Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 46 (2016) 185 – 188

www.elsevier.com/locate/procedia

7th HPC 2016 – CIRP Conference on High Performance Cutting

Microfluidic balancing concepts for ultraprecision high speed applications

Timo Dörgeloh, Arne Beinhauer*, Oltmann Riemer, Ekkard Brinksmeier

Laboratory for Precision Machining (LFM), University of Bremen, Germany

* Corresponding author. Tel.: +49 421 218 51162; fax: +49 421 218 51102. *E-mail address:* a.beinhauer@lfm.uni-bremen.de

Abstract

High-speed, ultraprecise air-bearing spindles require accurate balancing in order to minimize vibrations and achieve an optimum surface quality in diamond machining. In this paper, novel concepts for balancing of aerostatic spindles based on microfluidic pumps and valves are being investigated. Conventional, manual balancing methods are usually time-consuming and lack the required accuracy for ultraprecision High Performance Cutting (HPC). Using remotely controlled micropumps and -valves, minimum amounts of a few nanoliters of a fluid (e.g. water, oil) can be handled, allowing shifts of the center of mass two orders of magnitude more precise than those achieved with conventional balancing operations. Thus, a remote-controlled and automated balancing process is possible.

Peer-review under responsibility of the International Scientific Committee of 7th HPC 2016 in the person of the Conference Chair
Prof. Matthias Putz

Keywords: ultra precision; metrology; bearing; diamond machining; air-bearing; balancing; microfluidics

1. Introduction and target of the investigations

Diamond machining of optical elements with a surface roughness below 10 nm and figure accuracy below 1 µm relies on machine tools that are capable of meeting the highest requirements regarding e.g. motion accuracy and damping [1-2]. Air bearing spindles are most commonly used for both ultraprecise milling and turning operations. In order to avoid damages to the highly sensitive air bearings, and to avoid the excitation of vibrations, these spindles have to be exceptionally well balanced [3]. While balancing does not have a major influence on surface quality and form accuracy in conventional machining [4], it has been proven that unbalance-induced vibrations has a measurable effect in ultraprecision machining [5].

High setup and machining times make ultraprecision machining an overall time-consuming process. Recent research aims at reducing machining and setup times, on which balancing has a considerable impact. Firstly, balancing of air bearing spindles is usually carried out manually and requires multiple iterations, which is inefficient [6]. Due to the high requirements regarding balance quality, counter-balance weights in the range of a few micrograms and below have to be installed. The conventional approach of using set screws as counterbalances is therefore limited in its achievable balancing quality. This is particularly true for the fly-cutting process in which the rotating tool has a much larger swing radius than in ball-end milling, where an equal set screw generates a much smaller centrifugal force than in a fly-cutting process.

Secondly, the aim of lowering the manufacturing time requires higher rates of material removal, thus higher spindle speeds are necessary. As shown in (1), the centrifugal force shows a quadratic growth with increasing angular velocity. Due to the fact that balancing has to be carried out at operational speeds, manual balancing is not suitable for high performance cutting applications in ultraprecision machining.

$$F_c = m \cdot r \cdot \omega^2 = m \cdot r \cdot (2\pi \cdot n)^2 \qquad (1)$$

An automated balancing system with the ability of generating low centrifugal force alterations at operational speeds would provide the necessary means for these applications. Therefore, two microfluidic balancing concepts will be evaluated for their capability to transport low amounts

Peer-review under responsibility of the International Scientific Committee of 7th HPC 2016 in the person of the Conference Chair
Prof. Matthias Putz
doi:10.1016/j.procir.2016.03.174

of fluid and the applicability in a novel in-process-balancing device in order to realise these low changes of centrifugal force.

2. Balancing: Theory and concepts

In general, an unbalance exists if a rotor's principal axis of inertia does not coincide with its geometrical axis of rotation. Unbalances in rotating machinery cause vibrations that can be detected and used for the calculation of required counterbalances. The principles for balancing of spindles, shown in Fig. 1 and Eq. (2), involve the addition, removal or rotary redistribution of one or several masses m_i on the spindle rotor in such a way that the resultant vector U_c of the centrifugal forces acting on those masses counteracts the initial unbalance U.

$$\vec{U}_c = \sum m_i \cdot \vec{r}_i = -\vec{U} \tag{2}$$

Unbalance forces have proven to be influential on radial and axial error motions of high-speed air-bearing spindles [7]. Negative effects of unbalance forces on form accuracy and surface quality have been observed in diamond turning [5]. For excessive amounts of unbalance, the machining spindle's air bearings may be damaged.

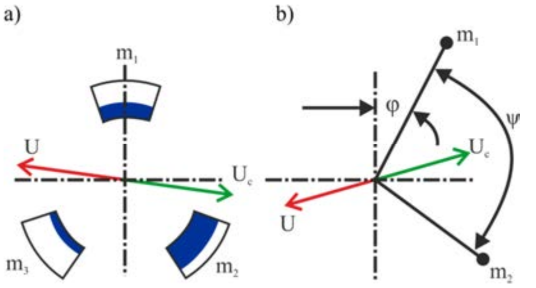

Fig. 1. Balancing a residual unbalance (U) by generating a counterbalance U_c (a) by addition or removal of mass (m_1, m_2, m_3) on defined circumferential positions.
(b) by rotary redistribution (Ψ, φ) of masses (m_1, m_2).

In order to define tolerable unbalances for different fields of application, the DIN ISO 1940-1 standard defines several balance quality grades over a wide range of rotational speeds. The balance quality grade represents the maximum permissible angular velocity of the rotor's center of mass, e.g. v_{rot} = 0.16 mm/s for G0.16, for all rotational speeds. The permissible specific unbalance e_p then depends on the rotational frequency ω [8]:

$$G = v_{rot} = e_p \cdot \omega = const. \tag{3}$$

While rotational speeds in conventional ultra-precision cutting processes are in a range of $n = 100 – 2{,}000\ \text{min}^{-1}$, ultra-precision high performance cutting (UP-HPC) applications aim at rotational speeds larger than $n = 10{,}000\ \text{min}^{-1}$ in order to achieve a higher rate of material removal per increased productivity. At an exemplary rotational speed of $n = 20{,}000\ \text{min}^{-1}$ that is used as a reference for the following considerations, the permissible specific unbalance at the lowest official ISO balancing quality grade G0.16 is $e_p = 0.076$ g·mm/kg, which is considered unsuitable for UP-HPC applications. In comparison, aerostatic spindles are factory-balanced to a grade below G0.06 [9].

ISO balancing grades differ by the factor 2.5. Following this logic, the next balancing grade below G0.16 would be G0.064, which is close to the factory balance quality of air bearing spindles and therefore defined as a reference for the analysis of the balancing capabilities of the concepts presented in this paper. For rotational speeds of $n = 20{,}000\ \text{min}^{-1}$ the permissible specific unbalance for the quality grade G0.064 is $e_p = 0.03$ g·mm/kg. An exemplary calculation for a balancing system with a compensation radius of r_c = 60 mm and a total rotor mass of m_r = 4.5 kg results in a tolerable unbalance mass of m_p = 2.25 mg at this grade (see Eq. 4).

$$m_p = \frac{e_p \cdot m_r}{r_c} \tag{4}$$

Currently, the predominant procedure for balancing air-bearing spindles is the manual addition of set screws of known weight on the circumference of the rotor. Several balancing concepts based on fluid injection or redistribution have been presented, some of which evolved into commercially available systems. These concepts inject cooling lubricant into a chambered disk during operation [10]. They are mainly designed for hydrostatic or ball-bearing spindles in conventional machining processes, where comparatively large unbalances have to be counteracted. Due to their large size and weight, a limited balancing precision and the incapability of retaining the balance state between operations, these balancing systems are unsuitable for diamond machining applications.

Subtractive fluidic balancing methods that involve the controlled release of a fluid from a prefilled chamber in a balancing device attached to the spindle so far have more or less been neglected both in conventional and ultraprecision machining. However, the emergence of microfluidic devices with reasonable dimensions and extremely low flow rates allow for a new approach towards ultraprecise balancing of air-bearing spindles using a subtractive principle.

The main performance factor of such a system based on fluidics is the minimum amount of fluid that can be transported, determining the theoretically achievable balance quality grade. To theoretically achieve G0.064 under the aforementioned exemplary conditions, the handled fluidic mass has to be significantly lower than the tolerable unbalance mass of 2.25 mg. A microfluidic pump and a microfluidic valve will be evaluated for their ability to transport and dose minimum fluidic masses below 1 mg in a static experimental setup in order to determine their suitability for application in an ultraprecise balancing system.