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Automated algorithm for the evaluating of burr formation in micro milling

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Abstract

Micro milling is a machining process that enables the fabrication of surfaces with defined structures in the micrometer range. Applications for micro structured surfaces can for example be found in bioprocess engineering. However, burrs are formed on most metal materials during machining. This impairs the precision of the structures produced, leading to the need to minimize the formation of burrs. To achieve the greater goal of minimizing burr formation, a reliable method to describe burrs quantitatively is needed first. This paper presents an automated algorithm that enables a quantitative evaluation of changes in burr formation. Its development was based on slots created by micro milling using tools with diameters of 50 µm. 3D images of these slots were taken by a confocal microscope. The influences of the size of the image section and the brightness of the sample exposure during measurement on the results were investigated.

micro milling, burr evaluation algorithm

1. Introduction

Micro milling can be used to machine micro structured surfaces in a wide range of materials. Applications for micro structured surfaces can e.g. be found in bioprocess engineering. Here, the adhesion of microorganisms to various surface profiles is improved by creating defined structures [1,2]. Such applications require a high surface quality. Burrs impair the quality of the produced microstructures. Their subsequent removal in micro machining is associated with considerable time and costs and carries the risk of damaging the manufactured structures. It is therefore advantageous to take measures during the milling process to minimize burr formation [3]. This results in the necessity to make burrs evaluable quantitatively, so different series of experiments can be compared to each other.

Medeossi et al. [4] addressed this topic by developing an algorithm for burr evaluation based on confocal microscope images. The burrs were created by micro milling slots in cp titanium grade 2. The diameter of the micro mills was 300 µm. The algorithm developed uses a z-height histogram to divide the sample surface and the slot bottom. The dividing line was set by the centre of mass of the histogram. All points higher than two times the standard deviation of the height distribution of the sample surface were considered burr. Three parameters were chosen to characterize the burrs: mean burr width, max burr width and burr ratio. Burr ratio is the ratio between mean width and max width.

Akkoyun et al. [5] micro milled slots with tool diameters of 1,000 µm in Inconel 718 alloy. 2D images of the slots were taken by a scanning electron microscope (SEM). The burrs were evaluated by an automized algorithm. The picture was processed by different filters and converted into grayscale. For every row of pixels parallel to the slot, the color values of the pixels were summed up. The peaks of the resulting profile were used to define the slot borders. This way two regions of interest were defined, which include the burrs on the up milling side (UM side) and on the down milling side (DM side). For each region, the burr was extracted. The burr width was calculated to evaluate the burrs.

Hajiahmadi et al. [6] used a milling tool of 1,000 µm in diameter to machine slots in stainless steel 316L. They used an optical microscope to determine the burr height and a SEM to determine the burr thickness. The values were calculated as the mean values from eight discrete measurements at different points. The measurements were executed by researchers and not automated.

The first attempt involved reproducing and using the Medeossi et al. [4] algorithm on cp-Ti. It was found that in our case, the center of mass of the histogram does not allow a clean division of the surface from the slot bottom. So, using this method to divide the surface from the slot bottom is not reliably applicable in general. Furthermore, even if the surface was already detected correctly, the threshold of two times the standard deviation proposed by Medeossi et al. [4] did not allow a generally reliable distinction between surface and burr.

The work of Akkoyun et al. provides only two-dimensional information and was also preliminary examined. The detection method for the slot borders can lead to parts of the burr areas next to the slot and protruding into it being attributed to the slot. The algorithm had to be adjusted for each burr type investigated to detect the burrs correctly.

Hajiahmadi et al. did not use an automated algorithm but measured the burrs at discrete points by hand. This leads to a strong dependency on the researcher and the chosen measurement points. The results are therefore not reproduceable.

This paper presents an automated algorithm, applicable to different kinds of burrs and image sizes. Parameters are defined to describe the burrs quantitatively. The influence of the brightness of the sample exposure during measurement and the size of the surface area captured next to the slot on the calculated burr parameters was investigated. Furthermore, an investigation was conducted to determine if the measured slot length of 0.52 mm is sufficient to quantify the burrs or whether the measured length is too short for a global statement.

2. Methodology

The investigated slots were manufactured on a desktop machine tool using micro end mills with effective diameters of 50 µm and a helix angle of 0°. A helix angle of 0° is chosen, because it maximizes the core cross section of the tool and reduces deflection effects. Micro mills have very small diameters and therefore exhibit low stiffness and high susceptibility to tool deflection and breakage. Consequently, tool geometries with increased structural rigidity are preferred [7]. The manufacturing of the tools is described by Aurich et al. [8]. The depth of cut was 5 µm and the feed per tooth 1 µm. The rotational speed of the spindle was at 30,000 rpm, resulting in a cutting speed of 4.71 m/min. The sample surface was face milled before the slots were manufactured.

To enable the development of a new algorithm applicable for a wide range of burr types, slots were created and evaluated for four different Materials: Stainless steel 316L, commercially pure titanium grade 2 (cp titanium), AlCuMgSi and brass. An overview of the resulting burr types is shown in figure 1.

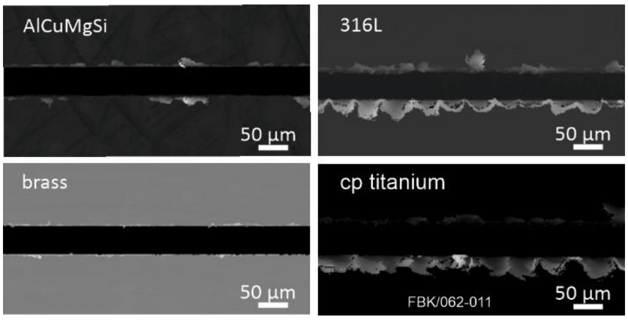

Figure 1. Comparison of the investigated burr types

The created slots were measured using the confocal microscope µsurf OEM from the manufacturer nanofocus[2]. The confocal microscope provides height information for each recorded measuring point, which makes three-dimensional images possible. The used objective is of the type 260S, has a magnification of 60x and a numerical aperture (NA) of 0.9. Its measuring field size is 260 µm x 260 µm. Since larger slot areas were analyzed, multiple individual images were taken and stitched together within one measurement. This was done automatically by the measurement software µsoft metrology by nanofocus[2]. Measurements were carried out consisting of two and nine stitched pictures in the length direction of the slot per measurement. This resulted in evaluated slot length of 0.52 mm and 1.9 mm. Furthermore, some measurements concerning brass were executed with different brightness of the sample exposure during measurement.

The images were post processed using the software MountainsMap by Digital Surf[2]. In this software, the images were aligned so that tilting caused by the camera not being perfectly perpendicular to the surface was corrected. Then, void pixels were filled with the average value of the neighbouring pixels. Void pixels are pixels for which no height value could be measured. If environment of the sample was part of the image, it leads to regions mostly filled with void pixels. These regions cannot be processed by the algorithm and were cut off. The slot had to be horizontally aligned if this was not the case. The up milling side needed to be on the top to later ensure correct assignment of the two edges. Finally, the height values of each pixel of the surface layer were extracted and the data was exported to a .txt file, hereinafter referred to as height map. This height map was then imported into MATLAB[2], the programming and development environment used to develop the algorithm.

3. Burr evaluation algorithm

This section describes the algorithm and the parameters used to quantify the burrs. The influences of the image size and the brightness during measurement on the results of the algorithm are presented.

3.1. Functionality of the algorithm

The detection of the burrs is done by calculating a height threshold and defining the image regions above this threshold as burrs. This corresponds to the approach of Medeossi et al. [4] However, the procedure is different. Based on Akkoyun et al. [5], the height values for every row of pixels parallel to the slot are summed up. A resulting height profile plotted into the corresponding height map shows figure 2.

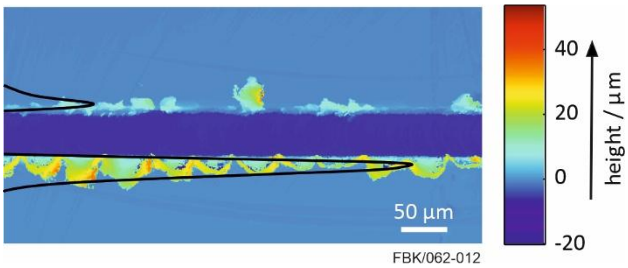

Figure 2. Height map with corresponding height profile

The profile is smoothed by a moving average, so the number of peaks is reduced to the two main peaks. The peaks enclose the slot and parts of the burrs next to it. The vertical positions of the peaks are calculated. The height values of all pixels below the lower peak and above the higher peak are used to calculate an arithmetic mean value of the surface height and a standard deviation. The mean value and the standard deviation are used to calculate a confidence interval. The upper value of the confidence interval defines the threshold between sample surface and burr. The burr areas lie above the threshold and are separated from the surface by converting the height map into a binary matrix.

A resulting problem is that investigating different burr types leads to the need for different confidence intervals to detect the burrs properly. For this reason, the algorithm uses different confidence intervals for detecting the burrs depending on different standard deviations of the surface height.

Contaminants like chips, material accumulations or dirt on the sample surface are detected as burrs, if they exceed the threshold. To exclude such falsifications, a band is defined between the two detected peaks in figure 2. Only image regions detected as burrs that are included in this band or touch it are considered as burrs. All burrs detected outside this band are considered as measurement errors.

The burr areas include holes surrounded by burr that are considered surface by the algorithm. These holes are filled to create a throughout burr area. The result is a binary image used to evaluate the burrs. The binary image is directly used to calculate planar burr parameters and as a mask to extract height information from the height map. The planar and height parameters are calculated for the UM side and the DM side separately. Therefore, the image is split in the middle of the slot. To detect the middle of the slot, the two peaks in figure 2 are used again. The slot middle is defined as the middle line between these two peaks.

3.2. Burr parameters

A system of parameters is developed to describe the burrs quantitatively. The mean burr width w is calculated as mean of the burr widths y in each of the n columns of the height map. When calculating the mean burr width, the edge areas without burr are not taken into consideration. So, the mean burr width only refers to those edge areas where burrs develop. The mean height is calculated in the same way as the width, using the height information z for each of the p pixels that are considered part of the burrs in the final binary matrix. The mean values of burr width and burr height give information about the sizes of the burrs. The deviation ratios dw and dh for the burr width and the burr height are the quotient between the standard deviation and the mean value. The deviation ratios add information about the uniformity of the burrs. The ratios are chosen instead of the standard deviations, because they give information about how large the size of the burrs varies relative to the mean values. On the other hand, the standard deviations are absolute values and therefore not suitable to compare burrs that differ in size to a high degree. The length ratio lr is the ratio between the summed lengths of the machined edge parts with burrs to the length of the machined edge as a whole L in percent. It defines the proportion of a milled edge, that is afflicted with burr. The calculation of the parameters is shown below:

$$w = \frac{\sum_{i=1}^{n} y_i}{n} \quad (1)$$

$$h = \frac{\sum_{i=1}^{p} z_i}{p} \quad (2)$$

$$dw = \frac{\sigma_w}{w} \quad (3)$$

$$dh = \frac{\sigma_h}{h} \quad (4)$$

$$lr = \frac{\sum_{i=1}^{m} l_i}{L} \cdot 100\,\% \quad (5)$$

As an example, for the calculated burr parameters the mean burr widths for the four investigated materials differentiated according to UM side and DM side can be seen in figure 4. Each value but the ones from AlCuMgSi represents the mean of four different slots. Only three different slots are used with AlCuMgSi. The error bars represent the combined standard deviations of the measurements.

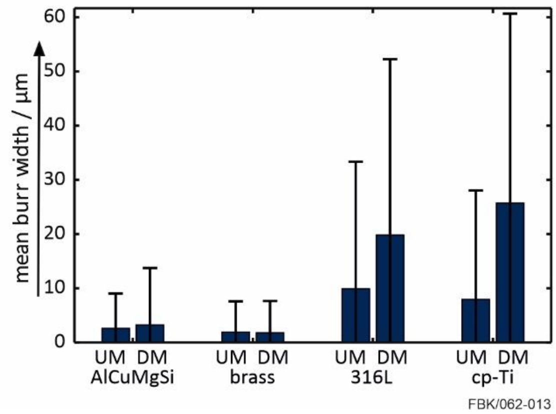

Figure 4. Mean burr widths and combined standard deviations

3.3. Influences on the accuracy of the algorithm

For the sake of clarity only the size of the burrs is discussed based on the mean burr width. This is possible because the mean burr height shows tendencies like the mean burr width. The length ratio and the two deviation ratios are left out in this section since the focus is on identifying relevant influences rather than conducting a comprehensive parameter study. Table 1 shows the change in mean burr width if the image is narrowed by 20 % and 40 %, thereby reducing the proportion of the sample surface to the slot width in the overall image.

Table 1 Change of the mean burr width with changing proportion of the surrounding surface area of the slot by -20 % and -40 %

material	milling strategy	Absolut value of the parameter changes / % -20 % image width	-40 % image width
316L	UM	1.81	0.19
	DM	0.43	1,85
cp Ti	UM	0.04	6.89
	DM	0.1	0.8
AlCuMgSi	UM	0.03	0.68
	DM	0.14	1.2
brass	UM	1.21	3.22
	DM	0.73	0.83

In both cases, the cropped areas are distributed equally across the top and bottom edges of the image. The deviations between original image and narrowed image with less surface area are small in most cases. However, the deviation tends to increase with a further reduction of the surface area surrounding the slot. Furthermore, table 1 includes one single value of up to nearly 7 %. Even if it is an outlier, it means significant deviations are possible and cannot be ruled out. For this reason, the images taken to compare burrs should be roughly the same width to obtain reliable results.

Table 2 provides an overview over the deviations occurring in burr width, if the brightness of the sample exposure during measurement is varied for three different slots manufactured in brass.

Table 2 Change of the mean burr width with varied brightness specified in % of the maximum brightness value during the measurement of brass samples

breightness 1 / % | brightness 2 / %	milling strategy	Absolut value of the parameter changes / %
32.3 | 38.9	UM	5.4
	DM	0.1
33.1 | 46.7	UM	7.8
	DM	1
36.2 | 56	UM	2.2
	DM	4.4

The deviations can be significant with values up to 7.8 %. For good reliability, a brightness as constant as possible should be chosen during measurement. These results suggest that a quantitative comparison between different burr types are only possible with larger uncertainties. This is because of different ratios between burr width and surrounding surface area and the brightness during measurement must often be adjusted for each measurement.

Table 3 shows the comparison between the calculated mean burr width resulting from the two different slots length 0.52 mm and 1.9 mm. The deviations with a minimal value of 11.6 % suggest that the small slots excerpts include not enough information to allow a reliable calculation of globally valid burr parameters. This does include a statement of whether the long slots are capable of doing so, or not.

Table 3 Change of the parameters from the long slot to the short slot

material	parameter	milling strategy	Absolut value of the

			parameter changes / %
316L	mean burr width	UM	18.3
		DM	22.7
cp Ti	mean burr width	UM	14.6
		DM	11.6
AlCuMgSi	mean burr width	UM	12.7
		DM	47.6
brass	mean burr width	UM	28.7
		DM	26.1

4. Qualitative validation of the algorithm

To validate the algorithm qualitatively, the contour of the detected burrs is determined and plotted into a top few of the original height map. Figure 5 shows an example for such a plot. The plot includes an illustration of the micro mill cross section. Furthermore, the directions of the rotational speed n and the feed rate v_f are presented. The determined contour encloses the structure recognizable as burr. This is the case for all measured slots.

The deviations detected in section 3.3 are not directly striking when comparing the corresponding contour plots. For this reason, the images are not presented here. Only small deviations between plots can be seen in the edge areas of the burrs. So, the quantitative deviations measured in section 3.3 do not result from an incorrect workflow of the algorithm itself. This suggests that a different brightness used during the measurement or different amounts of surface area next to the burrs only change the calculated threshold to cut off the burrs from the surface.

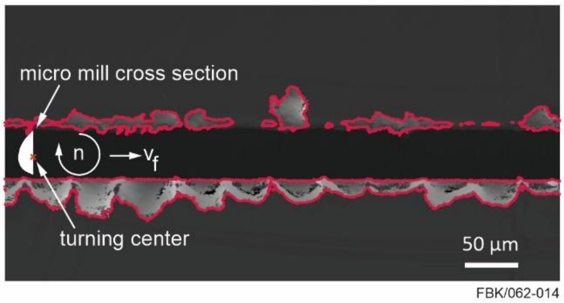

Figure 5. Height map with contour plot of the burrs

5. Conclusion

An automated algorithm was developed that can detect burrs of different magnitudes and with different proportions of sample surface next to the slots to slot width. Five parameters are defined to describe the burrs quantitatively. The parameters are the length ratio, the mean burr width and its deviation ratio and the mean burr height and its deviation ratio.

It has been shown that the proportion of surrounding surface area next to the slot and the brightness of the sample exposure during measurement can have a significant influence on the calculated burr parameters.

Furthermore, it was shown that a measured slot length of 0.52 mm is not enough to describe the burrs globally. However, the necessary measured length to do so is not yet specified.

Through the successful development of a new evaluation algorithm, it is now possible to describe different kinds of burr automatically without major adjustments. The same is achieved for different amounts of sample surface areas next to the slots.

It was shown that the brightness during measurement and the size of the analyzed image section influence the results of the algorithm. They should therefore be kept as constant as possible to acquire comparable, quantitative results. There have been no other studies found concerning burr evaluation addressing these issues.

Larger parts of the slots than 0,52 mm need to be evaluated to make a global statement about the burr size.

The next step will be an evaluation of how long the measured part of a slot must be, to calculate global burr parameters for the experimental setup used. Another investigation will be done into how reliable the results are for different slots machined with parameters as constant as possible. Then, the algorithm is used in studies that aim on minimizing the burr formation when micro milling slots in cp titanium and stainless steel 316L.

Acknowledgement

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[2] Naming specific manufacturers is done solely for the sake of completeness and does not necessarily imply an endorsement of the named companies nor that the products are necessarily the best for the purpose.

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