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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.

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

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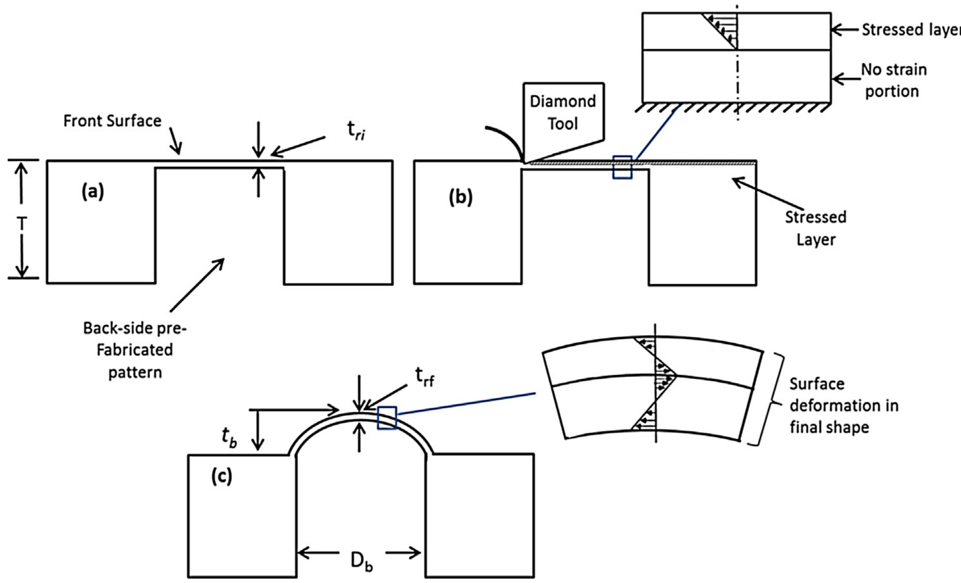

Fig. 1. BPT process mechanism showing the cross-section of workpiece, where t_{ri} and t_{rf} shows the workpiece thickness at thinner portion before and after diamond turning, respectively, whereas t_b represents the average height of created feature, (a) pre-fabricated workpiece, (b) diamond face turning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

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 ultra-precision 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