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A review of surface roughness generation in ultra-precision machining

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ABSTRACT

Ultra-precision machining (UPM) is capable of manufacturing a high quality surface at a nanometric surface roughness. For such high quality surface in a UPM process, due to the machining complexity any variable would be possible to deteriorate surface quality, consequently receiving much attention and interest. The general factors are summarized as machine tool, cutting conditions, tool geometry, environmental conditions, material property, chip formation, tool wear, vibration etc. This paper aims to review the current state of the art in studying the surface roughness formation and the factors influencing surface roughness in UPM. Firstly, the surface roughness characteristics in UPM is introduced. Then in UPM, a wide variety of factors for surface roughness are then reviewed in detail and the mechanism of surface roughness formation is concluded thoroughly. Finally, the challenges and opportunities faced by industry and academia are discussed and several principle conclusions are drawn.

Contents

1. Introduction

With the increasing requirement for high quality surfaces of a nanometric surface roughness and a sub-micrometric form error,

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ultra-precision machining (UPM) is only one efficient and low-cost means. It has been commonly utilized to fabricate high precision optical parts without any post-polishing, such as digital camera lens, CCD camera lens, VCD lens, DVD lens etc. The typical optics applications cover lighting, telecommunications, medical facilities, automotives, military, and aerospace. Recently, in order to serve the ever-growing demands for much higher performance, higher reliability, longer lift cycle and miniaturization, optical elements have been more specialized, functionalized and complicated. The development and applications of optical elements are from spherical/aspheric lens, F-theta lens and micro-lens arrays, to micro-grooving and freeform lens along with the development of UPM from two-axis to multi-axis [1–6]. As information and multimedia technologies have been rapidly developed over the last few decades, there is a huge potential market for high quality optical elements of UPM. The optical element market at $3.6 billion in 2012 is expected to reach $12.3 billion by 2019 [7].

UPM means the achievable level of machining form accuracy in the order of less 0.2 μm and surface roughness in the order of less 10 nm [8,9]. The resolution and repeatability of the machines is less 10 nm [10]. The machining accuracy for UPM is 1000 times greater in surface roughness and 100 times greater in form accuracy than that for conventional machining. In fact, UPM is a progressive developmental form of conventional machining. Fig. 1 illustrates the development trend of the achievable machining accuracy over the last seventy years [1,3,5,10,11]. Currently, the accuracy of UPM has reached up to the nanometer level. In the early 1960s, UPM was pioneered at the Lawrence Livermore National Laboratory (LLNL) [12,13]. In the beginning, it was only designed in order to meet the demand for producing high precision military products [8]. Not until the 1970s, it was applied to meet the demands of the computer, electronics and defense industries in fabricating high precision parts [14]. Owing to the scientific and technological advances, the 1980s and 1990s saw the wider development of highly advanced machine tools. In the recent years, multi-axis control UPM has been widely employed to meet the special demands for freeform surface products. Certainly, the typical representative of UPM is still ultra-precision diamond turning (UPDT) or single point diamond turning (SPDT).

Though UPM has the excellent capability of fabricating high quality components with a nanometric surface roughness, the nanometric surface roughness is easily influenced by a wide variety of factors in a complex cutting process. Until now, much research work has been devoted to studying the effects of the factors on surface roughness formation in UPM. The general factors are machine tool [15], cutting conditions [16], tool geometry [16], environmental conditions [17,18], material property [19], chip formation [20], tool wear [21], vibration [22] etc. Significantly, optimum conditions of the factors can be selected to achieve better surface quality. This paper majorly reviews the current state of the art in the investigation into the factors influencing surface roughness formation in UPM. And, the challenges and opportunities associated with surface roughness formation in UPM are discussed with some key conclusions.

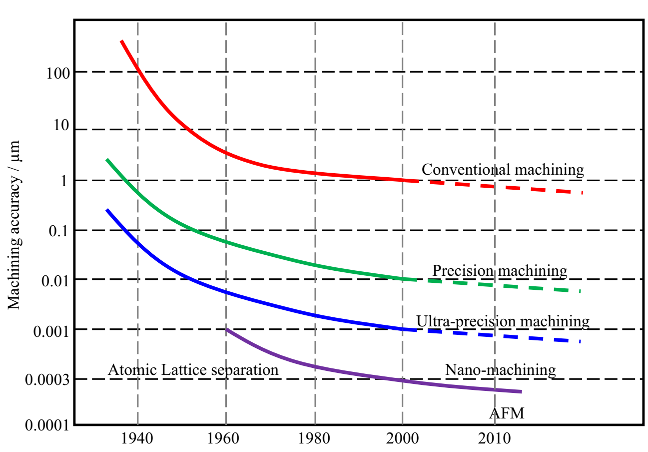

Fig. 1. Achievable machining accuracy [1,3,5,10,11].

2. Characteristics of surface topography

In UPM, surface topography is formed as a result of the transaction of tool profiles with a workpiece, i.e. it is majorly determined by the relative motion between tool and workpiece and material removal mechanism (material deformation and material separation). Therefore, surface topography provides a much faithful signature of the cutting process and material removal mechanism and features the behaviors of material cutting. And the imprint of all static and dynamic factors during cutting is left in surface topography.

As shown in Fig. 2, surface topography in UPM is characterized by tool mark, material swelling and recovery, vibration induced wavy, material pile-up, and material crack/surface wrinkle/fracture/defect/dimple. And the profile per tool mark is irregular or random to a certain extent. For surface characteristics, much research work has been conducted to study cutting mechanism. Early, Sata [23] reported the existence of material swelling. Then, the material swelling and recovery in UPDT has been studied with depth [24,25]. The elastic recovery and plastic deformation varies with the crystallographic orientation of the materials being cut whereby to result in a wavy surface forming. Lee et al. observed a wavy surface through a straight cutting test [26], as shown in Fig. 3. Cheung et al. [27] proposed that the pits and cracks formed at the surfaces of Al6061/15SiCp in UPM were caused by the hard

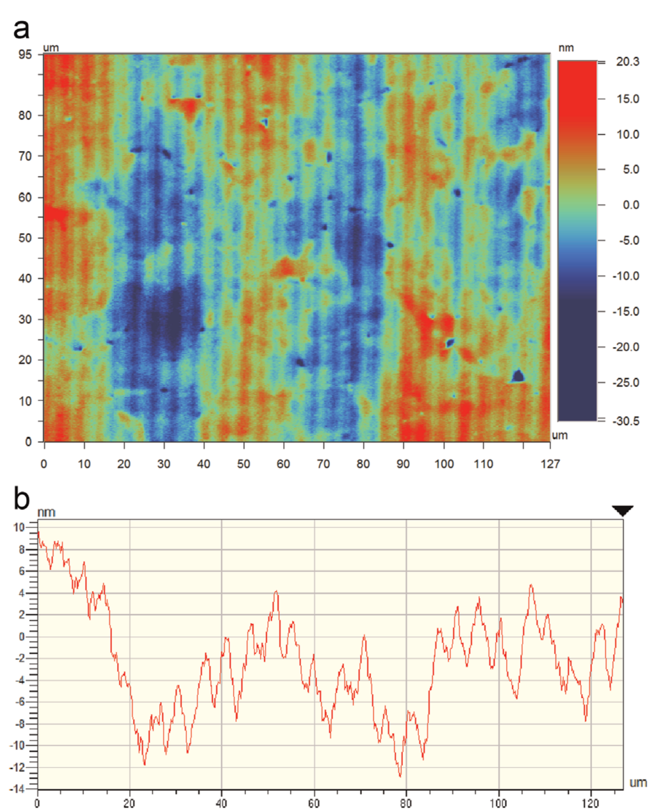

Fig. 2. Ultra-precision machined surface of brass alloy: (a) surface topography and (b) its one horizontal profile.