Towards industrial

Micro-milling is an attractive technology for manufacturing micro-components. To enable its industrial application, some technical hurdles need to be taken. In this article, two important issues are addressed. First, a significant improvement in tool life is discussed, which was obtained by redesigning the geometry of the micro-endmill. Second, a solution for cutting force estimation is presented that uses the available signal information in active magnetic bearings. Using this cutting force information, tool failure can be detected and tool condition can be monitored.

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The ongoing trend of miniaturization has led researchers to explore different ways to manufacture components in the micro-scale accurately and cost-efficiently. With continuous developments of high-precision machine tools, unit chip removal in the (sub-) micrometer range has become possible. This has triggered great interests among research institutes and industries, both worldwide and in the Netherlands, to investigate the feasibility to scale down conventional mechanical chip removal processes, such as milling.

Introduction

At first sight, the mechanics of micro-milling appear similar to those of macro-scale milling: material removal happens through the interaction between a rotating micro-endmill and a workpiece, where the milling tool tip traces a predefined contour along the workpiece through coordinated motion of the axes of the machine tool. The typical cutting diameter of commercial micro-endmills is in the range of 50-500 µm. Compared with currently used micro-fabrication processes, such as etching, LIGA (Lithography, Electroplating, Moulding), and micro-EDM (see the article in this issue), micro-milling offers many advantages, such as fast material removal rate and the ability to manufacture parts with true 3D features in a broad range of workpiece materials, including hardened tool steels. One of its potential applications is to make micro-moulds for mass replication of micro-parts by injection moulding.

However, micro-milling has shown some special characteristics that are fundamentally different from conventional milling due to the scaling effect. For example, when the chip thickness is in the same order of magnitude as the edge radius of the cutting tool, the cutting edge can not be assumed to be sharp anymore. The effect is that at the micro-scale it appears that the cutting takes place with a rather blunt tool. This causes the cutting mechanism to be rather different than at the macro-scale. Additionally, with chip sizes in the micrometer range, small disturbances (e.g. due to mass imbalance, or machine vibrations) have a significant influence on the cutting process. At this stage, these issues are not sufficiently understood and more research on micro-milling is required before it can be introduced in an industrial setting.

Scope

In this article two factors are addressed that may accelerate industrial application of micro-milling. The first concerns the lifetime of micro-tools. It is observed that the tool life of currently available commercial micro-endmills is too short to conduct a reliable cut, especially in hard milling applications. With these endmills, tool wear is severe, and catastrophic tool breakage is high. The research question that will be addressed first is how tool life of micro-tools can be extended, in particular by redesign of the tool geometry.

The second issue concerns the monitoring and control of the micro-milling process. To improve the micro-milling process, online process monitoring and control becomes of high importance. Due to reduced tool diameters, signs of problems are almost unnoticeable without the use of special equipment. Techniques are needed to detect and possibly even predict anomalies in the process, and to monitor online the condition of the cutting process. This information is then to be used to optimize the cutting process in a closed-loop control setting. It appears that milling spindles with active magnetic bearings (AMBs) are particularly interesting for development of such monitoring techniques [1]. It will be discussed how the cutting forces can be estimated using available sensor signal information from the AMBs.

Finally, an outlook is provided on both the tool-life improvement and the cutting force monitoring with AMB spindles, and it is discussed how effective monitoring and control can further extend the tool life of micro-endmills.

Improving micro-endmill tool life

In order to get a better understanding of the micro-milling process, some preliminary experiments were conducted with commercial Ø 0.5 mm 2-flute square endmills, as shown in Figure 1 [2]. All the endmills were TiAlN coated and the substrate material was ultra-fine grain tungsten carbide. The workpiece materials were hardened tool steels (such as SAE H11, H13, and D2, up to 56 HRC), which are commonly used in dies and moulds industries. The Fehlmann Picomax 60 HSC and Kern EVO were used as machine tools.

The tests showed that the tested micro-endmills suffered from severe tool wear at the cutting edge corners. As a result, the lifetime of micro-tools was shortened severely. A typical worn tool is shown in Figures 2a and 2b. It was observed that the dominant tool wear type was the

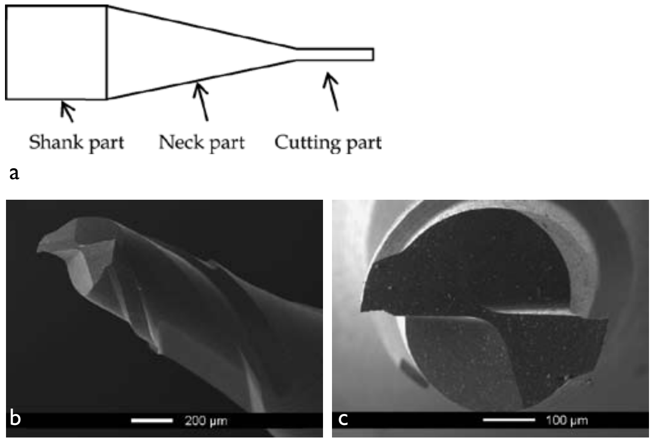

Figure 1. Geometry of a micro square endmill.
(a) Illustration of the global geometry.
(b) 3D view of the cutting part.
(c) Top view of the cutting part of a Ø 0.5 mm square endmill.

breakage of cutting edge corners. Figure 2c shows the progress of tool wear. At the beginning of the machining (200 mm slot milling), a sudden change in the cutting diameter was observed, which was due to breakage of cutting edge corners. Afterwards, the reduction of tool

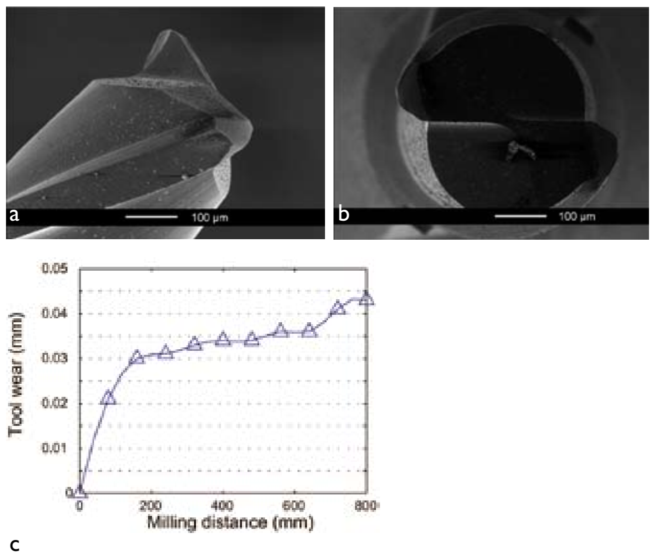

Figure 2. Wear of tested commercial Ø 0.5 square endmills.
(a) 3D view.
(b) Top view of the cutting part of a worn tool.
(c) Tool wear curve; tool wear was evaluated as reduction of the cutting diameter at the endface of the tool.

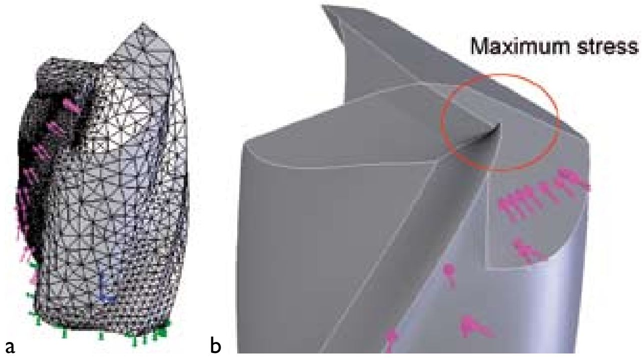

Figure 3. Study of tool geometry by FEM.
(a) CAD drawing of the cutting part of the commercial tool geometry.
(b) Stress distribution at the cutting edge corner.

diameter became gradual, which can be attributed to abrasion. This figure shows that in order to improve tool life, the breakage of cutting edge corners at the early stage of machining should be prevented.

The failure of micro-endmills can be attributed to many aspects, such as the quality of micro-cutting tools, workpiece properties, selection of machining parameters and tool paths, and performance of machine tools. Among these factors, the geometry of micro-endmills plays an important role since it directly influences the interaction between cutting tool and workpiece. Unlike in macro-scale milling, in micro-milling the cutting is mainly done by the cutting edge corners due to the small depth of cut. To study the effect of this, FEM analysis (finite element method) was performed on the geometry of tested commercial micro-endmills; see Figure 3. Under simulated cutting conditions, it was found that with this geometry the maximum stress in the tool tip is located at the cutting edge corners, as shown in Figure 3b. When this stress is higher than the transverse rupture strength of tungsten carbide, the cutting edge corners will break away, as observed in experiments.

This analysis was used as starting point to extend the tool life [3]. The main objective was to modify the geometry of the micro-endmills such as to improve the strength of the cutting edge corners. In order to achieve this target, the relationship between tool geometrical features (such as rake angle, relief angle, etc.) and tool performance (such as stress distribution along the tool and tool stiffness) should be understood. This was done by means of analytical modeling and FEM analysis. Having gained insight in this relationship, the geometry of the micro-endmill could be designed adaptively to achieve the required performance. Two new geometries were proposed to improve micro-tool performance. The CAD drawings of the cutting part of the newly-designed micro square endmills are shown in

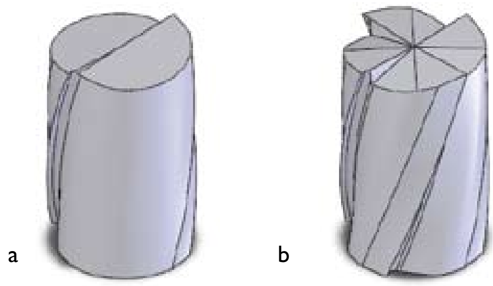

Figure 4. Cutting part of newly-designed micro-endmills.
(a) 2-flute endmill.
(b) 4-flute endmill.

Figure 4. Compared with the commercial tool geometry, the new designs have improved strength of cutting edges which makes them suitable for hard milling. Besides, the new geometries are relatively simple, making them easy to manufacture.

The new designs were manufactured and verified through experiments in comparison with commercial micro-endmills. The results show that tool life improved significantly when using the new designs, as shown in Figures 5a and 5b. Besides, since the wear of the newly-designed endmills reduced, the workpiece quality also improved accordingly, in terms of form accuracy and burr formation, as shown in Figures 5c and 5d.

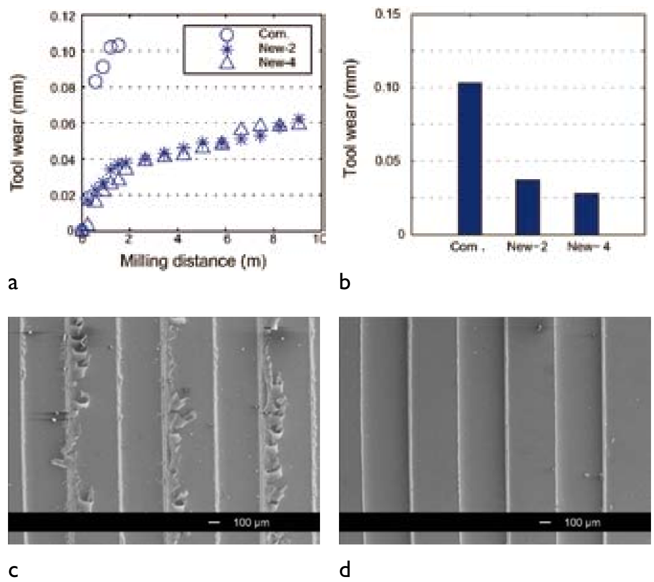

Figure 5. Results of experimental validation of new tool designs in comparison with commercial tools.
(a) Tool wear comparison after material removal of 5.3 mm^3.
(b) Comparison of milling distance.
(c) Top view of milled grooves by the commercial tool; burr formation was a serious problem.
(d) Top view of milled grooves by the newly-designed tool.

However, it was also realized in the research that the improvement of tool performance by only tool geometry is limited. As discussed earlier in this paper, the performance of micro-endmills is influenced by many factors. In order to achieve a reliable micro-milling process, efforts should also be made in other aspects such as process monitoring.

Force estimation

More than in conventional milling, it is important in micro-milling to monitor the cutting forces during machining in order to maintain a stable cutting process. These forces can be measured directly with force transducers, however commercially available systems are limited by their bandwidth and the additional space needed in the machine.

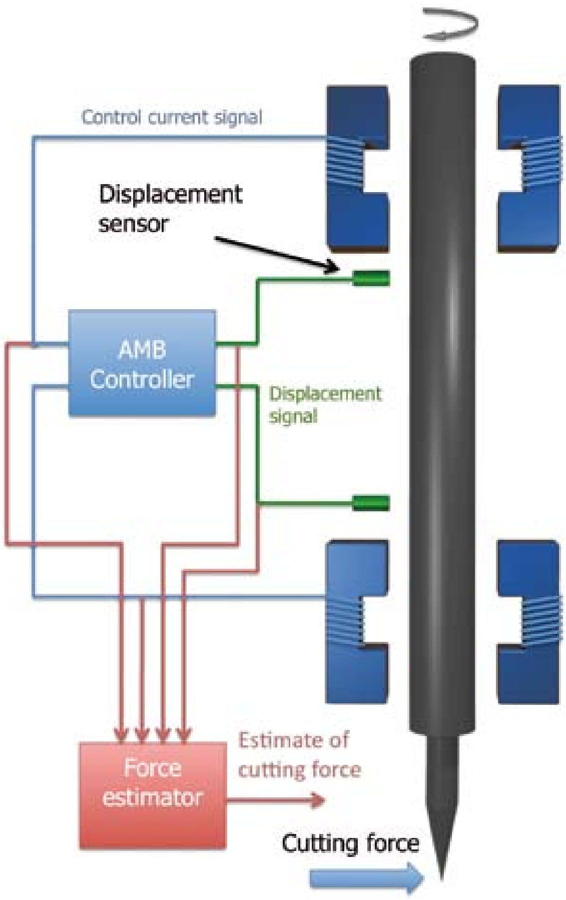

Figure 6. Schematic illustrating the concept of cutting force estimation with an AMB spindle. Cutting forces acting on the tip of the endmill can be estimated from the closed-loop current and displacement signals of the magnetic bearings.

When the milling is performed by a spindle with AMBs (active magnetic bearings), the active nature of the bearings can be employed to observe the cutting forces from the signals of the bearings. In AMB spindles, the rotor is levitated by generating electromagnetic forces at the front and rear side of the rotor, as well as in the axial direction; see Figure 6. A stable system is obtained by using position measurements in a closed loop to control the currents of the electromagnets. Force estimation based on the current and position signals is attractive, as it eliminates the need for additional sensors, thus saving cost and space.

The problem of observing cutting forces from the signals of an AMB spindle can be considered an input estimation problem. This can be seen as follows. Modeling the open-loop AMB spindle dynamics as G and the controller as K, it follows that the cutting forces constitute an unknown input to a partially closed-loop dynamical system; see Figure 7. Measurements are available of the currents through the coils (denoted by y_1) and the displacement of the rotor (denoted by y_2). Having these available, the objective is to estimate the unknown input u_2, representing the cutting forces.

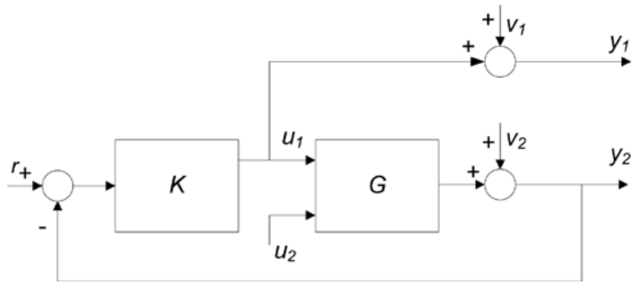

Figure 7. Block diagram of the closed-loop AMB spindle system. Cutting force estimation can be formulated as an input estimation problem, where the forces are the unknown input u_2 to a partially closed-loop system consisting of the AMB spindle dynamics G and controller K.

Optimal estimates $\hat{u}_2$ can be obtained by minimizing the mean square error $E\|\hat{u}_2(t) - u_2(t-N)\|^2$, where $N \geq 0$ is some fixed time lag. When the unknown input sequence is treated as white noise filtered by known dynamics, the optimal estimator will have a Wiener filter structure. The adjustable delay N allows to trade-off the estimation error against the lag in the estimation results [4].

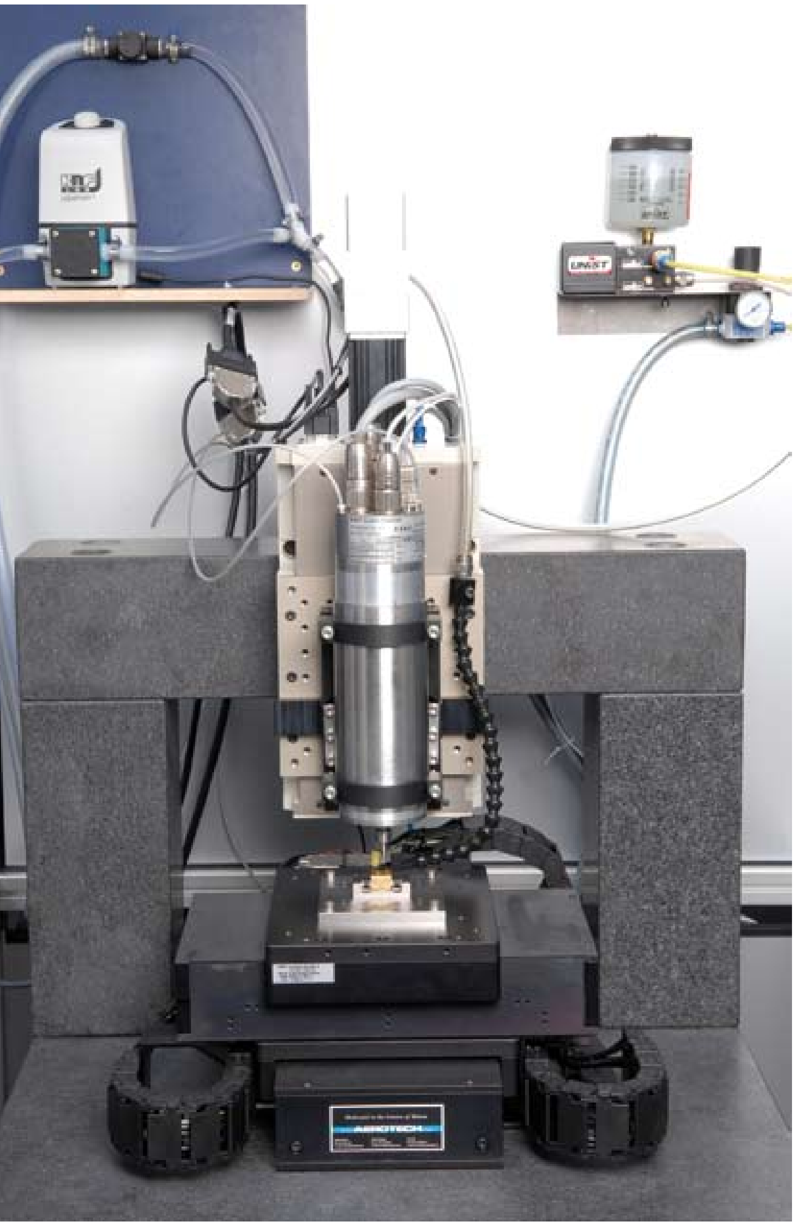

Figure 8. Micro-milling setup at Delft University of Technology, with an AMB spindle with max. rotational speed of 120,000 rpm.

In a simulation study, this concept is demonstrated by modeling of the AMB spindle in our lab; see Figure 8. This is a state-of-the-art AMB spindle from EAAT GmbH Chemnitz (Elektrische Automatiserungs- und Antriebstechniek), with a relatively high maximum rotational speed of 120,000 rpm. The rotor length is 250 mm and the rotor mass is 1.1 kg. The displacement sensors used in the bearings have a resolution of 0.1 µm. The AMB controller hardware also provides measurements of the currents through the coils with an accuracy of 1 mA. The magnetic bearings are controlled by analog PID controllers.

An analysis of the properties of the resulting force estimator reveals that the maximum estimation bandwidth that can be achieved with this spindle is 1.8 kHz. The resolution is 0.17 N. These numbers are dependent on the properties of the AMB spindle, and are found to improve when reducing the AMB spindle dimensions [5]. A time-domain simulation result is depicted in Figure 9. A known cutting force is applied to the AMB spindle, and current and displacement signals of all four radial bearings are used to estimate the cutting forces in X and Y direction. This figure, showing the result only in Y direction, illustrates the favorable results of the presented approach. Practical implementation of this approach hinges on the availability of a reliable model of the dynamics of the AMB spindle. Currently ongoing research is to obtain such model by system identification from measured data sequences.

Force-based tool condition monitoring

In micro-milling, condition monitoring of the tool plays an important role to improve the reliability of the process. First, detection of tool failure is challenging due to the small cutting edge diameter and untimely detection of failure can cause damage to the workpiece and hours of work to be wasted. Second, monitoring of the wear status of the tool is important to maintain the quality of the workpiece and to avoid breakage due to progressed tool wear.

Cutting force information is essential for development of tool-condition monitor techniques. The above presented cutting force estimation approach is very suited to be utilized for this purpose and therefore offers opportunities to further improve tool life and performance of the micro-milling process.

Conclusion

Micro-milling is an attractive technology for manufacturing of miniature components, but additional research on different aspects of the process is needed to enable industrial application. Design of micro-endmill geometry needs to be driven by understanding of the micro-milling process. It was shown that this implied for hard milling applications that the cutting edge corners needed to be strengthened. Experiments demonstrated that newly-designed tools had significantly improved tool life. Monitoring of the cutting forces during milling can be achieved by employing the active character of spindles with active magnetic bearings. It was shown that forces can be estimated from the current and displacement signals of

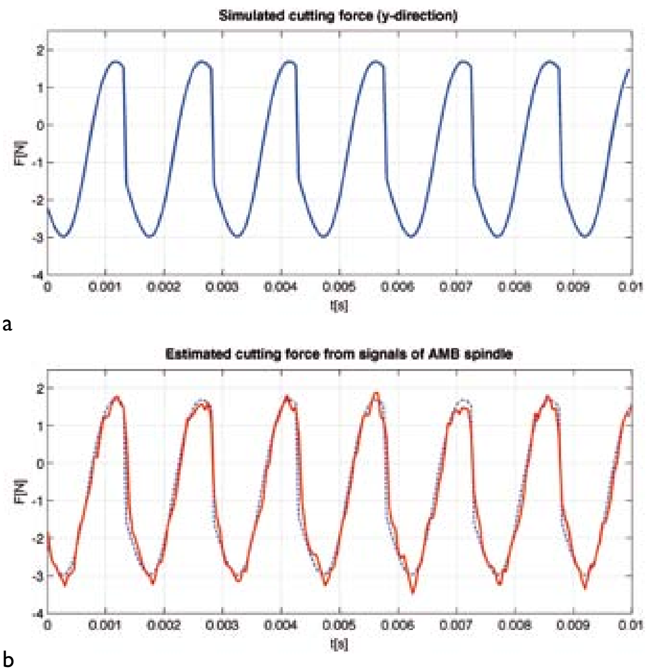

Figure 9. Simulation results of cutting force estimation from the signals of the AMB spindle. Results are only shown for one direction.
(a) Simulated cutting force signal.
(b) Estimated cutting force.

the AMBs with sufficient bandwidth and accuracy. This offers opportunities to directly improve the reliability of the process.
These results may contribute to industrial application of the micro-milling process. Further research at Delft University of Technology and TNO Science and Industry is being undertaken.

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Information

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