International Journal of Machine Tools & Manufacture 101 (2016) 52–64

Contents lists available at ScienceDirect

International Journal of Machine Tools & Manufacture

journal homepage: www.elsevier.com/locate/ijmactool

# Micro-patterning technique using a rotating cutting tool controlled by an electromagnetic actuator

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ARTICLE INFO

*Article history:*
Received 27 July 2015
Received in revised form
9 November 2015
Accepted 11 November 2015
Available online 22 November 2015

*Keywords:*
Micro-pattering
Surface texturing
Rotating tool
Cutting force model
Tool path generation

ABSTRACT

This work describes a micro-patterning or surface texturing technique on the fixed work surface using a proposed new spindle system with a rotating cutting tool controlled in real time. The proposed spindle system creates micro-sized patterns using rotating tools such as a micro-milling tool and a micro-grinding wheel. The shaft of the spindle is suspended by air bearings, and an electromagnetic actuator controls the radial motion of the spindle housing instead of the shaft. This generates a micro-pattern array on the electro-less Ni-coated workpiece in the micro-milling process. A PID controller is adopted to make the system stable, and adaptive feedforward cancellation is used to effectively compensate for the run-out of the spindle system during machining. The machining results show that this compensation improves the pattern accuracy. It is expected that micro-patterning using the proposed spindle system can be applied over a large surface area.

## 1. Introduction

The importance of surface texture has been recognized recently as an indispensable functional element in industrial products, and its potential applications keep increasing. To create and use these textures, there is a need for adequate control of the surfaces and an understanding of properties resulting from the topography. For example, textured surfaces are used to provide particular functionality in diffractive optics, micro-optics, vacuum chucks, adhesion, friction, and other applications [1–4]. There exist a few micro/nano-patterning and surface texturing manufacturing methods, such as cutting, burnishing, laser machining, lithographic methods, focused ion beam machining, and replication. Among those methods, micro-cutting is typically adopted by industry. Micro-cutting methods are classified into two categories: fixed tool and rotating tool. In micro-cutting methods using the fixed tool, fast tool servo (FTS) mechanisms have been often installed in machine tools to vary the depth of the cut in real time and machine the surface of a rotating workpiece [5–8]. But the FTS is mostly limited in the rotating surface. The micro-patterning method using the grinding wheel is to use an engineered grinding wheel with the desirable topography through optimized cutting process [9,10]. But this method is very limited in simple geometry. Research using the micro-milling tool has been presented [11–13], in which an active magnetic bearing (AMB) is used to suspend the rotating shaft. However, the tool motion range is limited to a small fraction of the clearance between the shaft and bearings.

In the present research, a new spindle system was proposed that electromagnetically actuates the spindle for machining used to create micro-patterns on a workpiece. Spindle systems equipped with an electromagnetic actuator (EMA) were introduced by the authors several years ago [14–17]. The prior spindle system consisted of ball bearing supports, and the EMA actuated the shaft directly within the bearing compliance. This design was constrained by the elasticity between the ball and race, which may degrade the bearing performance. In the proposed spindle system, the shaft is supported by air bearings and the EMA actuates the spindle housing instead of the shaft. Thus, one can widen the range of motion of the tool without influencing the bearing compliance. Eventually, this can generate a micro-pattern in addition to compensating for the spindle run-out.

Many spindle run-out control methods have been introduced, such as neural networks [18], iterative learning control (ILC) [19], online iterative control (OIC) [20], and repetitive control (RC) [21]. Among these methods, we selected adaptive feedforward cancellation (AFC) derived from the RC technique because it does not need a precise system model and it is easy to implement. AFC is used to compensate the run-out while the PID controller is used to stabilize the spindle system. Here, we discuss the cutting force and tool path in consideration of the cutting condition and tool shape when the run-out compensation is activated. We performed

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http://dx.doi.org/10.1016/j.ijmachtools.2015.11.005
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**Nomenclature**

| | |
|---|---|
| $g_i$ | controller gain of the AFC |
| $\phi_i$ | phase advance to compensate the phase delay of the spindle system (radians) |
| $\omega_i$ | rotational speed of the spindle (rad/s) |
| $H$ | initial height of the cutting tool's center (m) |
| $h_0$ | undeformed chip thickness (m) |
| $h_d$ | desired depth of cut (m) |
| $R$ | radius of cutting tool (m) |
| $F_t$ | tangential component of cutting force (N) |
| $F_r$ | radial component of cutting force (N) |
| $F_f$ | feed directional component of cutting force (N) |
| $F_x$ | component of the cutting force acting in the $x$-axis direction (N) |
| $F_y$ | component of the cutting force acting in the $y$-axis direction (N) |
| $F_z$ | component of the cutting force acting in the $z$-axis direction (N) |
| $f_z$ | feed per edge (m) |
| $A_0$ | cross section of the tool mark ($m^2$) |
| $a$ | height of the cross-sectional area (m) |
| $b$ | width of the cross-sectional area (m) |
| $\theta$ | rotation angle of the cutting tool (radians) |
| $\varphi$ | inclination angle of the cutting tool (radians) |
| $K_t$ | specific cutting force ($N/m^2$) |
| $K_r$ | cutting force ratio of $F_r$ to $F_t$ |
| $K_f$ | cutting force ratio of $F_f$ to $F_t$ |
| $m_u$ | mass unbalance of the shaft (kg) |
| $l_u$ | distance of the unbalance from the shaft center (m) |
| $r_u$ | amplitude of the tool vibration induced by the unbalance (m) |
| $r_e$ | eccentricity (m) |
| $A$ | center of the shaft |
| $B$ | center of the cutting tool |
| $\theta_i$ | relative angle of the cutting edge to $\vec{AB}$, constant after fixing to the shaft |
| $V_f$ | feed rate (m/min) |
| $Y_{yt}$ | run-out of the shaft along the Yt-axes |
| $Y_{zt}$ | run-out of the shaft along the Zt-axes |

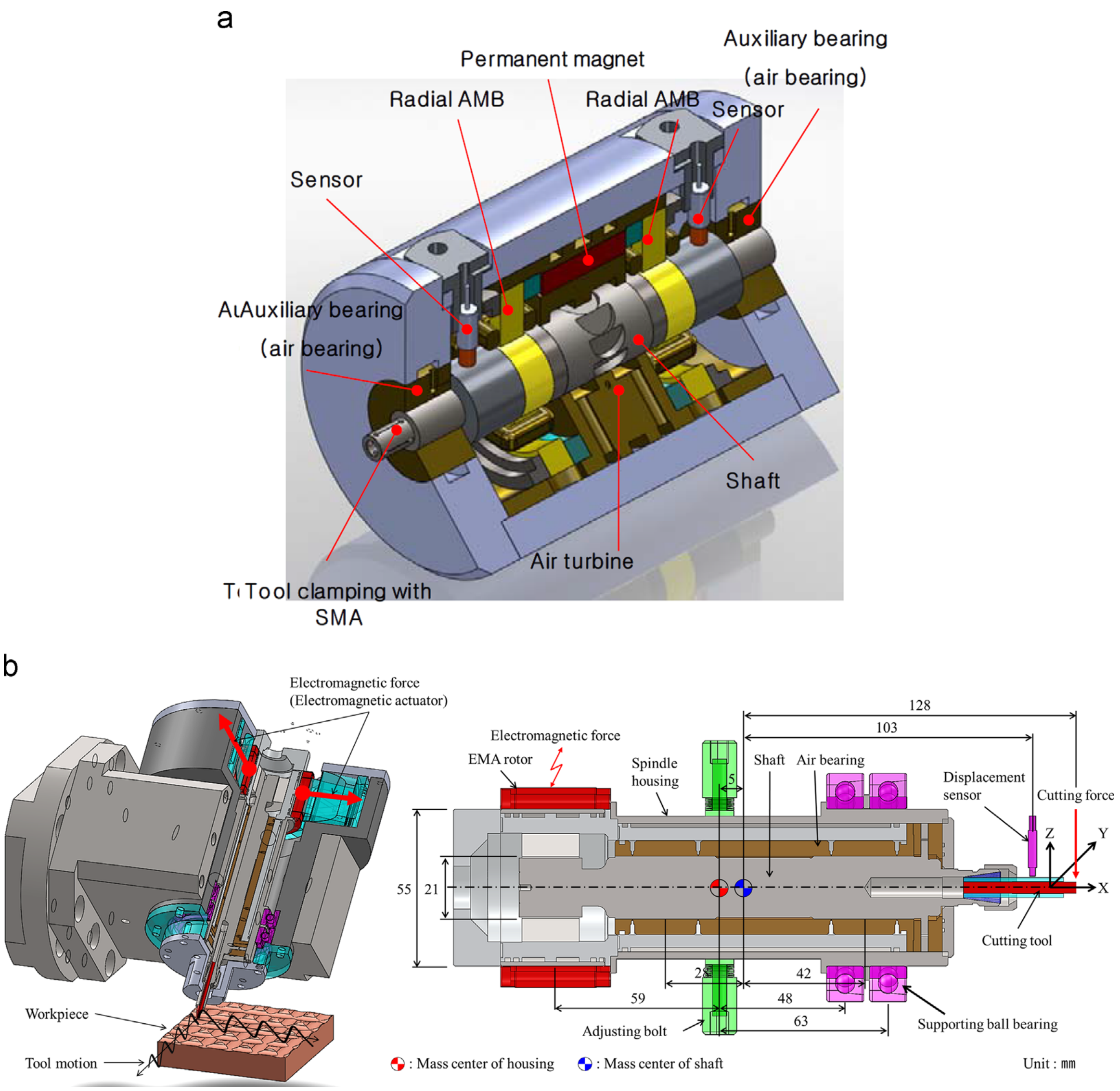

**Fig. 1.** Structure of the proposed spindle system. (a) Existing spindle system [12], (b) Proposed spindle system.