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# Control of a thermal actuator for UP-milling with multiple cutting edges

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**Abstract**

Ultra-precision (UP) milling processes can be dramatically sped up, and thus made more cost-efficient, by utilizing tools with multiple cutting edges. This, however, requires a dedicated actuating mechanism to interactively control the cutting radius of the individual cutting edges with nanometer precision. This paper presents recent advances in developing a tool holder for diamond fly-cutting that enables the alignment of two or more cutting edges via thermal elongation of the substrate material. After building a comprehensive model of the actuator and verifying it in a static test setup, a closed-loop control was developed that allows setting the elongation in a static setup with nanometer accuracy.


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## 1. Challenges in ultra-precision milling

Ultra-precision machining is a flexible way to machine complex optical components and microstructures [1–3]. With respect to the shape and symmetry of the part, different machining processes are typically applied [4]. Rotational symmetric shapes and even mild aspheres, for example, are preferably generated by turning operations [5], linear groove structures may be machined by planing [6], while freeform surfaces are generally machined by milling [7].

Compared to conventional machining processes, however, diamond machining suffers from some severe disadvantages: Firstly, Only a limited spectrum of materials can be machined with acceptable tool wear (e.g. Al, NiP, Cu, but not Fe) [8]. Secondly, due to the tight tolerances of optical components long processing times are inevitable. Machining a surface with optical finish and high form accuracy, i.e. $Sa < 10$ nm and $PV < 0.1$ µm, can easily require several hours or even days. Furthermore, there is only limited possibility for introducing common automation techniques into the setup procedure, e.g. for referencing the part or the tool, which therefore has to be conducted manually.

In case of diamond milling, further restrictions are at hand: For a high precision rotary movement of the tool, air bearing spindles are typically applied. Being specifically susceptible to imbalances, these are typically operated at comparably low speeds, i.e. $n < 5000$ min$^{-1}$ [9]. Last but not least, only one diamond cutting edge is commonly applied, to obtain a defined circle of rotation, thus resulting in the common denotation “fly-cutting” for such processes [10].

The necessity of the last point can be understood best, when looking at the true scale dimensions in chip removal. In combination with a lateral feed motion $v_f$, the cutting edge, moving on the radius $r_{fly}$, generates a so-called kinematic roughness $R_{kin}$ on the surface (Fig. 1).

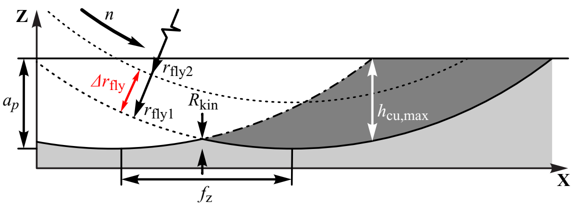


Fig. 1. Dominant dimensions in chip removal.


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Thus, a supplementary cutting edge has to move on exactly the same circle of rotation as the previous one. If the deviation is larger than the kinematic roughness (i.e. $\Delta r_{fly} > R_{kin}$), the additional cutting edge removes some of the substrate material, but is not involved in generating the final surface topography. Furthermore, if the deviation is larger than the maximum undeformed chip thickness $h_{cu,max}$, the respective cutting edge is not engaged in cutting at all.

As a consequence, using multiple cutting edges in diamond machining requires additional mechanisms to align their circles of rotation to a common radius. However, designing such a mechanism in a purely mechanical way cannot achieve the required precision of only a few nanometers. While this precision is easily achieved by electrical actuators, e.g. piezos, integrating these systems on a milling tool requires complex electronic systems for power supply, dramatically increasing the rotating volume and mass of the tool holder. This might be a reason why no references for such systems being applied to diamond milling can be found in recent reviews (cf. [10]).

A practicable approach, however, is seen in a thermo-mechanical actuator in which the tool holder is heated up locally and thus reacts with a thermal elongation of the substrate material (Fig. 2a). As the physical properties of the tool holder (e.g. specific heat capacity, coefficient of thermal expansion) are known, the required heat input may be calculated in advance, according to the desired elongation. Because heat can easily be transferred without physical contact, e.g. via infrared radiation, much of the required electronics may be set up statically and thereby does not introduce any disturbances to the milling process.

## 2. Design of a thermo-mechanical actuator for aligning multiple diamond cutting edges

In the early design phase of the actuator, basic calculations of heat transfer and thermal elongation had shown that an elongation of $\Delta l = 10$ nm could be achieved by heating up a 10 x 10 x 30 mm³ 42CrMo4-steel-bar by $\Delta T = 0.03$ K [11]. Using a high-power LED emitting in the infrared domain (e.g. Osram SFH 4783), the required amount of heat may be generated within a couple of seconds.

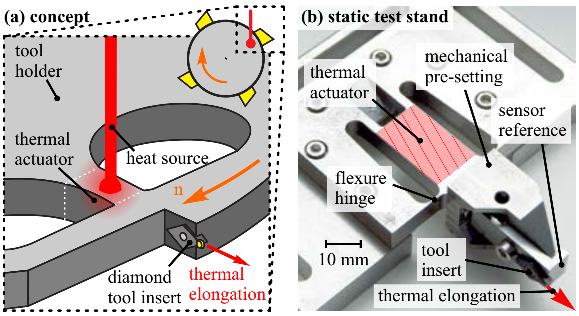


Fig. 2. (a) Concept and (b) static test stand for thermo-mechanical actuator.

Hence, the thermo-mechanical actuator was initially designed as a beam structure that is heated via an infrared light source (Fig. 2b). The thermal elongation was limited in radial direction by adding flexure hinges at the front of the actuator. Furthermore, a mechanical pre-setting mechanism was implemented in order to compensate tool shifts beyond the capacity of the thermal actuator.

In general, an effective control of the actuator's thermal elongation is only possible, if a suitable control scheme is chosen and properly parametrized. Thus, the actuator's transfer function will be discussed in the following.

When illuminating the actuator with an infrared light source a specific heat flow $\dot{Q}_{in}$ is generated. The heat is partially absorbed by the actuator ($\dot{Q}_{ab}$) while another part is dissipated to the surrounding ($\dot{Q}_{dis}$). All heat flows combined are in a state of equilibrium (Eq. 1)

$$\dot{Q}_{in} = \dot{Q}_{ab} + \dot{Q}_{dis} \quad (1)$$

The absorbed heat $Q_{ab}$ depends on the physical properties of the actuator (namely its mass $m$ and specific heat capacity $c$) and its temperature difference to the ambient temperature ($\vartheta_{ac} - \vartheta_{am}$). The respective heat flow $\dot{Q}_{ab}$ is obtained after derivation with respect to time (Eq. 2). For simplicity, the ambient temperature is regarded as constant and thus removed by the derivation.

$$\dot{Q}_{ab} = m \cdot c \cdot \dot{\vartheta}_{ac} \quad (2)$$

The dissipated heat flow $\dot{Q}_{dis}$ can be modeled as a free convection, depending on the surface area of the actuator $A$, the heat transfer coefficient $\alpha_K$ and the difference to ambient temperature (Eq. 3).

$$\dot{Q}_{dis} = \alpha_K \cdot A \cdot (\vartheta_{ac} - \vartheta_{am}) \quad (3)$$

In all, the resulting differential equation for the actuator identifies it as a first-order lag element (Eq. 4).

$$\dot{Q}_{in} = m \cdot c \cdot \dot{\vartheta}_{ac} + \alpha_K \cdot A \cdot (\vartheta_{ac} - \vartheta_{am}) \quad (4)$$

On this basis, the temporal behavior of the actuator temperature $\vartheta_{ac}(t)$ can be described as a step response (with $\sigma(t)$ as unit step function) of the input heat flow (Eq. 5-8).

$$\vartheta_{ac}(t) = \vartheta_{am} + K_\vartheta \cdot \dot{Q}_{in0}(1 - e^{-\frac{t}{T}}) \quad (5)$$

$$K_\vartheta = \alpha_K^{-1} \cdot A^{-1} \quad (6)$$

$$T = m \cdot c \cdot \alpha_K^{-1} \cdot A^{-1} \quad (7)$$

$$\dot{Q}_{in} = \dot{Q}_{in0} \cdot \sigma(t) \quad (8)$$

The thermal state of the actuator can be linked to the resulting elongation $\Delta l(t)$ via the coefficient of thermal expansion $\alpha_D$ of the substrate material (Eq. 9-11).

$$\Delta l(t) = l_0 \cdot \alpha_D \cdot (\vartheta_{ac}(t) - \vartheta_{am}) \quad (9)$$

$$\Delta l(t) = K_L \cdot \dot{Q}_{in0}(1 - e^{-\frac{t}{T}}) \quad (10)$$

$$K_L = l_0(t) \cdot \alpha_D \cdot K_\vartheta = \frac{l_0 \cdot \alpha_D}{\alpha_K \cdot A} \quad (11)$$