Assessing Uneven Milling Cutting Tool Wear using Component Measurement

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ABSTRACT

Tool wear is a complex phenomenon inherent in any cutting process. Cutting tool wear monitoring is therefore deployed in CNC milling to support machining operations in order to plan tool changes and avoid economic losses. The application of tool life management strategies can lead to premature removal of healthy tool or the continued use of a dangerously worn tool. This has led to the investigation of more appropriate strategies. Depending upon the nature of the sensor technology deployed tool wear monitoring methods are categorized as being either direct or indirect. The benefits and challenges to machine tool users of both approaches are subject to a body of ongoing research.

In this study, a series of milling machining tests were performed in order to allow the confirmation of the presence of uneven tool flank wear. This was enabled by the indirect assessment of the tool condition by utilising a Coordinate Measurement Machine (CMM) to accurately measure the workpieces. Using a defined machining process with set cutting parameters each workpiece was machined to produce eight off 40 mm cylindrical holes; in this manner using four workpieces a series of 32 holes were machined. Each cylinder was machined using four separate cuts, at increasing depths, producing four identifiable sections.

Each section was measured and the form of the geometry produced was established. After assessing the diameters of all the sections for each cylinder, the presence of uneven flank wear was confirmed and the levels obtained. This is related directly to the differing amount of metal removed by the cutter during the established cutting cycle. The same processes was undertaken using three different sets of cutting parameters. The analysis showed the CMM to be a reliable basis for the measurement of uneven tool wear based upon the geometry of the component.

Keywords: Tool Wear, Coordinate Measure Machine CMM, Component Feature Geometry, spindle motor load monitoring.

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1. INTRODUCTION

In this investigation the indirect assessment of the uneven tool flank wear was undertaken based upon monitoring the changes in the cutting process as indicated by component features. CMM based measurement of component feature geometry is shown to be capable of measuring tool wear indirectly. The measurement of the changes in the geometric features and form and the surface metrology of the machined component can be used in preference to assessing the state of the cutting edge of the cutting tool directly. This is shown to be particularly relevant in the context of uneven tool wear. The intention of this study is to inform ongoing tool wear monitoring research for which an understanding of the level and nature of the tool wear arising is vital. The intention is to then build a more accurate tool wear monitoring approach based upon this knowledge.

Monitoring the condition of cutting tools and tool life prediction plays an important role in improving machine productivity. It can enable and support techniques aimed at maintaining the quality and integrity of the machined part, minimizing material waste and reducing the cost. To be most effective it is necessary to be able to observe tool wear during the material removal process. The wear of the cutting tool, which develops due to the dynamic interactions between the cutting tool and the workpiece, results in a reduction in the quality of the machined parts and the associated reduction in productivity. This may be related to reduced cutting speeds and less than optimal machining processes, which in turn may mean more parts may be rejected and/or have to be possibly reworked. Of the different types of tool wear the most commonly occurring in end milling are cutter flank wear (VB) and crater wear. Of the two flank wear is widely used as tool life criterion, with the established tool wear versus cutting time curve following the general form shown in figure 1. This is because flank wear in particular can have adverse effects on the final surface finish quality and the dimensional accuracy of the component. It is also perhaps the most convenient tool related property to measure, as it can be discerned by inspection of the machine artifact.

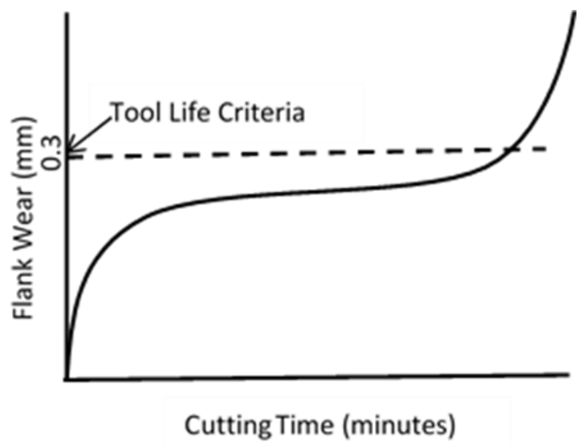

Figure 1. The relation between flank wear and tool life criteria

It is normal practice to assert that a tool should be considered to have reached the end of its useful life when flank wear has been attained to result in a specified dimension. According to ISO 8688-2 recommendations for both roughing and finishing cuts, for end milling cutters the end of useful tool life can be assumed to occur when tool wear levels equal to 0.3 mm for uniform wear and equal to 0.5 mm for a non-uniform (localized) wear arise [1]. These values are used in this work as an indication of the presence of unacceptable levels of tool wear.

The earliest effective approach to determine tool life for a given cutting speed was proposed by Taylor 1906 [2]. This approach suggested that, for progressive wear, the relationship between the time to tool failure for a given wear criterion and cutting speed was of the form:

$$V.T^{n} = C \quad (1)$$

Where: *V* is the cutting speed (m/min) and *T* is the tool life. This is normally measured in the most relevant time base (minutes). In this simplest of forms the constants *n* and *C* are defined for the particular combination of tool and workpiece material combinations and other machining variables such as feed rate and depth of cut. Values for *n* and *C* can be obtained from standard tables for different workpiece materials and different cutting tools. However, this equation does not include the effect cutting tool geometry, cutting feed, depth of cut and is limited to a certain range of speed [3]. Taylor's extended equation addresses this:

$$V^{\frac{1}{n_1}} f^{\frac{1}{n_2}} d^{\frac{1}{n_3}} T = C \quad (2)$$

Where the exponent *n1, n2,* and *n3* are constant and determined empirically. *f* is the feed (mm/rev.) and d is the depth of cut (mm). Since the provision of this, and similar considerations, various methods to calculate tool wear and tool life have been proposed. However, none of these equations can be applied with absolute certainty due to complex nature of the machining process [4]. The application of tool life management strategies based upon these equations is difficult as machining conditions can change and the nature of the metal removal process depends upon the geometry of the component and the selected tool path. Part of this consideration is then related to uneven tool wear which reflects the nature of the cutting undertaken by a tool during its life. Thus it is likely that in real-life conditions the unguarded application of tool life calculation can lead to premature removal of healthy tool or the continued use of a dangerously worn tool.

Tool wear measurement can be broadly split in to two types, direct and indirect methods [5]. Direct measurements can be fast and accurate. They entail measuring the actual wear, using different methods including; optical measurement, radio-activation analysis and electrical resistance measurements. However, the direct measurement of tool wear during machining operations is difficult. Alternatively, indirect measurements may be online (or in process) and use machining process signals, such as cutting force, acoustic emission, sound, vibration [6] and current power for various drives [7]. There are other indirect measurements that are basically offline and relate to workpiece condition, including the measurement of the changes in machined component dimension or geometric form, the value of the volume of metal removed and component surface finish and/or roughness. However, in practice, tool wear is a very much more complex problem and it is potentially simple to determine tool wear quantitatively but is complicated in a practical context [8].

A considerable amount of research has been directed towards indirect measurements the tool wear based upon measuring the changes in geometric form or machined component dimension such as cylinder form and quality [9-15]. Little or no research into the quality of milling cylindrical features, such as the holes used in this work, has been previously published. The intention of this research is to explore how it is possible to under or overestimate the levels of tool wear when adopting a "traditional" method to calculate the average cylinder diameter as the measure of the actual tool wear. By simply averaging features that are measured the offset tool wear based on the component measurement will be inaccurate. Most importantly it is possible that the critical amount of tool wear especially for the bottom section of the cutter will be underestimated. This can mean that the machine tool operator will carry on machining using a cutter that is near to or exceeding the end of its life. It is also likely that the geometric form of a component machined using this cutter will be less than optimal.

2. EXPERIMENTAL UNEVEN TOOL WEAR ASSESSMENT

The aim of the experiments performed within this initial work was to establish and verify the approach adopted to form and feature measurement, which was designed to directly measure tool flank wear. In this work, the tool wear estimation method was developed based on component metrology. This approach was established to enable the consideration of the effect of machining conditions on tool wear. The key concept the method is to employ the appraisal of the form and dimension of features of a milled cylindrical cavity to quantify and classify the tool wear status.

2.1. Milling Machine

The initial experimental work was performed on a Mazak Vertical Centre Smart 430A (MVCS). The MVCS's ability to machine in three-axes enables the production of complex components and shapes. Using the full range of available spindle speeds, up to the maximum 12000 rpm, allows for a broad range of cutting parameters. Another feature that made the MVCS a suitable machine was its capacity to hold multiple tools and to undertake workpiece setting using on-machine probing. As the complete testing of tools needed more than one workpiece, this function allowed the cutting tool to remain in the machine without having to be removed and reset. This process could have potentially caused the tool setting to be different, thus affecting results.

2.2. Workpiece and Cutting Tool Material

In this study, a bright mild steel workpiece was used as the machining material. It was milled by using a high-speed steel 16 mm diameter 4-flute end mill cutter. The machining of bright mild steel is challenging due to the mechanical properties of hardness, tensile and yield strengths. It is also desirable to machine at higher cutting speeds and feeds while maintaining a good surface finish. The particular combination was selected to induce tool wear on a realistic but accelerated basis. Figure.2 represents the workpiece condition after machining. The dimensions of the test piece were 125 mm x 220 mm x 25 mm. There are eight 40 mm diameter holes, numbered 1 to 8. The test piece design was intended to highlight the effect of tool wear via the measurement of the dimension of the machined features using a CMM.

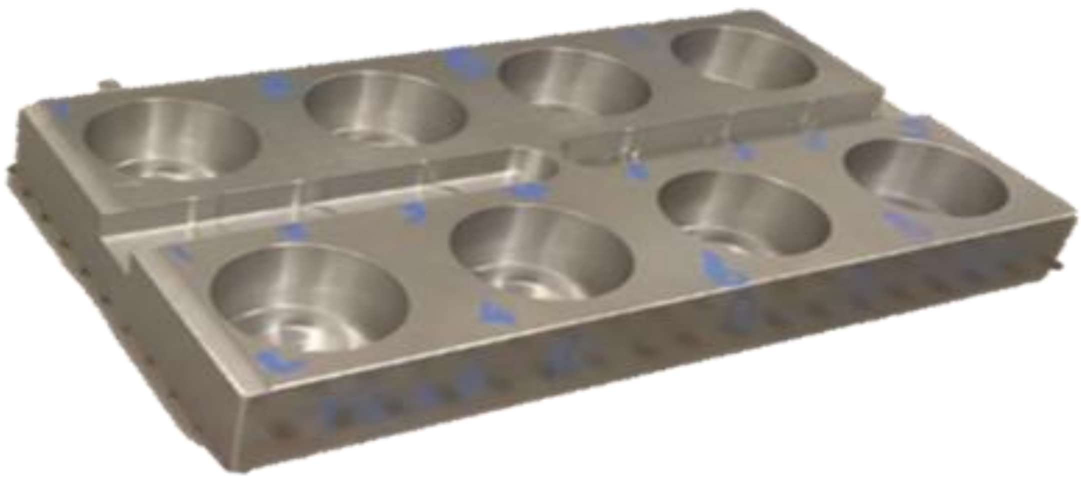

Figure 2. Eight-cylinder test piece

The conditions for the initial tests were selected by taking the recommended cutting speed for a milling operation. The cutting conditions chosen for this initial study were: spindle speed 1035 rpm, feed rate 258.7 $mm.min^{-1}$ and cutting speed 52 $m.min^{-1}$.

2.3. Experimental Procedure

At the start of each test cycle, a new cutter was used to machine the first 5mm deep cylinder C1 as shown in figure 3. A sequence of three further cylinders were then machined to depths of 10 mm cylinder C2, 15 mm cylinder C3 and 20 mm cylinder C4, again shown in figure 3. This sequence was repeated in each of the eight locations on a workpiece, as indicated in figure 2. On the basis that the material removed in machining Hole 1 Cylinder 1 was using the new tool, this hole was used as the reference hole. It is very important criterion because the diameter of the other holes at different depths and across different workpieces could be compared with it and the measured differences could then be treated as the tool flank wear.

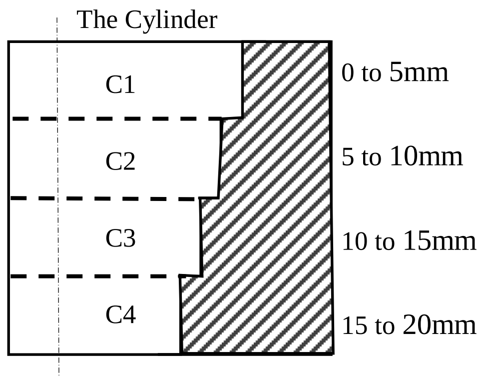

Figure 3. Cylinder measurement depth dimensions

The method adopted was aimed at indirectly measuring flank wear of the major cutting edge of the tool based upon feature metrology. In this set-up each cylinder was machined following the sequence shown in figure 4. The cycle was designed to remove a 5mm deep section of the 40 mm cylinder following a sequence of plunge-linear movecircular cut cycle, as indicated. Each cutter was used to produce eight times 40 mm holes that were machined in four workpieces. Each cylinder was then measured at each of the four depths and an average diameter was established for each separate 5mm section cylinder. Using the measurements obtained at the four different depths an average diameter was established. The values of the average diameter for each of these four cylinders was then calculated, based on the coordinate measurements obtained. After assessing the cylinder diameters of all the holes and calculating flank wear, it was possible to produce plots from which underlying trends could be determined.

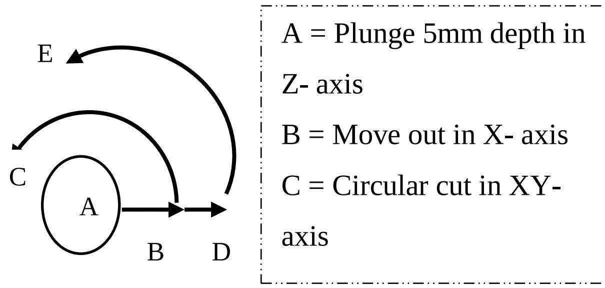

Figure 4. The Diagram of Cutting Operation for Each Cylinder

The CMM deployed in this research operated using a Renishaw 5-axis controller with state of the art measurement, sensor and control technology. The use of this 5-axis system enabled the accurate measurement of cylindrical features using a circular scan of the inside of the designated cylinders at the controlled depths indicated in figure 3. A cylinder feature was then constructed for each pair of measurements to provide the cylinder data used to produce figure 5. The application of this measurement process provided a precision of <0.1 µm. The deployed Revo system is also capable of surface finish measurement, which will be utilised in the later stages of this research.

3. RESULTS AND DISCUSSION

Figure 5 presents the initial results from the CMM measurements of the four diameters, D1, D2, D3 and D4 corresponding to the four cylinders C1, C2, C3 and C4. The calculated values for the average whole diameter D ave is also presented.

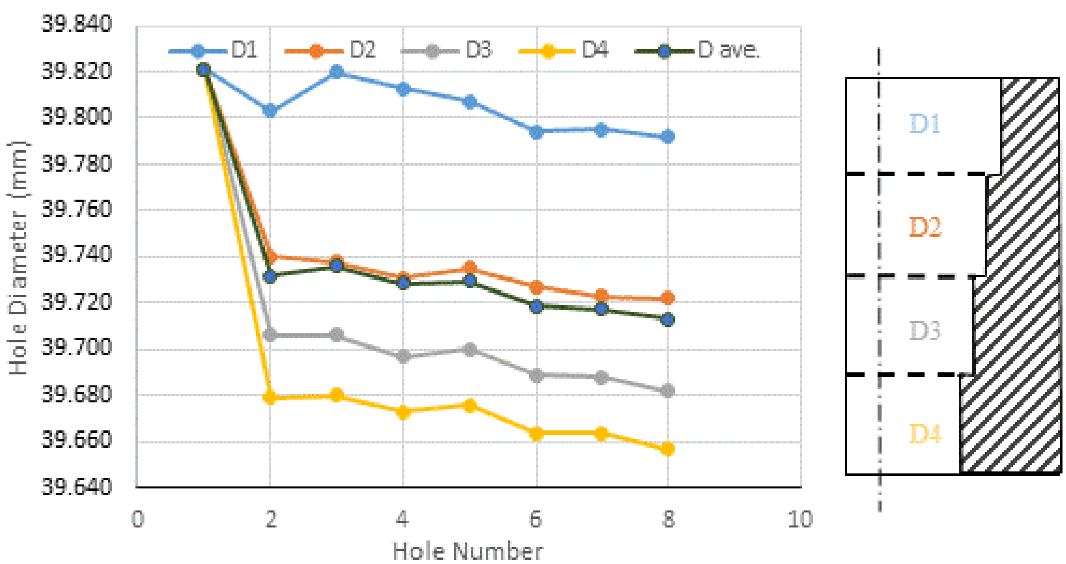

Figure 5. Variation in Cylinder Diameter

Based on the metal removal process outlined in figure 3 it must be the case that that the bottom section of the cutter C4 was cutting for longer and removing more metal than the upper regions. Moving up the tool each section of tool actually removes less metal. It is also clear, from figure 5, that the diameter of the cylinders at the same depth of the corresponding regions became smaller as the milling experiments went on. In addition, there are variations between the values of the actual diameters at the different levels (D1, D2, D3, and D4) with the value of the calculated average diameter (D ave.). This analysis suggests that the geometric form of a component machined using the uneven wear cutter will be less than optimal.

This effect can also be seen from the levels of tool wear shown figure 6. These values were calculated from the changes in cylinder diameter which represent the apparent tool wear at each of the corresponding levels, resulting in the dimensions shown in figure 6.

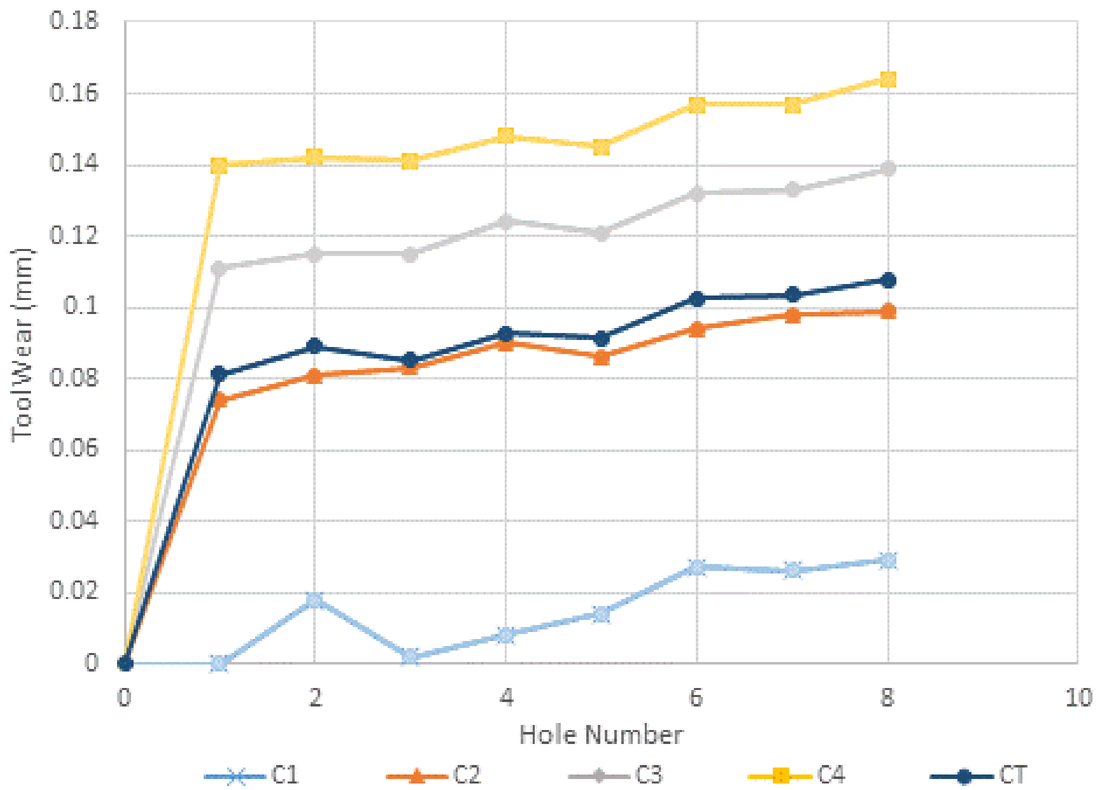

Figure 6. Tool Wear as a function of Hole Number

The occurrence of uneven tool wear is clearly shown in figure 6. As anticipated, the amount of indicated tool wear is least in the top section of the cutter (segment C1) where the maximum value reaches 0.03mm. The highest level of tool wear occurs in the section C4, which corresponds to the bottom section of the cutter, where the maximum approaches 0.16 mm. Figure 6 also indicates the results for the average tool wear value, CT, which reaches a maximum of 0.11 mm on figure 6. This indicates the potential for error associated with the non-allowance for differential tool wear in the cutter when using the average value to inform the resetting of the tool offset and also shows how this can possibly reduce the dimensional accuracy of the product.

To provide more definite assessment of the nature and level of this effect the cutting per cylinder process depicted in figure 4 was combined with the tool wear measurements in figure 6 to produce a plot of tool wear versus cutting time. This is shown in figure 7. It is important to stress that this figure represents the tool wear associated with this particular set of cutting processes. The rate and level of tool wear will obviously vary, in accordance with the expectations identified in the tool life equations.

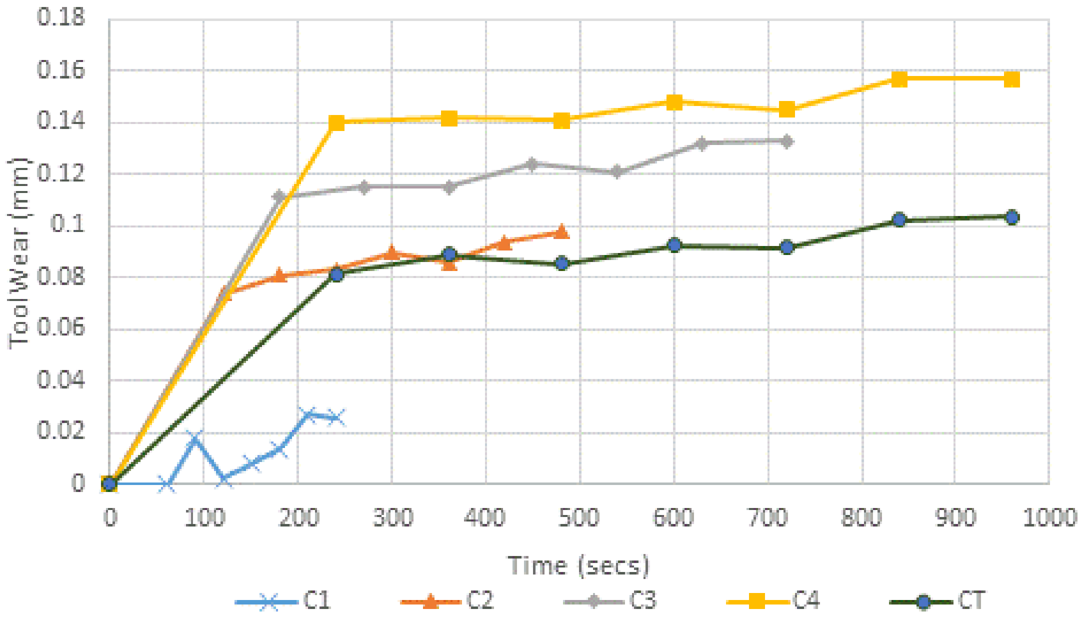

Figure 7. Tool Wear as a function of cutting time

Based upon the experimental results shown figure 7 anticipated tool life was extrapolated for three of the acquired trend lines; for C1, C4, and CT, This approach was intended to explore the potential variation in indicated tool life by estimated the cutting time at which tool wear reached the maximum advisable 0.3mm limit. From this analysis it was determined that the first segment C1 for the cutter will reach the end of usable tool life criteria at 66 minutes. The bottom section, C4, will reach to the end of tool life criteria after 49 minutes work. Finally, based on the average tool wear Ct, the cutter will reach this point after 60 minutes cutting.

The effect of basing anticipated remaining useful tool life on the measurement of tool wear is clearly important. Each of the different times indicate the error that could potentially occur. Assuming that the assessment of remaining useful life is based upon the average tool wear CT; this would indicate a value of 60 minutes. Applying a tool management strategy on this basis would mean, in this instance, the section of tool performing most of the cutting, section C4, would be at risk of failing once the cutting time passes 49 minutes. This is clearly not a viable position as it could result in tool breakage. At the other extreme, in this case, the remaining useful life of the lightly used section of cutter would be more that allowed for by using the average value; this is less important as it is not possible to make use of this section of tool and no tool failures would result.

4. CONCLUSION

This approach makes it possible to calculate the differential tool wear arising during the specified cylindrical cavity machining process. The intention of this work was to show how CMM based measurements can be used to quantify how much the different sections of the tool are worn. The analysis showed that the measurements obtained by deploying the CMM could be a reliable basis for the identification of uneven tool wear based upon the geometry of the component.

Using the accepted tool life criteria, this investigation has indicated that the flank wear arising in the bottom section of the cutter is likely to exceed the identified limit of 0.3 mm if the estimation of tool life is based upon average tool wear. In this case, the operator could continue to use a tool which is reaching a dangerous level of tool wear because this has been in hidden by the fact that the average tool wear have been taken rather than the actual value.

It is recognized that this is only a very simple investigation but it has confirmed the presence of an important process and the conclusion must therefore be that more work is required, which is the aim of this on-going research. This will support these assessments but based upon more direct tool wear-related measurements acquired from the machine tool controller.

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