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Novel method for burrs quantitative evaluation in micro-milling☆

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ABSTRACT

One of the major issues of the micro-milling operations pertains to burrs formation, which affects the quality of the final product, and, thus, the capability to meet the part desired performances. Burrs characterization and evaluation are still a challenging task in micro-machining, especially if on-machine monitoring of burrs is desired. This paper proposes a newly developed method based on optical microscopy, a-priori information on the manufacturing process, and an unconventional use of void pixels for fast and non-destructive evaluation of multiple geometrical quantities. Newly defined parameters on burrs lateral distribution and axial depth of cut are presented in addition to the standard surface texture parameters. The proposed methodology is applied to slotting micro-milling operations on pure titanium grade II. The obtained results show the method potential that can be exploited for on-machine monitoring of micro-milling operations.

1. Introduction

Nowadays, micro-milling is increasingly used in the production of micro-sized components in many different fields, such as automotive, aerospace, biomedical, optics and electronics [1], thanks to the high performances it assures, among which high material removal rate, high flexibility, and possibility to machine different metals in 3D complex shapes. However, one of the major issues of the process pertains to burrs formation, which affects the quality of the final product and, thus, the capability to meet the part desired functionality [2].

Though it is noted that both macro- and micro-milling operations produce burrs on the machined parts, burrs removal on small size components is more difficult, producing an increase of both the time and cost for deburring, the latter being as high as 9% of the total machining costs [3].

Burrs removal in case of micro-machined components cannot be carried out by means of traditional methods, such as brushing, etching, and electrolytic ultrasonic, since these technologies can result in unacceptable damage of the part [4]. Therefore, control of burrs formation in micro-machining has recently assumed a lot of significance [5]. To this regard, many studies in the literature are focused on the modelling and prevention of burrs formation in micro-milling, analyzing the factors that affect these phenomena. In particular, as reported by Cardoso et al. [6], the main process parameters influencing the effectiveness of the micro-milling process were identified to be the cutting speed, undeformed chip thickness, tool sharpness, tool feed, and workpiece material. In his work, Jahanmir [7] demonstrated that machining at ultra-high speed and high feed rate improves the surface integrity leading to the generation of burr-free and damage-free micro-machined parts. Also Filiz et al. [8] in their work investigated the effect of different micro-milling conditions in order to minimize burrs formation, demonstrating a linear dependence between the burrs height and feed per tooth. Moreover, Özel et al. showed how low values of the cutting speed as well as high values of the feed rate reduced burrs formation [9]. Câmara et al. in their review [10] demonstrated how burr reduction could be obtained by increasing the tool diameter, number of flutes and depth of cut. Also lubrication/cooling strategies play a fundamental role in micro-milling process: Bruschi et al. [11] demonstrated how, cryogenic cooling conditions improved surface integrity, especially in terms of presence and quality of burrs, when micro-machining additive manufactured titanium alloys.

The aforementioned studies prove that the mechanism of burrs formation in micro-milling has been extensively studied, using both analytical and experimental approaches aimed at reducing and/or predicting the occurrence of this phenomenon. Since some applications require burr-free components, as in the biomedical and optics fields [12], on-machine measuring techniques become mandatory for a timely identification and characterization of the burrs, providing an immediate feedback on the effectiveness of the process. Non-destructive methods, including mechanical and optical systems, can be suitable for on-machine measurements. However, mechanical-based methods are always limited in their application range due to the workpiece stiffness,

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since burrs can be destroyed or pushed down because of the contact forces. As reported by Aurich et al. [13], contact methods can be employed to measure burr heights only. Moreover, due to the conical shape of the tracer point, the real profile of the burr could be falsified. Another limitation related to the mechanical methods is the necessity of acquiring many closely spaced traces, making the process very time-consuming [14].

Various optical systems to detect or measure burrs are available, which do not modify burrs during the measurement operations. The most important optical systems are camera systems, scanning electron microscopy, laser triangulation and confocal microscopy [13]. Ko [15] analyzed the triangulation method, conoscopic holography method, and interferometry method for the effective measurement of micro-burr geometry in micro-drilling process, demonstrating that the conoscopic holography was effective for measuring steep slope surfaces. Tsai and Lu [16] developed a machine vision system based on a contour detection algorithm for the automatic recognition of burrs and peripheral defects of cast parts, but limited to macro-sized burrs. Nakao [17] presented a system for measuring the profiles of the height and thickness of drilling burrs using image-processing techniques: an additional function was implemented to evaluate the uniformity of the burr profiles and remove the influence of irregular burrs from the original data. A laser-based measurement system for control and characterization of micro-burr parameters was instead presented by Toropov [18].

It is worth noting that these systems, specifically developed for burrs measurements, do not usually provide information about the geometry and surface roughness of the machined features, and therefore additional measurements are needed using dedicated equipment (e.g. optical distance sensor, micro-probe and/or image processing sensor; scanning electron microscope, image processing or system based on triangulation or interferometry). To this aim, Table 1 reports a summary of available measuring techniques highlighting their suitability for the evaluation of different characteristics of micro-machined parts [19].

All the reported methods are clearly not flexible enough for a complete characterization of the micro-machined parts.

In this framework, the method proposed in this work aims at providing information about all the aforementioned characteristics, enlarging the capabilities of confocal microscopy using a-priori information on the manufacturing operation and with a non-conventional use of void pixels. A standard optical profiler was used to record the topography of the part and demonstrate the proposed methodology. The use of the data acquired through the optical profiler allows a comprehensive geometrical characterization of the machined part, besides the evaluation of its surface topography, including the burrs geometrical characteristics in terms of longitudinal width and morphology. Therefore, on the basis of a single acquisition, it is shown that multiple parameters related to the geometrical quality of micro-machining features can be assessed.

The paper is divided into three main sections. The newly proposed approach for assessing the quality of the micro-machining process is discussed in Section 2, highlighting its main innovative contribution to the quantitative characterization of burrs generated during micro-milling operations. Section 3 describes the case study that was used for validating the proposed method. Finally, Section 4 shows the obtained results.

Table 1
Summary of measuring techniques and their suitability for evaluating micro-machined features. V = applicable, (V) = partially applicable.

Technique	Geometry	Roughness	Burrs characterization	On - machine
Contact probing	V			(V)
Image processing	V		(V)	V
SEM	(V)		(V)	
Triangulation	(V)	(V)	(V)	V
Interferometry		V		(V)
Confocal microscopy	V	V		(V)

2. Method description

The newly developed method, whose flow chart is reported in Fig. 1, is based on the idea that it is possible to extract more information from a set of measured data using application-specific understanding of the manufacturing process. The specific aim is to enable a more complete geometrical characterization of micro-machined features, including burrs, by extending the measuring capabilities of a standard confocal microscope. The case study used in this work is a slot machined through micro-milling (details in §3).

The use of an optical profiler enables a more complete characterization of the machined slot, since: (i) data acquired on the bottom of the slot can be used for the quantification of surface texture parameters, and (ii) profiles on sections orthogonal to the machining direction can be used for the characterization of the slot geometry and related process parameters (e.g. actual depth of cut, tool geometry). Additionally, using a newly developed procedure to extract process-specific information, the acquired data can be processed for (iii) quantitative evaluation of the burrs geometry.

Since burrs have complex geometry, their surfaces result in measuring conditions mostly unsuitable for the measuring technique, e.g. high surface slope. As a result, the corresponding surface cannot be measured through optical systems (because of their numerical aperture limitations [20]), and results in void pixels, namely pixels of the topography map without height information.

The proposed procedure for burrs evaluation combines image processing techniques and surface topography evaluation algorithms, enabling the extraction of the burrs longitudinal profile and projected area. A preliminary thresholding step is applied on the height map, on the basis of a-priori information on the manufacturing operation. Subsequently, the height map is transformed into a binary image and the projected area of the burrs, as represented by void pixels, is evaluated using image processing algorithms. A mean burr width can be computed, dividing the area by the longitudinal length. The methodology is described with more detail in the following.

2.1. 3D height map elaboration

The optical profiler allows the acquisition of a points cloud containing the spatial distribution of the scanned points along the 3 axis (*x,y,z*). Fig. 2-a reports an example of the 3D topography of a micro-machined slot. From the 3D map, it is possible to identify two different regions, namely the machined bottom area (1), and the top plane reference area (2).

The two regions are determined using the z-height histogram, as shown in Fig. 2-b.

The higher frequencies of the points are related to the top and bottom areas, the centre of mass of the histogram (represented with the red line in Fig. 2-b) is evaluated and all the points higher than this value are associated to the top plane.

From the bottom region of the machined area, 10 different profiles are extracted in order to evaluate the surface roughness parameters. According to ISO standards [21,22], form correction and filtration are applied to each profile. On the contrary, the top regions are used for the 3D alignment procedure. A roto-translation matrix is determined applying a least-square algorithm between the top region points and a plane. A linear least square fitting is applied, using a polynomial plane equation. The coefficients of the equation are then used for the matrix creation, referring to the reference *x-y* plane. The obtained matrix is then applied to the entire points cloud along the three main directions *x,y,z*. The alignment of the top plane is necessary for the thresholding