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Speeding up ultra-precision manufacturing

Ekkard Brinksmeier[1] and Lars Schönemann[2]

[1,2] *LFM Laboratory for Precision Machining and MAPEX Center for Materials and Processes, University of Bremen, Germany*

[2] *schoenemann@lfm.uni-bremen.de*

Abstract
Ultra-precision machining is a versatile process for generating precision parts and optical surfaces. A major drawback, however, are the inevitably long machining and set-up times associated with the applied processes. These can easily exceed several hours or even days, having a huge impact on the economic efficiency of the ultra-precision manufacturing.
Recently, the research unit "Ultra-precision high performance cutting", a collaboration of scientists from Bremen and Hannover, has achieved remarkable research results which give clear evidence that the manufacturing time for ultraprecise parts can be reduced considerably. The ultimate aim to reduce the manufacturing time of ultra-precise parts by the factor of 10 seems to be feasible in near future. Based on the identified limiting factors of today, several measures, such as high speed diamond milling, automated balancing procedures or diamond milling tools with multiple cutting edges, haven been taken and implemented.

Keywords: Ultra-precision machining, high performance cutting, diamond milling

1. Introduction

Ultra-precision machining comprises various cutting processes, such as diamond turning or diamond milling, and is commonly applied for generating high precision parts and optical surfaces [1]. The utilized processes offer a high versatility and thus allow for increasingly complex shapes to be made. However, while high speed machining operations have been introduced to conventional machining processes several decades ago [2], ultra-precision manufacturing still suffers from inevitably long primary and auxiliary machining times [3]. Durations exceeding several hours or even days of machining time are not uncommon and have a huge impact on the economic efficiency of ultra-precision manufacturing.

2. State of the art and current drawbacks

In optics manufacturing, the tight tolerances on surface roughness and figure accuracy, with Sa < 10 nm and PV < 0.1 µm being typical desired values, imply a precise control of the tool engagement conditions. Therefore, ultra-precision milling is typically conducted as a fly-cutting operation with only single-edged tools [4]. This restricts the applicable feed velocity of the process. Furthermore, only low spindle speeds of n = 1500 to 3000 min^{-1} are applied to minimize dynamic disturbances induced by the spindle and to protect the delicate air bearings from damage due to the acting centrifugal forces [5].

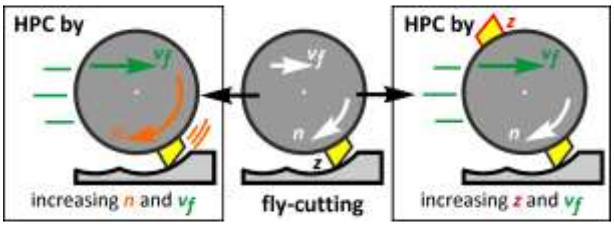

Figure 1. Advancing ultra-precision milling/fly-cutting to high performance cutting (HPC) by increasing v_f in combination with n or z

Considering these limitations, the economic efficiency of ultra-precision machining processes could be easily increased either by the application of higher spindle speeds n and thus a higher cutting velocity v_c (high speed cutting, HSC) or by increasing the number of cutting edges z engaged in cutting. If the feed speed v_f is increased along with n or z, high performance cutting (HPC) is achieved, as depicted in Figure 1.

Both of these measures, however, introduce new challenges, as will be described in the following chapters.

3. Ultra-precision high speed cutting

When thinking about enhancing the performance of a milling process it is obvious to increase the applied spindle speed and thereby allow for higher feed velocity while maintaining the required kinematic roughness.

As recent studies in ultra-precision machining have shown [6], this does not only have a positive effect of the machining time, but also reduces the acting cutting forces (due to adiabatic shearing in the cutting zone) and thereby the wear of the diamond tools (Figure 2).

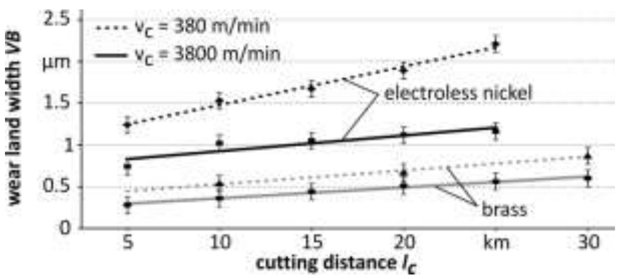

Figure 2. Development of wear of a V-shaped diamond tool applied at low and high cutting speeds

4. Balancing of air bearing spindles at high speeds

Major constraints for the application of (peripheral) diamond milling are the unbalances generated by the tool holder. As the acting centrifugal force induced by the unbalance and the swing radius feature a quadratic relation, i.e. $F_z = m \cdot r \cdot (2\pi \cdot n)^2$, it is generally favourable to apply small milling tools with a swing radius of <30 mm. However, in diamond milling tools with a swing radius of 100 mm or more are not uncommon.

Balancing of these tools is usually done manually, by adding set screws of a defined mass at specific radial position. This, however, is a time consuming (iterative) process and is limited concerning the achievable balancing grade. By developing new approaches for improving the balancing grade and for automating the overall procedure the set-up times for the milling process can be drastically decreased.

A possible solution for automatable high precision balancing is the defined release of fluid from pre-filled tanks on the rotor using remotely controlled micro valves (inverse hydro balancer). Such a system is currently developed at LFM and is able to balance a diamond fly-cutter to an ultra-high balancing grade within a few minutes [7].

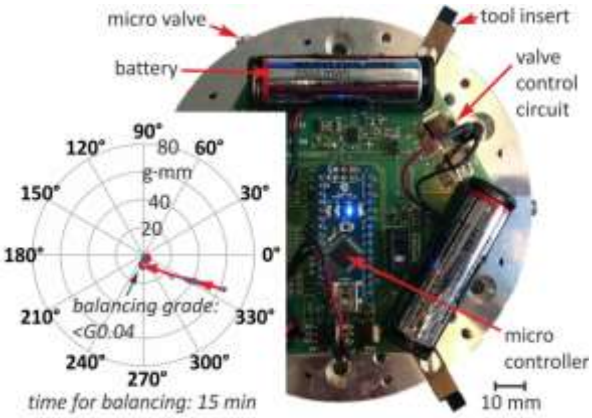

Figure 3. Fluidic balancing system and exemplary balancing chart

5. Diamond milling with multiple cutting edges

A further progress was made by developing a new thermo-mechanical tool alignment mechanism and integrating it into a diamond milling tool (Figure 4). With this device, a defined section of the substrate is illuminated via an infrared LED in order to induce a thermal elongation in radial direction. By using a closed loop control with the radial displacement measured at a reference plane, a tool setting precision of <10 nm is achieved, as is described in [8] in further detail.

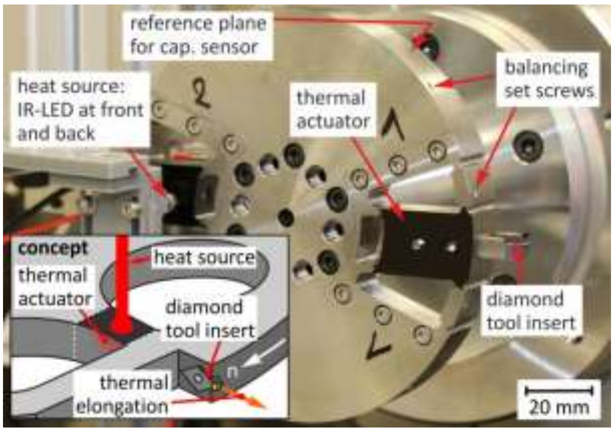

Figure 4. Diamond fly-cutter with two cutting inserts and thermo-mechanical actuator for tool alignment in radial direction

This device enables ultra-precision milling with multiple cutting edges in comparison to the commonly applied fly-cutting techniques using a single cutting edge. Machining times can be cut down accordingly.

6. High performance feed axes and control systems

Finally, the application of high cutting speeds and multiple cutting edges ultimately requires highly dynamic feed axes. While for fly-cutting with a 160 mm at 5000 min^{-1} a feed velocity of <400 mm/min is sufficient for achieving an optical surface finish, higher spindle speeds and more cutting edges easily imply a feed velocity of >3000 mm/min. Here, an electromagnetically levitated linear axis in combination with a model-based control system offers the possibility to counteract dynamic deviations and thus allows for higher feed velocity. Such a system (Figure 5) is currently under development at the University of Hannover [9,10].

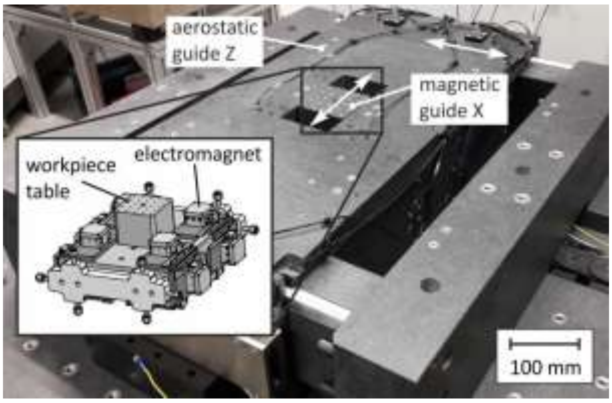

Figure 5. Ultra-precision magnetic guide (courtesy of IFW Hannover)

7. A roadmap to ultra-precision high performance cutting

In this paper several individual measures were shown, that are able to increase the economic efficiency of ultra-precision manufacturing processes. However, as Byrne et al. stated in their recent keynote paper to the CIRP HPC conference, *'the new capabilities at our fingertips will be multiples of what was available to us in the past'* [11]. Thus, the next steps towards true ultra-precision high performance cutting will be the integration of all individually developed components into a common platform in order to fully demonstrate the capability of this technology.

Acknowledgement

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