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Reverse engineering and scanning electron microscopy applied to the characterization of tool wear in dry milling processes

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Abstract

An innovative method of tool wear assessment, based on the digitization of the cutting tool performed by a piezoelectric 3D scanner and on the analysis of the surfaces of a 3D model generated using the Reverse Engineering technique, has been developed. To this purpose, face milling experiments were carried out under dry cutting condition on AISI 420 B stainless steel using inserts in cemented carbide, with a two-layers coating (TiN and TiAlN). The time dependence of the insert wear was analysed by interrupting milling at predetermined time values. The proposed approach has been validated by comparing the output provided by the reverse engineering method to that measured experimentally by analysing the worn insert images obtained using a stereo microscope. An excellent agreement between the results given by the two different methodologies has been found. The worn tools have also been analysed using the scanning electron microscopy technique in order to understand the wear mechanisms operating during dry milling.

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Keywords: Reverse engineering; CAD; dry cutting; milling process; tool wear; FEG-SEM.

1. Introduction

The high temperatures generated at the tool – workpiece interface during machining operations, especially as they are performed under dry cutting condition, strongly affect the tool life [1-4]. Unfortunately, the very high temperatures developed during dry machining can reduce the accuracy and increase the risk of thermal damage of the work-part surface. Moreover, the increase in temperature and friction can strongly influence the tool wear [1-6]. The precise and accurate evaluation of the tool wear is critical to define the tool life, i.e. the time interval during which the tool is able to perform the machining operation by ensuring the obtaining of the desired values of dimensional and form tolerances, and surface quality of the workpiece [6-10].

The international standard ISO 8688-1 specifies recommended procedures for tool-life testing with cemented carbide tools used for face milling of steel and cast iron workpieces by microscopy at low magnification [11]. In order to overcome such drawback, innovative methods of evaluating the tool wear, based on the digitization of the cutting tool and on the analysis of the surface of a 3D model generated using the Reverse Engineering (RE) technique [12], should be developed. Then, the three-dimensional model of the wear cavity can be used to compute the total mass loss, the wear rate and the influence of the operating conditions on them.

Many papers have investigated metrics for quantifying the quality of measurements in order to assess the reconstructed virtual models [13-15]. Same authors have also evaluated the precision of reconstructed surfaces by RE systems by comparing it with the one measured using a CMM machine [16, 17]. The grooving interest towards the RE in inspection of manufactured parts is also demonstrated by the application of such technique in the tolerance control field [18].

In the present work, face milling operations were carried out under dry cutting conditions on blocks in AISI 420B stainless steel using PVD-coated cermet inserts. The analysis of tool wear was carried out by interrupting the milling process at predetermined time values and scanning the inserts

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through a piezoelectric 3D scanner. The small sizes involved required a preliminary validation of the correctness and reliability of the measurement accomplished [19]. Then, repeatable geometric procedures were defined in order to build the nominal shape of the insert and to evaluate the wear behaviour as a function of processing time. The comparison between the results obtained through the RE analysis of the worn inserts and those experimentally measured by stereo-microscopy has shown that the reverse engineering can be effectively used in the tool wear evaluation. Finally, in order to understand the mechanisms leading to the formation of the wear cavity in the inserts during dry milling, the worn tools were analysed using the scanning electron microscopy (SEM) technique.

2. Experimental techniques

2.1. Face milling operations

Face milling operations were performed without any cooling lubricant (dry cutting) using a vertical machining center on blocks in AISI 420B stainless steel (0.16C, 13Cr, 1.05Mn, 1.0Si, 0.04P, 0.03S, wt.%). Blocks with a width of 32 mm, a length (along the feed direction) of 345 mm and a height of 130 mm were used as workpieces. For each condition the tests were repeated different times.

A tool holder with a diameter of 63 mm was used. Five inserts in cemented carbide (R245 12T3 E-ML 2030) with a two layers coating (TiN and TiAlN) [20] were mounted on the tool holder. The face milling operations were carried out with only one tooth – workpiece contact each time. The cutting parameters were selected according to the tool manufacturer recommendations [20]: a cutting speed equal to 230 m/min, a feed rate of 0.14 mm/tooth, and a depth of cut of 0.2 mm were used. The process time on the workpiece for each pass is about 26 s. In order to accurately measure the tool wear, the milling operations were interrupted at fixed time values, equal to 12, 36, 64, 92, 116, 136, 172, 200, 224, 250, 280, 310, 350, 400, 450, 500 e 520 min. At any interruption of the milling process, the inserts were analyzed by means of a stereomicroscope (Leica EZ template 4D). Two supports were made in order to correctly arrange the worn face of the insert parallel to the lens of the stereomicroscope. By superimposing the image of the wear-free insert with that of the worn one, it was possible measure the height of the worn part.

2.2. Scanning by piezoelectric 3D scanner

After each working interval, the tool inserts have been removed from the tool and acquired by 3D scanning devices which are commonly used for Reverse Engineering purposes, i.e. to track the progression of the material erosion.

Preliminarily, different scanning systems were evaluated, i.e. contact and optical types. In particular, an attempt has been performed using a laser scanner (Minolta Range 7). This scanner ensures a high spatial resolution and a good behaviour in minimizing the speckle phenomena typical of optical scanning systems based on laser beam. However, the insert material properties and the deterioration of the surface due to wear has made measurements quite noisy. With this respect, a scanner piezoelectric contact PICZA Roland MDX-15 was used, since it is not affected by reflection phenomena. The sensor is constituted by a needle mounted on a piezoelectric sensor moved along the three coordinate axes resembling a CMM machine. The pointed shape of the needle, the absence of undercuts in the acquired insert area and the simplicity of the machine makes the process rather lean although far slower than optical acquisition systems. The scanner has a working volume of 200x150x60 mm^3.

The inserts were positioned in tilted positions such that the cutting edge were invested by the needle vertically. The measurement resolution was set at a pitch of 0.05x0.05 mm on the XY plane. The choice of scanning the insert from a single direction has required accurate positioning of the insert in order to ensure the absence of undercut areas in the portion of interest, namely the areas adjacent to the cutting zone. However, some undercuts were generated only in other areas leading to fictitious shapes which have been eliminated in a post processing phase. The insert has been acquired from a single point of view, thus errors due to the alignment of multiple views [21] has been avoided.

2.3. CAD elaboration of the digitized models

The scans of the inserts have been elaborated by a software with functionalities oriented to the standard Reverse Engineering process (Fig. 1). The models were processed by using the Rapidform software (Inus Technology, Inc.).

By overlapping the acquisitions of the unused and worn inserts, and by displaying the colour map of the deviations between the two acquisitions, the complexity and three-dimensionality of the worn volume are revealed.

In order to determine the insert degradation, and measurement procedures were developed. The main steps of such procedure are as follows: i) scan of the inserts and model cleaning; ii) scan alignment to the reference model; iii) identification of a reference measuring planes (Fig. 2); iv) monitoring the wear evolution.

Through the digital overlay of the scans obtained for each insert at various time intervals, it was possible to record the evolution of the wear parameter.

3. Results and discussion

The proposed method was validated by comparing the results obtained through RE and those experimentally given by the image analysis of the worn inserts, acquired using the stereomicroscope at predetermined cutting time values. Fig. 3 shows worn inserts, superimposed with the wear-free one at different milling time. It can be qualitatively observed the increase of tool wear as a function of the cutting time.

In order to better correlate the CAD modelling of thecutting edge deterioration with working hours, a systematic scanning electron microscopy (using a Zeiss™ Supra-40® FEGSEM) inspections were carried out. The cutting edge consumption by wear, during dry milling, is evident from the sequence of the electron microscopy documentation of Fig. 4.

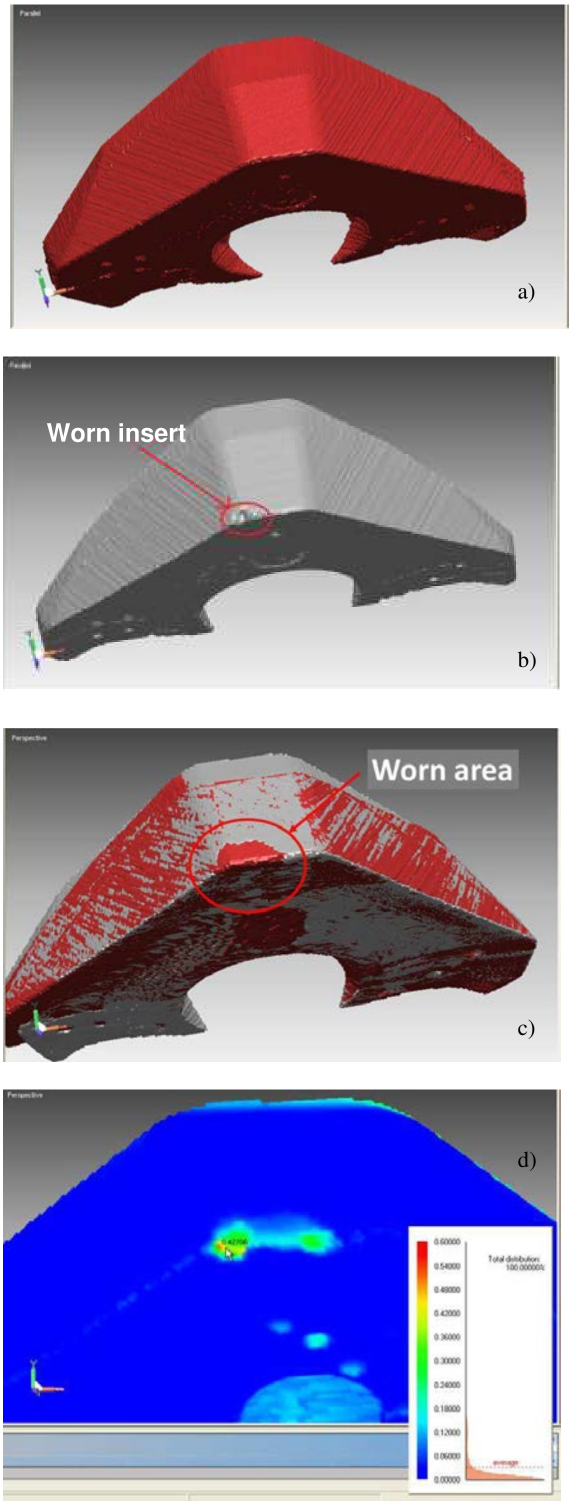

Fig. 1. CAD 3D models: (a) new insert, (b) the worn insert after 400 working minutes, (c) overlapping of the meshes of a new and worn insert, that is a)+b), and (d) colour map of the deviation between the two scans.

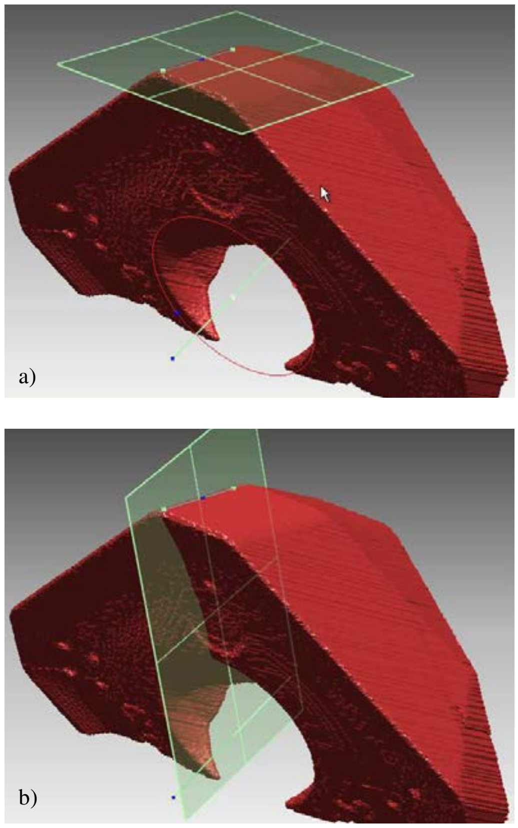

Fig. 2. Construction of the measuring plane: (a) construction of the reference elements and (b) definition of the profile section plane.

At the initial stages, i.e. after 176 min of dry milling, the cutting edge broaden although the cutting behaviour is still maintained. Part of the profile is consumed by a typical wear mechanism (Fig. 4a-1). The abrasion is characterized by micro-cracking initiation (Fig. 4a-2). The worked surface is also characterized by a diffuse microporosity (Fig. 4a-3), and this is most probably due to combined effect of the working pressure, dry milling conditions, and also the tool steel.

The cutting edge consumption progresses with the working time, and after 310 min of dry milling, the edge appears considerably modified, having a large portion deteriorated and, to some extent, flatten out (Fig. 4b-1, b-2). Micro-cracking formation was also and still documented (Fig. 4b-3), but this time together with consistent an exfoliation wear mechanism. At the longest dry milling time of 520 min, the cutting edge appears deeply damaged and irregularly consumed (Fig. 4c-1). The detail of the consumed region reveals a smooth surface (Fig. 4c-2), with consistent presence of microporosity (Fig. 4c-3). Exfoliation and micro-cracking are documented in the detail of Fig. 4c-3 and in Fig. 4c-2.

The analysis of the worn insert images has allowed to measure the height of the worn part hw as a function of the cutting time. As expected, the height of the worn part considerably increases with increasing cutting time (Fig. 5).

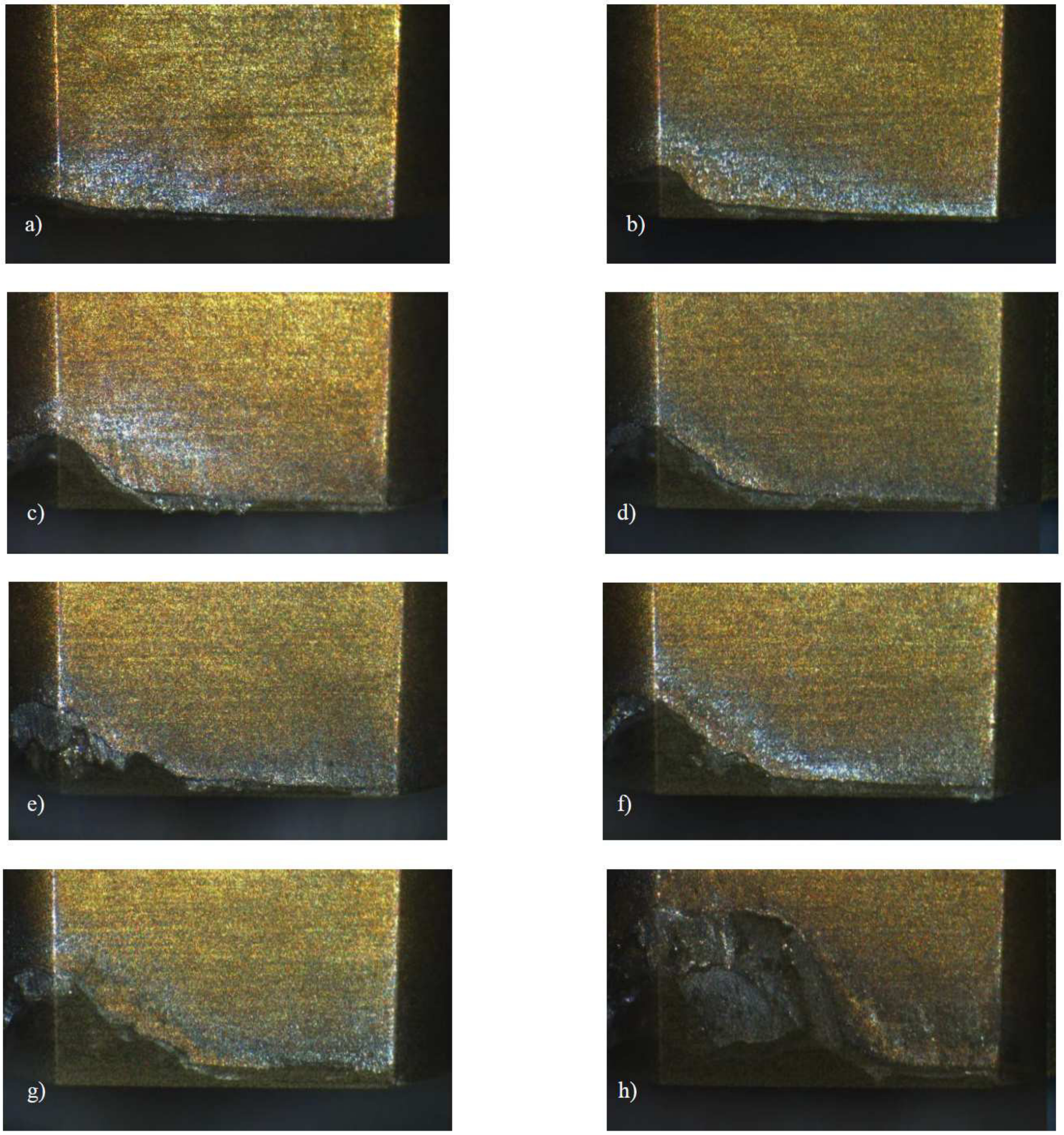

Fig. 3. Worn insert images acquired using stereomicroscope at predetermined cutting time values: 136 s, a); 176 s, b); 250 s, c); 310 s, d); 350 s, e); 400 s, f); 450 s, g); 520 s, h).

By comparing such experiment results with the output of the reverse engineering method, an excellent agreement between the results given by the two different methodologies has been found, demonstrating the accuracy of the new proposed methodology.

4. Conclusions

An innovative methodology of tool wear assessment, based on the digitization of the cutting tool performed using a piezoelectric 3D scanner and on the analysis of surfaces of a 3D model generated for the Reverse Engineering technique, was developed. Dry face milling operations were performed on blocks in AISI 420B stainless steel using PVD-coated cermet inserts. The worn inserts were also analysed using the scanning electron microscopy in order to understand the tool wear mechanisms operating during dry milling.

The excellent agreement between the results obtained through reverse engineering technique and those measured experimentally by the analysis of the worn insert images obtained by stereomicroscope, has allowed to validate the proposed methodology.

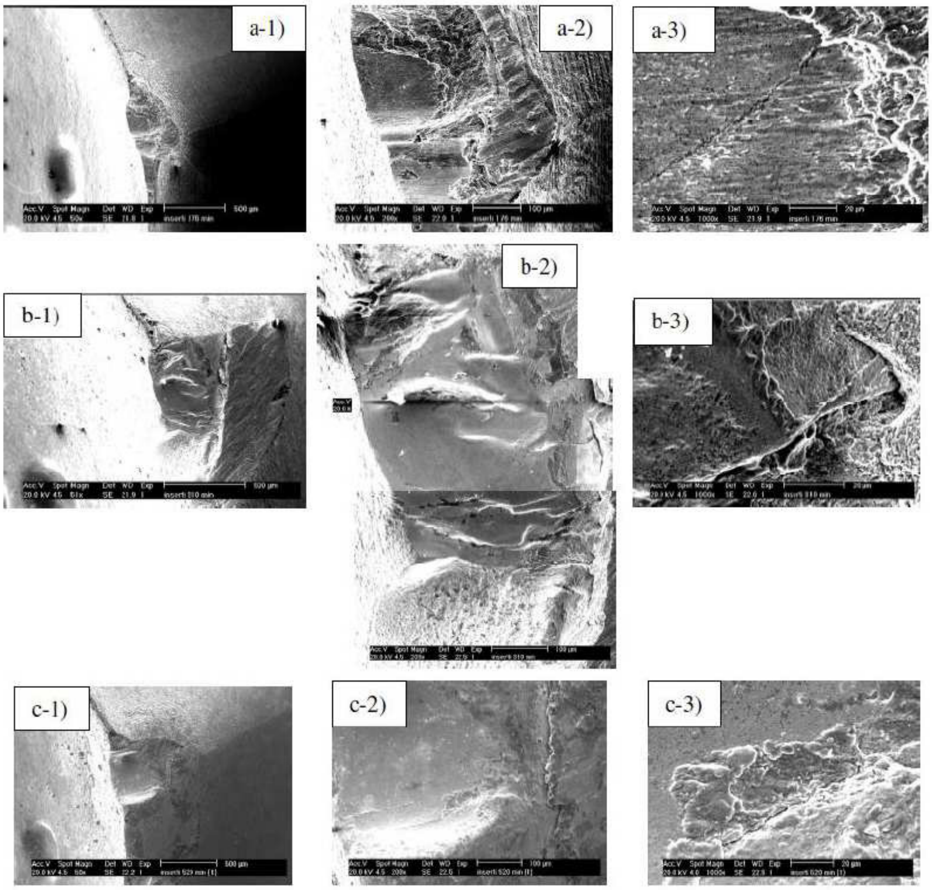

Fig. 4. FEGSEM images of the dry milled tool after different cutting durations. 176 min, a), 310 min, b), and 520 min, c). For each cutting condition, three different magnifications, under the same section-view, are reported: 50x, 200x, and 1000x. A secondary electron (SE) signal was used, the acceleration voltage was of 20 keV, with a working distance of ~22 mm.

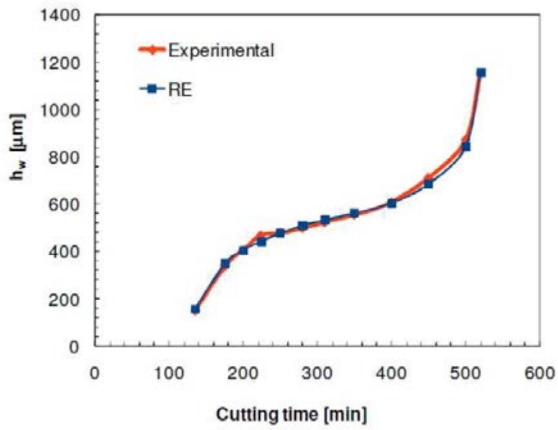

Fig. 5. Comparison between height of the worn part vs. cutting time curve measured experimentally and that obtained by the reverse engineering method.

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