film-substrate deformations, and thus the resulting cutting loads and the coating fatigue failure.

For investigating the influence of cyclic impact load magnitude and duration on the film fatigue of coated specimens, an impact tester was employed which facilitates the modulation of the force signal. Using this device, repetitive impact loads with different duration and time profiles were applied on coated cutting inserts. These loads approximately simulate the developed ones in milling when the cutting edge penetrates the workpiece material. The attained coated tool life was associated with the developed maximum strain and its rate in the film during milling. The latter factors were correlated to the strain and strain rate dependent on coating fatigue endurance. In this way, the tool life in all examined milling kinematics and chip geometries was sufficiently explained.

1. Introduction

The wear mechanisms of coated tools in cutting vary from application to application and the ones dominating in steel milling are displayed in Fig. 1a. Mechanical overstressing as well as the exceeding of the fatigue strength during material removal leads to micro-chipping of the coating mainly at the transient cutting edge region from the flank to the tool rake (region I) [1,2]. The development of this wear phenomenon increases the width of the flank wear land at low cutting velocities, without any significant wear on the tool rake and causes tool failure. Moreover, depending on the temperature developed and coating composition, oxidation and diffusion mechanisms take place at higher cutting speeds, mainly on the tool rake face (region II). Due to these mechanisms, a deterioration of coating's mechanical properties occurs, which accelerates its abrasive wear. Furthermore, the film adhesion quality significantly affects coating wear, since inadequate interlocking of the coating with the substrate increases the developing stresses [3]. These mechanisms appear in the cutting wedge region I and lead to film fracture and rapid tool wear. Finally, adhesive micro-welding leading to micro-peeling can occur at low cutting speeds, in part, as a result of common elements between workpiece and coating materials.

In milling, impact loads with variable magnitudes and durations are subjected to coated cutting wedge, which may lead to fatigue failure of the applied film and subsequently intensive tool wear [2–4]. Physical Vapor Deposition (PVD) film's fatigue properties at ambient and elevated temperatures have been determined by perpendicular impact tests [1,5]. The fatigue fracture initiation mechanisms in thin hard coatings and their further evolution have also been thoroughly investigated by impact tests [6,7]. Moreover, via analytical evaluation of nanoindentation and impact test results, relevant film fatigue endurance stresses were determined in the form of Woehler-like diagrams [1,3]. During impact testing, the film loading conditions and the temperature are appropriately adjusted to describe the derived ones in the fatigue endangered cutting edge region, from the flank to the rake, during milling.

A characteristic example demonstrating the first substrate revelation of a coated tool versus the number of impacts in milling

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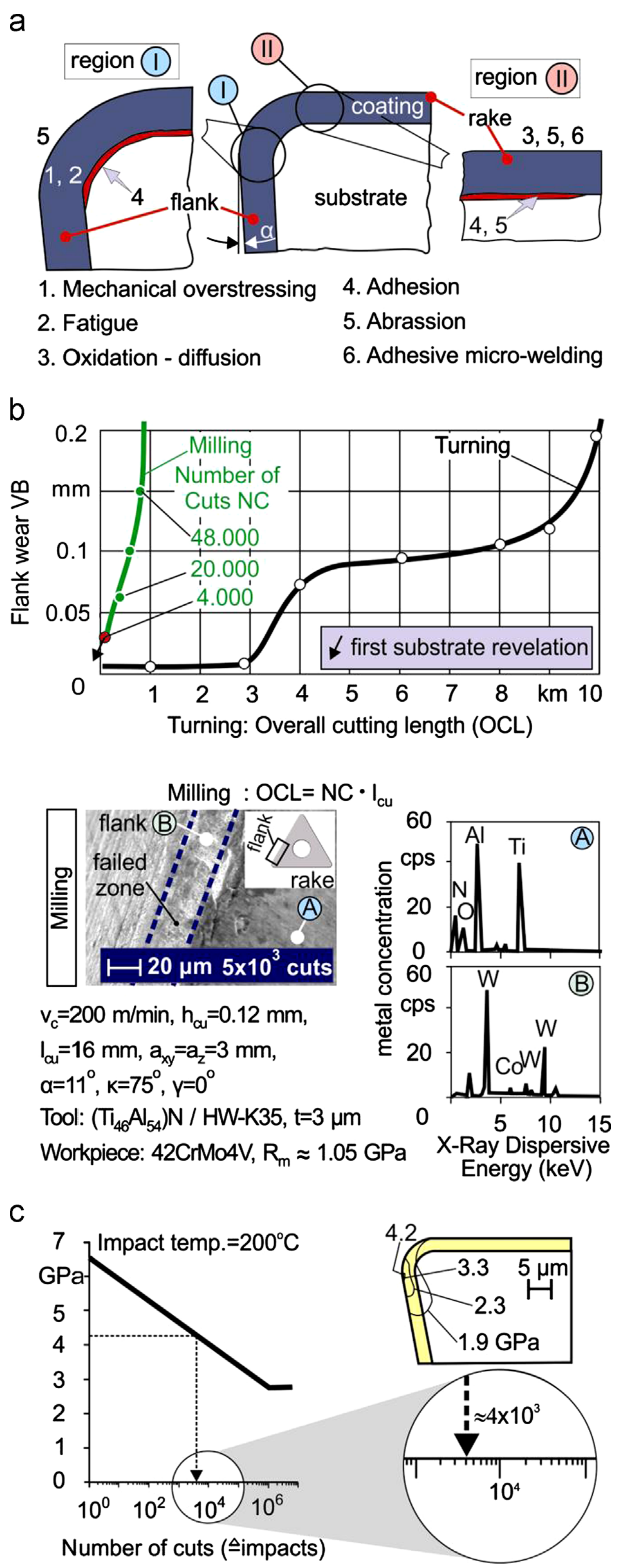

Fig. 1. (a) Developed wear mechanisms in coated cutting tools. (b) Flank wear development in milling and turning. (c) First film fracture expectation in milling considering the coating Woehler-like diagram.

is shown in Fig. 1b [3]. The first coating fracture, and thus a substrate revelation, appears after approximately 4000 cutting impacts, as the scanning electron microscope photo and the related microanalyses in regions A and B indicate. In region B, substrate chemical elements such as tungsten and cobalt are detected. In the rake region A, due to the developed low mechanical and thermal loads associated with the applied cutting conditions, no film failure occurred. In contrast, in turning, using the same material and coated inserts, since the cutting process is continuous and no repetitive impacts are subjected to the cutting edge, the flank wear evolution is drastically decelerated (see Fig. 1b). In this case, the prevailing wear mechanisms are the mechanical overstressing and abrasion and not the film fatigue [2]. Furthermore, the FEM determined maximum von Mises stress of approximately 4.2 GPa developed at the endangered cutting wedge region from the flank to the rake is inserted into the related film Woehler-like diagram (see Fig. 1c). In this way, it can be concluded that at this stress level coating fatigue damage is expected after approximately 4000 impacts. This number of impacts corresponds to the number of cuts up to the first substrate revelation monitored in Fig. 1b.

The further flank wear evolution of the coated tool after the first film fatigue fracture is affected by the developed equivalent strains and strain-rates. This dependency is qualitatively exhibited in Fig. 2a, in two milling cases. Here the strains induced by the film deformations are of different magnitudes ($\varepsilon_1 > \varepsilon_2$) although they change at the same rate ($\dot{\varepsilon}_1 \approx \dot{\varepsilon}_2$). The first film fatigue fracture appears at a lower number of impacts (number of cuts) if the coating is comparably higher deformed ($\varepsilon_1 > \varepsilon_2$). Moreover, the growth of the film strain intensifies the flank wear propagation. This is in compliance with tribological tests at various loads [6]. The developed strains in the coating do not depend only on the induced film strains, but also on the relevant strain rates. Fig. 2b graphically displays this effect. At roughly constant film strain ($\varepsilon_1 = \varepsilon_2$), if the cutting edge entry impact duration decreases, the film strain rate grows ($\dot{\varepsilon}_2 > \dot{\varepsilon}_1$). This may lead to an earlier film fatigue fracture and accelerated flank wear development compared to a longer cutting edge entry impact time. In this way, the coated tool cutting performance in milling can be correlated to the film fatigue endurance, which in turn is associated with critical strain and strain rate combinations. To render this correlation possible, innovative experimental-analytical film characterization methods and calculations supported by Finite Elements Method (FEM) analyses were applied [3]. Moreover, with the aid of impact tests at variable load data, coating fatigue critical strain and strain rate combinations were estimated [8].

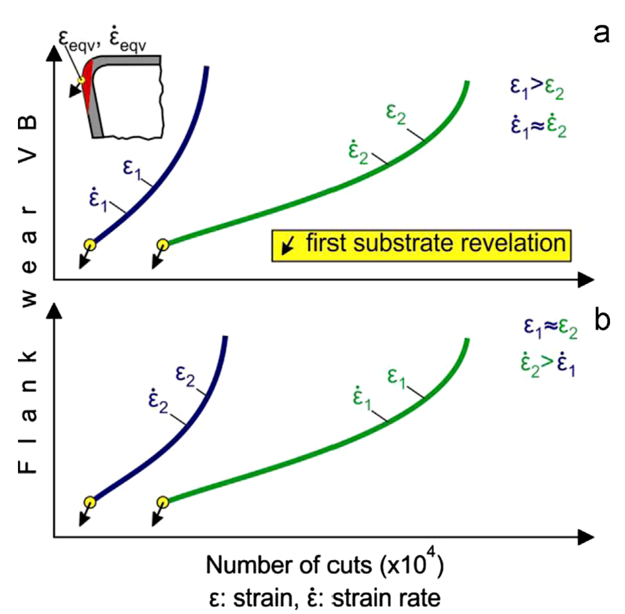

Fig. 2. Effect of the film (a) equivalent strain and (b) strain rate during milling on the flank wear development.