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FABRICATION OF 3D SUBMICRON TO MICRO TEXTURED SURFACES USING BACKSIDE PATTERNED TEXTURING (BPT)

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Abstract:

This work presents a novel fabrication method for submicron to micro size textures on flat surfaces using the backside patterned texturing (BPT). The proposed method utilizes the pre-fabricated macro-features on the backside of work material, and thereafter the front side is face turned with a single point diamond tool to generate textured surfaces. Different from existing texturing methods, BPT produces textured surfaces from submicron to micro scale without any external gadgets such as vibration assisted machining or synchronized tool-spindle motion. The miniature feature arises on the diamond turned surface due to the induced residual stresses when the specimen is unleashed from the machine. To demonstrate the efficacy of the method, a series of machining experiments were conducted to fabricate various types of freeform surface textures like water-drop freeform, cylindrical freeform surfaces, etc. The fabrication methodology of different sizes of bumps with precisely controlled surface quality is illustrated. The texture profiles comprising the deformation height from hundreds of nanometer to few micrometers with mirror surface quality were successfully fabricated on the diamond machined surface. The experimental results suggest that the pre-fabricated pattern, workpiece thickness and machining condition play a critical role to determine the final shape and geometry of generated textures.

Keywords:

Ultraprecision machining, micro texturing, submicron features, diamond turning, backside pattern texturing, induced stresses

1 Introduction

The increasing demands of micro- to submicron-textured components in micro-electronics, biotechnology, optics, tribology and aerospace applications necessitates better manufacturing processes which can produce the desired surface features with acceptable surface quality and form accuracy [1, 2]. Reliability and repeatability of produced features are the important characteristics of these types of fabrication methods [3]. Masuzawa [4] summarized various non-traditional technique for the fabrication of micro as well as submicron-textured surfaces, such as micro electrical-discharge machining, lithography, micro laser ablation, and micro electro-chemical machining. However, considering the low material removal rate and limitations in the fabrication of high-aspect ratio features, applicable shapes and materials used, these processes seem less suitable for mass production of micro to submicron scale textured surfaces.

Mechanical micromachining like ultraprecision single point diamond turning (SPDT) offers an alternative method for improving productivity, expanding the range of materials used and having the capability to manufacture micro-features [5]. The application of slow slide servo (SSS) and fast tool servo (FTS) assisted diamond turning synchronizes the motion of the X- and Z- axes of SPDT with the spindle (C-axis) to generate complex 3D axisymmetric and non-axisymmetric micro-features like Fresnel lenses, aspheric lenses and microlens array (MLA) with micrometer form accuracy and nanometer surface finish [6]. Kong et al. [7] utilized FTS assisted SPDT to manufacture MLA and developed an analytical model to predict the surface generation of lens array during the FTS machining process. Neo et al. [8]

used SSS process in 4-axis ultraprecision machine to manufacture textured surfaces with sinusoidal wave grid (SWG) and microlens array (MLA) and showed the significance of cutting tool trajectory optimization for accurate surface generation during diamond machining. X D Zhang et al. [9] utilized SSS to produce sinusoidal freeform surfaces and proposed a new method using cylindrical coordinate micromachining to improve overall form accuracy of created feature. D P Yu et al. [10] also fabricated SWG and MLA on brittle material using FTS assisted diamond machining. All these examples of surface texturing using SPDT and its associated processes are limited to produce features of an order of micrometer or tens of micrometer range.

Fabrication of submicron textured surface by mechanical micromachining processes is very challenging. Until now, very few studies are available in the literature to report on fabricating textures of sub-micrometer dimensions by SPDT or by its associated processes. Brinksmeier et al. developed a novel technique to produce high resolution elements by combining diamond turning with nano fast tool servo system (nFTS) to generate fine quality submicron structures [11, 12]. Z Zhu et al. [13] proposed a unique method by combining FTS and fly wheel cutting for submicron/micro texturing and successfully fabricated submicron size surface features on machined surface. The external gadgets of FTS/SSS to control the tool-spindle synchronized motion dictates the geometrical limitations of produced textures in UP machining. Keeping the production limitations of diamond machining processes in consideration, a simpler innovative fabrication technique seems highly preferable that can overcome the limitations and permits the micrometer and even sub-micrometer features fabrication with mirror surface quality.

In this work, a novel technique, named backside patterned texturing (BPT) is proposed for the fabrication of submicron to micro features by ultraprecision 2-axis SPDT. In this proposed technique, firstly the backside of work sample was pre-fabricated to generate a macro scale backside pattern. Then, the front surface of the sample was diamond machined up to a certain thickness to produce miniature features on the machined surface corresponding to pre-fabricated pattern. Unlike from conventional methods which require additional motion control system with complex tool path programming and are only suitable for micrometer scale textures generation, this technique produces the features from submicron to micrometer scale without any external gadgets or synchronized tool-spindle motion. This paper focuses on the principle and implementation of the proposed technique to fabricate a typical convex shape submicron/micro size array of bumps on Al 6061-T6. In the end, other types of freeform textured surfaces like water-drop freeform, cylindrical freeform, spiral freeform etc. with mirror surface quality also fabricated to show the efficacy and versatility of the proposed technique.

2 Basic principle of texture formation in BPT

The formation of submicron to micro size textures using BPT is attributed to the effects of induced residual stresses, which are generally undesired and considered detrimental to machining accuracy, on surface and subsurface of diamond machined workpiece. It is well understood that the cutting process induces residual stresses (tensile or compressive) on machining even when the workpiece is unleashed from external load after processing. Compressive stress is mostly desired as it improves the functional behavior of machined components by influencing their fatigue and creep properties. However, tensile stresses

adversely affect the performance of machined components. But with the perspective of the geometrical accuracy of machined components, both the types of residual stresses directly affect the deformation of machined workpiece and cause detrimental effects on part geometry which may lead to surface distortion beyond the acceptable tolerance limit [14, 15].

In machining, the possible causes of induced residual stresses are plastic deformation and phase transformation. The effect of these residual stresses is found predominantly in the surface and subsurface of the machined components due to the limited depth of penetration in the order of some hundreds of micrometers. However, in the case of thin workpiece machining, the effect can be more prominent and results in relevant surface deformation. In thin metallic workpieces, residual stress induces surface distortion and dimensional instability which may leads to discard the workpiece [16-18].

In the proposed BPT technique, the workpiece carries a pre-fabricated backside pattern which divides the overall workpiece into thick and thin portions (Fig. 1a). The initial thickness (t_{ri}) of thin portions remains in the order of few hundreds of micrometer. The machined surface of the workpiece clamped on the machine chuck remains flat during diamond turning. The mechanical loading during the machining process generates surface and subsurface deformation that induces stresses. The machining process also induces a plastically deformed layer; so called damaged layer or stressed layer just beneath the machined surface. In case of ultraprecision diamond machining, a very thin damaged layer up to 20 μm is expected because of low feed rate and cutting depth [19, 20]. The damaged layer depends on cutting conditions, material properties, and cutting tool geometries. Fig. 1b shows the stressed layer

near cutting surface and above the ‘no strain region’ of a machined sample after diamond turning. No elastic deformation of overall workpiece is expected as the specimen is still constrained by the machine chuck.

The depth of induced residual stresses after ultraprecision diamond machining is the same as plastically deformed layer under the cutting surface [20]. Diamond turning induces a very low level of damaged layer and residual stresses which is not generally concerned. However, in the case of thin parts even low residual stresses can lead to relatively high surface deformation which may be used for texture formation. Large surface deformation can be observed at low thickness of machined workpiece. Once the workpiece is unleashed from machine chuck, the workpiece becomes deformed due to redistribution of residual stresses at the surface and subsurface in order to achieve self-equilibrium to compensate the unbalancing forces and moments produced by material removal processes. Thus the machined components contain both the strain deformations: plastic strain caused by machining and elastic strain caused by the machining induced plastic strain. Fig. 1c illustrates the stress distribution in final shape after removal of the workpiece from the machine. Generally, the elastic strain deformation is more sensitive to the workpiece thickness and large surface deformation arises in case of thin workpieces [20, 21]. In BPT, the overall diamond machined surface experiences an out-of-plane surface deformation. However, the thinner portion corresponding to pre-fabricated backside pattern experiences relatively larger surface deformation and consequently results in submicron/micro scale texture formation. The thinner portion is constrained by the surrounding thick portion which actually helps for controlled/uniform bulging of thin portion.

Fig. 1. BPT process mechanism showing the cross-section of workpiece, where t_{ri} and t_{rf} shows the workpiece thickness at thinner portion before and after diamond turning, respectively, whereas t_b represents the average height of created feature, (a) pre-fabricated workpiece, (b) diamond face turning at front side, and (c) generated features at machined surface (dimensions are exaggerated for visibility)

3 Fabrication of submicron/micro textured surface

3.1 Experimental setup

The machining setup of BPT is shown in Fig. 2 for the fabrication of submicron/micro textured surfaces with convex shape bumps. The similar setup was also used for other types of pre-fabricated patterns, but for the elaboration of the proposed method, only some machined holes are shown here as a pre-fabricated pattern. As a first step, some holes were machined on the backside of the work sample as pre-fabricated pattern; this divided the whole workpiece into thick and thin portions. The workpiece material was Al 6061-T6 which is commonly used

for optical mold and components. The diameter and thickness of circular workpieces were 43 mm and 3 mm, respectively. The front surface of the workpiece was then diamond machined using consecutive face turning passes in order to get textures corresponding to backside pattern. The consecutive face turning passes gradually reduces the overall thickness of workpiece. For pre-fabrication, a multi-purpose micro-machine (Mikrotools DT-110) was used to machine some holes of 1.5 mm, 2 mm and 2.5 mm in diameter by carbide tools up to the depth of 2.6 mm. After the pre-fabrication, the workpiece thickness at thinner portion was arbitrary selected as 400 μm which is termed as initial workpiece thickness at thinner portion (t_{ri}).

Fig. 2. Experimental set-up for BPT, (a) pre-fabrication, and (b) diamond machining

The workpiece with backside pre-fabricated pattern was then clamped to the vacuum spindle of 2-axis ultraprecision diamond turning machine. The front surface (opposite side of pre-fabricated pattern) of the workpiece was subsequently diamond turned by a series of consecutive face turning passes. The workpiece thickness at thinner portion after diamond face turning process and the deformation height of the created features are denoted by t_{rf} and t_b , respectively (Fig. 1). After machining, the surface was cleaned by alcohol in order to remove the attached debris and chips. The diamond machined surface was observed at different workpiece thicknesses (t_{rf}) by Wyko™ NT 3300 white light interferometer and Talyscan™ surface profiling system. The diameter of the created bump is represented by D_b . Table 1 shows the specifications of experimental set-up.

Table 1 Specifications of experimental set-up.

Instrument	Specifications
Micro-machine	Mikrotools DT-110
Ultraprecision machine	2-Axis Precitech Nanoform 200
Interferometer	Wyko™ white light interferometer
Surface profiler	Talyscan™ by Taylor Hobsons
Drilling Tool	Carbide tool, diameter = 1 mm
Workpiece	Polycrystalline Al 6061-T6 (circular disc)

3.2 Experimental conditions

All turning experiments were performed by a single point diamond tool with a constant cutting speed (v_c) of 2 m/sec. In order to investigate the relationship between workpiece thickness (t_{rf}) and the deformation height of texture (t_b) a number of work samples were

machined. Table 2 summarizes the experimental conditions selected for diamond machining experiments.

Table 2 Experimental conditions for diamond face turning.

Condition	Content
Cutting Speed	2 (m/s)
Feed Rate	10 (mm/min)
Depth of cut	10 (μm)
Diamond Tool	Single point diamond tool; nose radius = 0.532mm, rake angle = 0° , clearance angle = 10°

4 Results and Discussions

4.1 Surface texturing

Wyko™ NT 3300 white light interferometry surface profiling system was employed to capture the 3D surface topography of the produced texture. A low pass Fourier filtering with low cut off frequency of 8 mm^{-1} was applied to eliminate high frequency roughness data from the measured profile and to get the pure waviness pattern. Fig. 3 shows the interferometry image of a single micro bump created at diamond machined surface when workpiece thickness (t_{rf}) reached to $170 \mu\text{m}$ for 2.5 mm diameter of pre-fabricated hole. Fig. 3a is the 3D surface topography while Fig. 3b shows the 2D cross-sectional trace profiles passing through the apex of the bump. For this case, the average deformation height (t_b) of the created bump was measured as $1.275 \mu\text{m}$.

Fig. 3 (a) 3D surface topography of created feature when $t_{rf} = 170 \mu\text{m}$ and $D_b = 2.5 \text{ mm}$, (b) 2D profile in X and Y-direction corresponding to 3D image

To fabricate an array of bumps, 9 holes were pre-fabricated at the backside of the work sample in 3x3 array format. The diameter of each hole was 2.5 mm. A pitch length of 3 mm was used in order to avoid the interferences of surface deformation by adjacent created texture. The front surface was then diamond turned and measured via TalyscanTM profiler when of workpiece thickness (t_{rf}) reached to 230 μm . Fig. 4 shows the machined samples for an array of 3x3 submicron bumpy textures. It was observed that the formed bumps in the array was uniform in shape and size, which ensure the controllability of BPT to reproduce uniform submicron/micro textures with very fine surface quality. The average deformation height (t_b) of texture was found as 475 nm with 60 nm standard deviation. The irregularities in the form profile of produced textures can be attributed to inhomogeneous nature of polycrystalline material and machining error occurred during the pre-fabrication process.

Fig. 4. Experimental results, (a) workpiece with pre-fabricated backside pattern (b) diamond machined surface (c) expected modeled surface, and (d) scanned area for 3x3 array of bumps

4.2 Surface quality

A $100 \times 100 \mu\text{m}^2$ area at the apex of the created textured was scanned to determine the surface quality. The specimen was randomly selected to avoid the possibility of a systematic error in measurements. Fringe contrast drops off at the periphery of the produced textures due to the slope changes, which may lead to measurement errors. Therefore a small area is selected at the top of the feature for roughness measurement. The average roughness (S_a) and RMS roughness (S_q) were obtained as 40 nm and 50 nm, respectively, which show the mirror surface quality of the produced texture. Fig. 5 shows the roughness profile of the created texture. The surface roughness during diamond turning primarily depends on the machining parameter (tool nose radius, cutting speed and feed rate). Generally, large nose radius and high cutting speed with fine feed rate produces better surface finish in diamond turning [22].

Therefore, further improvements in roughness may be obtained by fine tuning in process parameters.

Fig. 5. Surface roughness profile measurement when t_{rf} was 170 μm for 2.5 mm pre-fabricated hole

4.3 Effect of workpiece thickness (t_{rf})

The detailed experimental results for different pre-fabricated patterns and workpiece thicknesses (t_{rf}) are plotted in Fig. 6. It is found that the workpiece thickness (t_{rf}) has a critical influence on the final geometry of the generated texture. These results are in-line with the explanation shown in section 2. The non-linear deformation height (t_b) increases with a decrease in the workpiece thickness (t_{rf}) for all tested conditions. When the workpiece thickness (t_{rf}) is more than 230 μm , the residual stress has a greater effect on the texture formation. The experimental results also illustrate that no visible surface deformation was observed until a certain threshold thickness of the thinner portion was achieved. The threshold thickness also depends on the geometry of pre-fabricated backside macro features. For 2.5 mm backside holes, the textures started appearing after diamond facing when workpiece thickness (t_{rf}) reached to 310 μm . Whereas for 2 mm and 1.5 mm pre-fabricated holes, the threshold thickness was found 300 μm and 280 μm , respectively. Up to this threshold deformation at thicker and thinner portions remains almost identical. Once the threshold

thickness was achieved and the workpiece was removed from the vacuum chuck, the miniature feature started appearing on the machined surface. The minimum deformation height (t_b) of 280 nm was observed at the threshold thickness (t_{rf}) of 290 μm for 2.5 mm pre-machined holes. However, in case of 2 mm and 1.5 mm holes, convex shape bumps of minimum heights of 170 nm and 130 nm were formed, respectively. These experimental results imply that the deformation height (t_b) of the created texture can be controlled by proper selection of workpiece thickness (t_{rf}) and the geometry of pre-fabricated pattern.

Fig. 6. The influence of workpiece thickness (t_{rf}) to the average deformation height of texture (t_b)

Based on the results obtained, it was also observed that at a certain workpiece thickness (t_{rf}), the texture profile damaged at the periphery of the developed texture because of reduction in strength due to thinness of workpiece. During diamond machining experiments, surface damage started occurring when thinner portion workpiece thickness (t_{rf}) reached to less than

100 μm for all tested conditions. An example of the surface damage of machined workpiece is shown in Fig. 7.

Fig. 7. Damage of surface profile occurred when t_{rf} was 100 μm for 2.5 mm diameter of hole, (a) top view and (b) isometric view

The maximum deformation height (t_b) up to 5.0 μm was measured for undamaged machined surface in case of 2.5 mm pre-fabricated hole when workpiece thickness (t_{rf}) was 110 μm . Maximum deformation heights (t_b) for 2 mm and 1.5 mm holes were measured as 3.3 μm and 2 μm , respectively. This result shows the limitation of BPT and suggests the safe operational thickness of workpiece at thinner portion (t_{rf}) ranging from threshold thickness to damage thickness to fabricate submicron to micro features. Fig. 8 shows the 2D profiles of created bumps measured at the apex for different pre-fabricated hole geometries within safe operational workpiece thickness.

Fig. 8. 2D form profiles of created bumps at different workpiece thickness (t_{rf}) for 1.5mm, 2mm and 2.5mm diameter of pre-fabricated hole

It is also important to observe that no significant change was observed in the deformation diameter (D_b) of the created bump and it remained the same as backside pattern for all workpiece thicknesses (t_{rf}). This result is in contrast to the deformation height (t_b) of texture which increases with a decrease in workpiece thickness. It implies that the material deformation in lateral direction reflects the backside pre-fabricated pattern. However, the shape and geometry of pre-fabricated pattern affects the threshold workpiece thickness, damage thickness as well as the deformation height (t_b) of the created bump. When the deformation height (t_b) of created texture reached to 200 nm or below its form profile did not remain uniform and was difficult to capture. The variation in the form profile is attributed to the non-uniform elastic spring-back caused by the anisotropic nature of polycrystalline

aluminum 6061-T6. The spring-back is referred to the elastic strain recovery when the rounded cutting edge of the tool passes on the machined surface and burnishes the freshly machined surface. After burnishing of the surface, the material left behind the cutting tool edge recovers or springs back. The elastic spring-back depends on the physical properties of the workpiece material [23]. The magnitude of the spring-back recovery lies in the range of few nanometers to tens of nanometers which affects the surface quality in terms of roughness for diamond turned surfaces [24]. The effect of spring-back on the overall surface deformation of workpiece is not significant compared to the deformation caused by residual stresses, especially at lower material thickness ($t_{rf} \leq 260 \mu\text{m}$) where material deformation (t_b) up to an order of micrometer is achieved.

4.4 Effect of cutting speed

In order to investigate the correlation between cutting speed (v_c) and deformation height (t_b) of texture during BPT, some work samples were diamond faced with a constant cutting speed (v_c) of 4 m/sec as well. Other machining conditions were the same as mentioned in Table 2. The relationship of cutting speed (v_c) and deformation height (t_b) is shown in Fig. 9 for the cases when workpiece thickness (t_{rf}) reached to 260 μm and 230 μm . The result depicts the direct influence of the cutting speed (v_c) on the developed textures. Higher cutting speed (v_c) produces larger surface distortion which increases the height of generated texture.

Fig. 9. Comparison of cutting speed (v_c) vs deformation height (t_b), (a) $t_{rf} = 260 \mu m$, and (b) $t_{rf} = 230 \mu m$

The monotonically increasing trend of surface deformation (t_b) of Fig. 9 can be represented by following empirical relationship

$$t_b = A v_c^n \quad (1)$$

Where A is the coefficient and the power exponent n shows the slope. It can be seen that an increase of cutting speed increases the texture profile height (t_b) by a power factor of $n=0.6$ to 0.9 with $R^2 = 95-99\%$ for all tested pre-fabricated geometries and workpiece thicknesses (t_{rf}).

Generally, cutting speed (v_c) has a significant effect on the induced residual stress of machined surface. The increase of cutting speed increases the effective residual stress and its

penetration depth [25, 26]. From mechanics point of view, large magnitude of residual stresses causes more deformation in machined surface. Therefore, it is concluded that the higher cutting speed (v_c) causes a rise in induced stresses which ultimately produces large surface deformation of workpiece and results in texture formation.

4.5 Various types of freeform surface textures

At the given machining condition, the backside pre-fabricated pattern and workpiece thickness (t_{rf}) determine the shape and geometry of created textures on diamond machined surface. In order to show the efficacy of BPT, some other types of freeform surfaces are produced which are shown in Fig. 10. The backside pattern is pre-fabricated in advance by Mikrottools DT-110 according to the desired freeform surface/textures on diamond machined surface. The machining conditions for these experiments were the same as mentioned in Table 2 while the workpiece thickness (t_{rf}) after diamond machining was 200 μm . The light reflected close up image of the whole fabricated surface is shown in the last column of Fig. 10 which gives good qualitative visualization of the produced texture. The thicker portion of the machined surface acts as smooth reflecting surface that gives a rise to the bright image on screen; the thinner portion being elevated diffuses the reflection and gives a rise to the black patch on screen.

Freeform Surfaces	Backside Pre-fabricated pattern	Mirror finish of diamond machined surface	Projected pattern of machined surface
Spiral Freeform
Integrated Freeform
Water-drop freeform
Cylindrical Freeform

Fig. 10. Typical freeform surface textures composed by various patterns ($t_{rf} = 200 \mu\text{m}$)

4 Conclusion

In the present study, a new backside patterned texturing (BPT) technique was proposed for the fabrication of submicron to micro scale features using 2-axis ultraprecision diamond

machining. For this purpose, a number of samples were machined using diamond face turning for 1.5 mm, 2 mm and 2.5 mm diameter of pre-fabricated holes in order to produce single as well as an array of 3x3 convex shape bumps. Later, some other types of freeform surfaces like water-drop freeform, cylindrical freeform, spiral freeform and integrated freeform were also fabricated with mirror surface quality. The proposed method has been shown to fabricate user-defined submicron/micro scale features over a large area of machined surfaces.

Following conclusions can be drawn from the study:

- BPT can be employed to fabricate submicron to micro scale textured surface with mirror finish surface quality for macroscopic backside pre-fabricated pattern
- Unlike the other ultraprecision machining processes (FTS/SSS etc.) that use a diamond tool to fabricate the desired features sequentially; BPT is allowed to fabricate multiple features with different shape and geometry, simultaneously.
- The deformation height (t_b) of created textures is mainly influenced by the workpiece thickness (t_{rf}) at thinner portion of machined samples, geometry of pre-fabrication pattern and machining conditions. Hence, it is understood that various profiles can be fabricated just by controlling these influential factors.
- Higher cutting speed (v_c) causes an increase of the level and penetration depth of residual stresses that leads to induce more surface deformation at thinner portion. As a result, the higher cutting speed produces larger deformation height (t_b) of generated textures.

- In contrast to conventional mechanical micromachining methods, this technique has a potential to provide a simpler and faster solution, as it does not require any complex tool-workpiece path programming and additional aid for motion synchronization. The technique also provides flexibility for the fabrication of various types of features like freeform and asymmetrical surfaces with mirror surface quality.
- The proposed texturing method contributes to the capability improvement of ultraprecision diamond machining techniques and opens a new domain in miniaturization of component.

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References:

- [1] Evans CJ, Bryan JB. 'Structured', 'textured' or 'engineered' surfaces. *CIRP Annals - Manufacturing Technology*. 1999;48:541-56.
- [2] De Chiffre L, Kunzmann H, Peggs GN, Lucca DA. Surfaces in Precision Engineering, Microengineering and Nanotechnology. *CIRP Annals - Manufacturing Technology*. 2003;52:561-77.
- [3] Alting L, Kimura F, Hansen HN, Bissacco G. Micro Engineering. *CIRP Annals - Manufacturing Technology*. 2003;52:635-57.
- [4] Masuzawa T. State of the Art of Micromachining. *CIRP Annals - Manufacturing Technology*. 2000;49:473-88.
- [5] Davies MA, Evans CJ, Vohra RR, Bergner BC, Patterson SR. Application of precision diamond machining to the manufacture of microphotonics components. 2003. p. 94-108.
- [6] Yi AY, Li L. Design and fabrication of a microlens array by use of a slow tool servo. *Optics Letters*. 2005;30:1707-9.
- [7] Kong LB, Cheung CF. Modeling and characterization of surface generation in fast tool servo machining of microlens arrays. *Computers & Industrial Engineering*. 2012;63:957-70.
- [8] Neo DWK, Kumar AS, Rahman M. A novel surface analytical model for cutting linearization error in fast tool/slow slide servo diamond turning. *Precision Engineering*. 2014;38:849-60.
- [9] Zhang XD, Fang FZ, Wang HB, Wei GS, Hu XT. Ultra-precision machining of sinusoidal surfaces using the cylindrical coordinate method. *Journal of Micromechanics and Microengineering*. 2009;19:054004.
- [10] Yu DP, Wong YS, Hong GS. Ultraprecision machining of micro-structured functional surfaces on brittle materials. *Journal of Micromechanics and Microengineering*. 2011;21:095011.
- [11] Brinksmeier E, Riemer O, Glabe R, Lunemann B, Kopylow CV, Dankwart C, et al. Submicron functional surfaces generated by diamond machining. *CIRP Annals - Manufacturing Technology*. 2010;59:535-8.
- [12] Brinksmeier E, Gläbe R, Schönemann L. Review on diamond-machining processes for the generation of functional surface structures. *CIRP Journal of Manufacturing Science and Technology*. 2012;5:1-7.
- [13] Zhu Z, To S, Zhang S. Theoretical and experimental investigation on the novel end-fly-cutting-servo diamond machining of hierarchical micro-nanostructures. *International Journal of Machine Tools and Manufacture*. 2015;94:15-25.
- [14] Brinksmeier E, Sölter J. Prediction of shape deviations in machining. *CIRP Annals - Manufacturing Technology*. 2009;58:507-10.
- [15] Richter-Trummer V, Koch D, Witte A, dos Santos JF, de Castro PMST. Methodology for prediction of distortion of workpieces manufactured by high speed machining based on an accurate through-the-thickness residual stress determination. *Int J Adv Manuf Technol*. 2013;68:2271-81.
- [16] Brinksmeier E, Sölter J, Grote C. Distortion Engineering – Identification of Causes for Dimensional and Form Deviations of Bearing Rings. *CIRP Annals - Manufacturing Technology*. 2007;56:109-12.

- [17] Masoudi S, Amini S, Saeidi E, Eslami-Chalander H. Effect of machining-induced residual stress on the distortion of thin-walled parts. *Int J Adv Manuf Technol*. 2015;76:597-608.
- [18] Aijun T, Zhanqiang L. Deformations of thin-walled plate due to static end milling force. *Journal of Materials Processing Technology*. 2008;206:345-51.
- [19] Lucca DA, Seo YW, Rhorer RL, Donaldson RR. Aspects of Surface Generation in Orthogonal Ultraprecision Machining. *CIRP Annals - Manufacturing Technology*. 1994;43:43-6.
- [20] Horia K, Kasai T, Ogata Y, Kobayashi A. A Study on Damaged Layer Remaining in Diamond Mirror Cut Surface. *CIRP Annals - Manufacturing Technology*. 1992;41:137-40.
- [21] Brinksmeier E, Cammett JT, König W, Leskovar P, Peters J, Tönshoff HK. Residual Stresses — Measurement and Causes in Machining Processes. *CIRP Annals - Manufacturing Technology*. 1982;31:491-510.
- [22] Cheung CF, Lee WB. Study of Factors Affecting the Surface Quality in Ultra-Precision Diamond Turning. *Materials and Manufacturing Processes*. 2000;15:481-502.
- [23] Arcona C, Dow TA. An Empirical Tool Force Model for Precision Machining. *Journal of Manufacturing Science and Engineering*. 1998;120:700-7.
- [24] Kong MC, Lee WB, Cheung CF, To S. A study of materials swelling and recovery in single-point diamond turning of ductile materials. *Journal of Materials Processing Technology*. 2006;180:210-5.
- [25] Thakur A, Gangopadhyay S. State-of-the-art in surface integrity in machining of nickel-based super alloys. *International Journal of Machine Tools and Manufacture*. 2016;100:25-54.
- [26] Revel P, Jouini N, Thoquenne G, Lefebvre F. High precision hard turning of AISI 52100 bearing steel. *Precision Engineering*. 2016;43:24-33.