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RESEARCH ON TOOL LIFE IN MICRO END MILLING AS RELATED TO WORKPIECE QUALITY CRITERIA

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ABSTRACT

In this work a tool life study for micromilling is developed, based on practical quality criteria in the microworkpiece machined, such as the surface roughness and the workpiece dimensional accuracy. It is observed an increase in all these variables as the machining time increases. These variables are significantly influenced by tool wear and thus they are much related to tool life. The evolution of the different variables is strongly affected by the cutting speed, causing more rapid tool deterioration and a quick reaching of the critical quality values. A great change in machining forces is observed when cutting speed increases as well. All these evidences are consistent with Taylor's Law for the conventional machining.

INTRODUCTION

The miniaturization of devices is demanding nowadays the production of mechanical components with manufactured features in the range of a few to a few hundred microns in fields that include optics, electronics and medicine. Specific applications include microscale fuel cells, fluidic microchemical reactors requiring microscale pumps, micromoulds, and many more [1]. Some examples of micromachined features and parts are shown in Fig. 1. These applications require very tight tolerances, and both functional and structural requirements. Many of these pieces have to be metallic and micromilling is one of the most suitable methods to manufacture them.

The tool wear is one of the most critical issues in micromilling, as small amounts of this magnitude cause a lack of sharpness in the tool edge [2] and a great increase in machining forces. The increase of cutting forces causes, as well as roundness in the tool edge, a poor surface finish in the workpiece and bad dimensional accuracy due to deflection of the tool [3]. These features are especially important in micropieces. Furthermore, tool life in micromachining is likely to be different from that of conventional machining due to the high forces values as compared with the tool body and edges resistance. These high values demand that stiffness chain in the machine to be taken into account in many cases to assess the angular and lineal positioning error of the tool [4]. There are no studies on this issue in micromilling, though some authors have researched on the conditions of sudden tool breakage and monitoring the forces evolution to avoid this failure [5,6].

Figure 1. System Layout a) Micromilled trenches with stepped walls, b) neurovascular device component, c) microgear

The tool life is related with the magnitude of wear in different areas of the mill and a tool life criterion based on a certain amount of wear can be set, as some authors do for conventional milling [7]. This is a possible line to develop in micromachining. However, the final criterion of tool life is to be based upon the quality of the machining performed with the tool. Therefore, two variables are often taken into account when assessing the tool life: dimensional accuracy of the workpiece and surface finish. These variables are related with tool wear in the different areas usually considered in deterioration measurements [8].

In this paper a model for tool life in micro-end milling is developed to study the behaviour of the mill at the microscale, as compared to conventional milling. This model will be based on a series of tests and empirical measures, which relate the machining to the quality of the feature machined. Quality magnitudes and cutting forces were measured as well as machining time. The time of milling will be related with the roughness and dimensional accuracy of the workpiece for each set of cutting conditions. Cutting forces will be related with the machining time as well, in order to find out differences between forces at the microscale and the macroscale, as it has been pointed out [9].

EXPERIMENTAL PROCEDURE

Machining tests were performed in a KERN Micromilling and Microdrilling Machine with an up to 160.000 r.p.m. spindle speed and a Computerized Numerical Control with 0.1 μm resolution. Micromilling Machine is shown in Fig. 2. Micromilling was carried out in Aluminium 7075 fulfilling ISO recommendations about Tool Life testing in Milling [8]. A planning operation was performed on the pieces to get the mill weared by intervals and to measure the surface roughness. Tests were performed with 0.8÷3 mm diameter mills with 2 flutes. In order to assess the machining accuracy thin walls were made in which the thickness was used as an index for precision.

A Profilometer Hommelwerk LV-100 was used to measure the surface roughness. Wear measurements were carried out through images recorded with a Scanning Electron Microscope (SEM). In addition, cutting forces measurements were taken with a Kistler 9256C2 Dynamometer installed in the Micromilling Machine. This device can measure forces in the 3 axes. Dimensional measures of the workpiece were carried out by means of photographs taken with a DXM12200F digital Camera and a Nikon SMZ optic microscope.

Figure 2. Micromilling Machine

TOOL LIFE CRITERIA

A summary of the results for tool life from the different points of view indicated before is going to be given in this section.

Surface roughness. This is a very important parameter to control in micromachining since a very little roughness value in micropieces is usually very high as compared with the dimensions of the piece and could cause dangerous effects in sliding surfaces and assembly problems. The criterion used in this work is that the pieces machined must have a value of R_a smaller than 1 μm to consider that the tool is still operative. Thus, tool life is the time of machining till the measured roughness reaches the critical value pointed out before. This value can be varied according to the quality needs of the piece. However, the model of roughness increase extracted from this study can be used whichever tool life criterion is taken.

Several tests were performed with mills of 1 mm diameter, z=2 on aluminium. Some of the roughness measures for different cutting speed values are shown in Fig. 3 and Fig. 4.

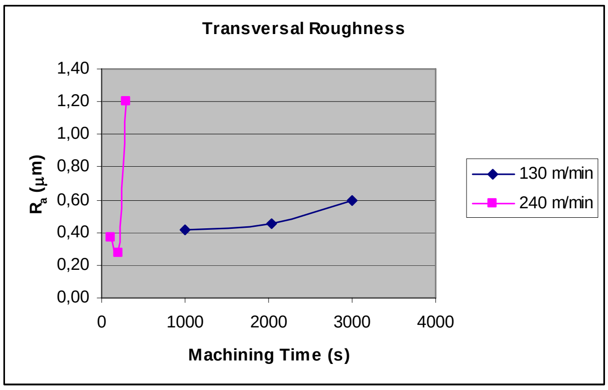

Figure 3. Evolution of Transversal Roughness with Machining Time

These results show a great difference in the trend of roughness values depending on the cutting speed used in the machining. For the lower value of speed tool life is much longer than for the higher value. Even with the higher speed the critical value of transversal roughness is reached in a relative small time (about 300 s) whereas for the lower one there is much time left to the mill to be totally weared.

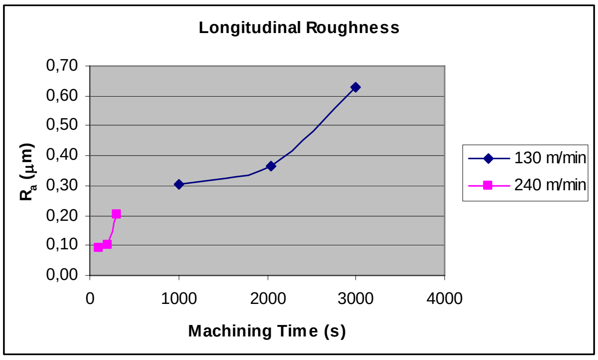

Figure 4. Evolution of Longitudinal Roughness with Machining Time

Dimensional Accuracy. Another criterion that can be used to assess tool life is the dimensional accuracy in the micropiece. When the mill has been used during too much time the edges change their original position due to flank wear, built-up edge or any other type of wear. This fact brings about a deviation of the feature machined from the theoretical position that causes a lack of accuracy. When the type of wear is flank wear, the dimensional error will consist on an increase in the wall thickness, since the actual radius of the edge will be lower than the theoretical one. A critical value of the dimensional error was set to recognise the point when the end of the tool life is reached. This value was set in 10%. In order to leave out the error caused by the run-out of the mill, thickness measures were compared with the thickness of a wall made with a totally new tool, since the run-out brings about a certain initial error that was not taken into account.

Some results of accuracy for 1 mm diameter mill machining are shown in Fig. 5.

A great difference between the two cutting speed values can be observed in this graph. The higher value causes a faster evolution towards the critical value of dimensional error whereas the lower value causes a longer tool life. In the second case tool life is about 7 times higher than in the first one. A decreasing trend can also be observed and thus, the critical value is negative in these cases.

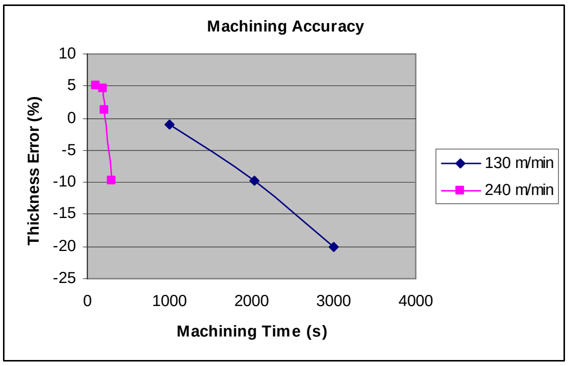

Figure 5. Evolution of Accuracy with Machining Time

FORCES MEASUREMENTS

Forces data are connected with the state of the tool in machining, since the deterioration of the tool can cause an increase in the forces due to the ploughing effect in the workpiece that takes place in chip removal when rounded edges appear.

Forces values depend mainly on the chip thickness and therefore vary with feed per tooth. However, the variation of the forces with the cutting speed is not easily predicted since it depends on vibrations in the tool-workpiece system.

Some of the forces results of the machining with a 1 mm mill are shown in Fig. 6 and 7.

A great difference can be observed between the two graphs. First of all, the oscillation frequency is much higher in the second case than in the first case since the turning speed of the spindle is bigger. Secondly, the forces values are clearly higher with a lower cutting speed in both axes even though feed per tooth is higher in the second case. With low speed all of them are above 1 N whereas at high speed they are smaller than that value.

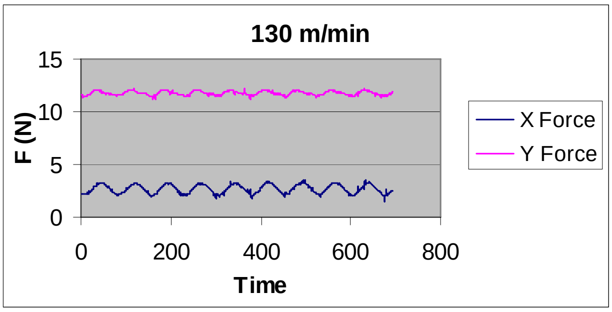

Figure 6. Forces Measures for v_c=130 m/min, f_z=0.003 mm

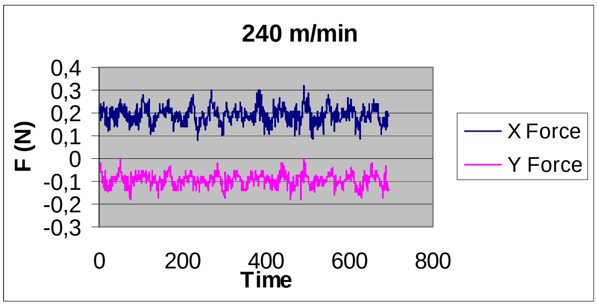

Figure 7. Forces Measures for v_c=240 m/min, f_z=0.005 mm

Another difference is the change in the force composition. In the first case force in Y direction is higher than that of X direction, whereas at higher speed forces composition is the other way round. Therefore, the cutting speed can make the forces change in many different ways.

The increase of the maximum force in Y direction as the machining goes on is especially interesting. This variable is connected with the accuracy of the wall machined (perpendicular to Y direction), as the force will cause tool deflection in that direction and thus a positioning error. This trend can be observed in Tables 1 and 2, in which an evolution of tool forces is presented. The values shown are higher than those of the figures 6 and 7 for they were taken at higher values of Machining Time. Cutting forces increase dramatically with Machining Time as can be seen in the tables.

130 m/min	
Machining Time (s)	**F_{ymax} (N)**
2000	26
3000	45

Table 1. Evolution of F_{ymax} with Machining Time at v_c=130 m/min

240 m/min	
Machining Time (s)	**F_{ymax} (N)**
100	2
200	8

Table 2. Evolution of F_{ymax} with Machining Time at v_c=240 m/min

TOOL WEAR

Mills wear can be observed and measured by means of photographs taken with a digital camera which includes a length reference for each zoom used. It can be observed a different type of wear depending on the cutting conditions used. In some cases can be measured as for the tip wear or flank wear, but in the case of built-up edge material added is thoroughly extended by the mill surfaces. Mill wear for different cutting conditions can be observed in Fig. 8 and 9.

The wear observed in the first case is caused by built-up edge. Some of the workpiece material was sticked to the mill and therefore a rough rake surface can be observed. In the second case, a clear flank wear can be seen along the end of the edge. By comparing the weared area with the reference length, a value for the wear can be obtained and related with the machining time.

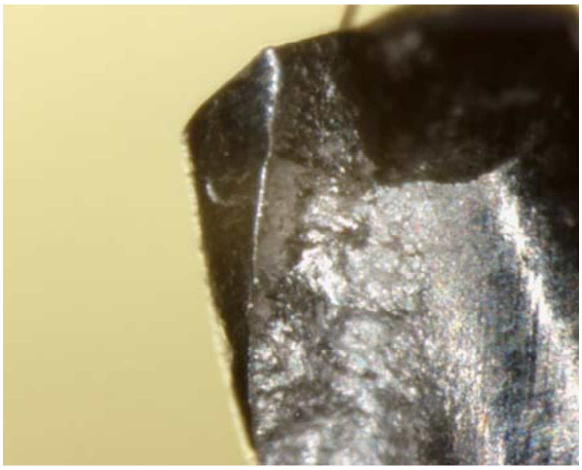

Figure 8. Wear of micromill working at v_c=130 m/min

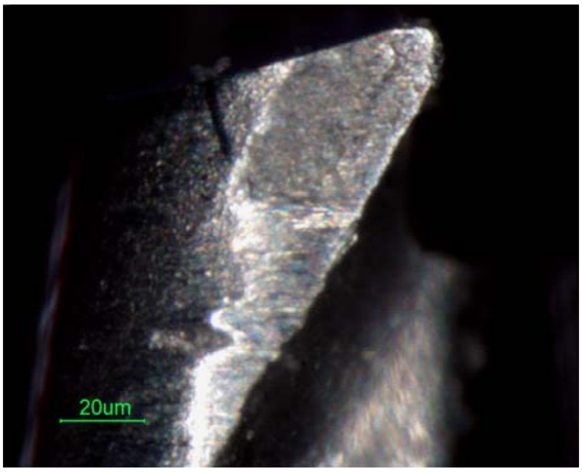

Figure 9. Flank wear of micromill working at v_c=240 m/min

RESULTS DISCUSSION

A lot of conclusions and evidences can be drawn from the results shown above. These evidences can be divided into groups of observations found out in each variable analysis.

Cutting speed. The first thing that can be noticed from the surveying is that the tool life depends strongly on the cutting speed. This trend can be observed clearly in the roughness and accuracy graphs, in which the evolution of the variables is much faster towards the critical value with higher speed. Evolution in roughness and dimensional error is therefore similar to tool wear, which increases with machining time. Furthermore, the higher the cutting speed the stronger is this trend. So, these variables can be used as an index of tool wear.

This trend is consistent with Taylor's Law, in which tool life is related with cutting speed based on a tool wear criterion. It can be observed that at the microscale this trend is also observed.

Machining Forces. It was stated before that cutting speed affects strongly the machining forces, even their composition. This seems to be inconsistent with the trend exposed in the previous paragraph, according to which the higher the cutting speed the faster the tool deterioration, and this deterioration seems to be dependent on machining forces. But, as it can be seen, there is no direct relationship between these two variables, as an increase in the forces does not cause a decrease in tool life.

Tool wear. Different types of tool wear appear when the cutting conditions are changed. At low cutting speed built-up edge turns up, but at high cutting speed flank wear appears. This effect occurs in conventional machining as well, so in micromilling mechanisms of wear are likely to be similar to those of machining at the macroscale.

CONCLUSIONS

A tool life surveying as a function of cutting speed according to a surface finish criterion and workpiece accuracy is presented. All variables related with the machining are strongly affected by the cutting speed, which causes rapid tool deterioration and therefore a little tool life. This model is correlated with flank wear values and machining forces so that it can be used in production planning of machined micropieces. In this initial surveying no significant differences between conventional machining and micromachining are noticed, except for changes in machining forces with cutting conditions.

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