Journal of Manufacturing Systems 37 (2015) 487–493

Contents lists available at ScienceDirect

Journal of Manufacturing Systems

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

Surface dimple machining in whirling

Takashi Matsumura*, Masaki Serizawa, Tomohiro Ogawa, Masanori Sasaki

Department of Mechanical Engineering, Tokyo Denki University, 5 Senjyu Asahi-cho, Adachi-ku, Tokyo 120-8551, Japan

ARTICLE INFO

Article history:
Received 20 July 2014
Accepted 20 July 2014
Available online 20 August 2014

Keywords:
Cutting
Whirling
Dimple
Modeling
Surface structure

ABSTRACT

Structured dimples on product surfaces are required for control of the surface functions such as friction. The dimple machining, therefore, should be performed in large surface areas at high machining rates. This study presents a novel machining to fabricate the dimples on the cylinder surfaces in whirling, which originally machines threads such as ball screws with rotating the workpiece and the tool mounted on a whirling ring. In the presented machining, the circumferential speeds of the workpiece and the tool are controlled so that the tool edge indents on the cylinder surface without cutting in the dimple machining. The configuration in the machining are discussed to characterize the indentation process. A mechanistic model in the dimple machining, then, is presented to control the dimple shapes. The time-series analysis in the indentation process is performed to simulate the dimples for the machining parameters. Some machining examples are shown to verify the high speed dimple machining.

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1. Introduction

The demand of functional surfaces, which control the physical and/or the chemical properties at the interface between substances, has recently been increasing in many industries. Many surface functions have been generally controlled by the material properties of the surface layers, which have been produced by the surface treatments such as deposition. The surface functions are also controlled by the micro/nano-scale surface structures manufactured artificially for industrial uses.

Bruzzone et al. discussed the functional properties of surfaces and reviewed many applications of the functional surfaces [1]. As an application of the surface structures, the tribological properties have been associated with the surface structures. Because friction coefficient depends on the surface roughness, the friction at the interface between substances is controlled by the surface structure. Wakuda et al. reduced the friction coefficient by the micro dimples, which were machined by abrasive jet or excimer laser beam [2]. The micro dimples have also been used to maintain lubrication at the interface. Basnyat et al. and Voevodin et al. improved tribological properties by micro reservoirs of solid lubrications [3,4]. Meng et al. analyzed the effect of the micro dimples on friction coefficient [5].

Many structured surfaces have been applied to control of functionalities on surfaces so far. Those surface structures have been manufactured in various processes. In etching, the machining area is specified by printing the mask and subsurface in the exposed area is removed in the chemical reaction. Basnyat et al. machined micro dimples to reduce friction and wear coefficients by reactive ion etching in mixed Ar/CF_4 plasma [3]. They made the microporous TiAlCN films and filled the pores with solid lubricants. The laser beam processing has also been applied to machining of the micro dimples. Wan et al. produced the micro dimples in laser coating-texturing and improved the abrasive wear resistance [6]. Luo et al. presented a CO_2 laser beam modulation with rotating polygon and machined the micro dimples on the roll surfaces [7]. Voevodin and Zabinski machined the micro dimples on surfaces of hard TiCN coatings in the focused UV laser beam [4]. They used the micro dimples as reservoirs for the solid lubricant and optimized the dimple surface coverage for the life of lubrication.

Although the chemical or the energy beam processes are effective in dimple manufacturing, some issues have been left on the environmental impact, the flexibility, the cost and the production rate. As an alternative process, the mechanical machining is expected for manufacturing of the functional surfaces. Wang et al. formed the micro dimples mechanically in pellet-pressing and improved tribological properties [8]. They controlled the width and the depth of dimples by the press load. The pellet-pressing was convenient and economical fabrication of the micro dimples on surfaces. They investigated the tribological properties with changing the dimples sizes from 100 to 500 μm. Kogusu et al. machined the micro dimples on flat surfaces in milling with a ball end mill [9]. Matsumura and Takahashi machined the micro dimples on the cylinder surfaces in milling with a miniaturized ball end mill [10]. Graham et al. presented a force model in the dimple

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* Corresponding author. Tel.: +81 3 5284 5474; fax: +81 3 5284 5693.
E-mail address: tmatsumu@cck.dendai.ac.jp (T. Matsumura).

http://dx.doi.org/10.1016/j.jmsy.2014.07.008
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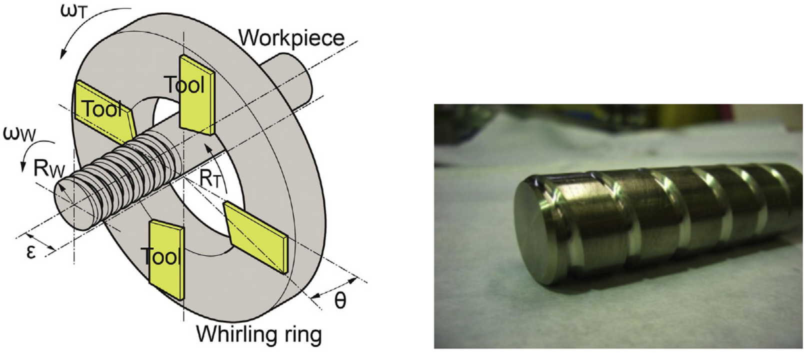

(a) (b)

Fig. 1. General whirling. (a) Configuration. (b) Thread whirling.

machining. They made micro asperities on surfaces in the injection molding using the micro dimple surfaces and investigated friction coefficients with changing the alignment of the asperities [11]. Matsumura and Takahashi controlled the reflection range on the dimpled surface machined with an inclined ball end mill [12].

This study presents a novel machining of the micro dimples at high production rates in whirling. Whirling has been generally applied to screw manufacturing in many mechanical industries so far. Worm and ball screws for motion controls and implant parts [13], which are made of hard materials such as stainless steels, have been machined in whirling. Having many advantages in terms of the tool wear and the chip control, whirling has been widely applied in the bearing and the medical industries. Mohan and Shunmugam presented a mathematical model to control the cutting processes and determined the tool profile in whirling [14]. Lee et al. made a model of the undeformed chip shape to estimate the cutting force with the maximum chip thickness and the tool-work contact length. They divided the undeformed chip shape into the material removed by the front cutting edge and that of the side cutting edge. Then, the cutting force was estimated in FE analysis [15]. Son et al. measured the cutting force components with a non-contact rotating tool dynamometer and compared the cutting forces in FE analysis tools, DEFORM and ADAMS [16]. Although the whirling cut has been performed in the machine shops, most of the applications are the screw machining. Matsumura et al. applied the whiling mechanism to machine helical blades at high machining rates [17]. According to their work, the non-helical blades are machined when the ratio of the spindle speeds of the tool to that of the workpiece is double. Then, the helical blades are machined with changing the ratio.

The paper presents the dimple machining on the cylinder surfaces with controlling the ratio of the circumferential speeds of the tool and the workpiece. In the presented machining, the tool indents to form the dimples during rotations without cutting. Based on the applications of the research done by Wang et al. [8], the presented machining forms the dimples about 100 μm deep and 500 μm long. First, configuration of the dimple machining is shown to characterize the indentation process. Then, a mechanistic model is presented to control the dimple shape. Some machining results, then, are demonstrated to verify the presented dimple machining. Finally the time-series simulation is shown to analyze the indentation process.

2. General whirling process

Whirling is normally performed to machine the screws in combination of the tool and the workpiece rotations, as shown in Fig. 1(a). The cutting tools on the whirling ring at the radius R_T rotate at the angular velocity ω_T. The workpiece with the radius R_W rotates at the angular velocity ω_W inside of the whirling ring with the eccentricity ε, which controls the depth of cut. In conventional whirling cut, the workpiece rotating at a low revolution rate is removed by the cutting edges rotating at a high revolution rate. In the thread whirling, the lead of the screw is controlled by the inclination of the whirling ring with respect to the workpiece axis and the feed rate of the whirling ring.

Fig. 1(b) shows a screw machined on a titanium alloy (Ti6Al4V) cylinder, as an example of thread whirling. The rotation radius of the tool is 16 mm; and the tool rotates at a spindle speed of 2000 rpm. A 20 mm diameter of workpiece (radius, 10 mm) rotates at a spindle speed of 10 rpm. The eccentricity of the centers of the tool and the workpiece rotations is 6.5 mm. Therefore, the cutting depth, which controls the depth of screw, is 0.5 mm.

3. Dimple machining in whirling

When the circumferential speed of the tool is nearly equal to that of the workpiece, the tool penetrates into the workpiece without cutting. A dimple, then, is formed in the indentation process. The alignment and the shape of the dimples are controlled by:

- the rotation radii of the tool and the workpiece,
- the ratio of the circumferential speed of the tool to that of the workpiece,
- and the eccentricity.

Although the paper discusses the indentation process with the tool insert conventionally used in turning, the dimple shape is controlled by the forming tool geometry.

Fig. 2 shows configuration of the dimple machining in whirling, where the rake angle of the tool, α, is shown as negative. The area colored by gray shows the penetration area of the tool into the workpiece. A point on the tool engages at P_1; passes at P_2 in the maximum indentation depth; and exits from the workpiece at P_3. When the angle $\angle P_1O_TP_3$ and $\angle P_1O_WP_3$ are defined as $2\alpha_T$ and $2\alpha_W$, α_T and α_W are given by:

$$\begin{cases} \alpha_T = \cos^{-1}\left(\dfrac{R_T^2 - R_W^2 + \varepsilon^2}{2R_T\varepsilon}\right) \\ \alpha_W = \cos^{-1}\left(\dfrac{R_T^2 - R_W^2 - \varepsilon^2}{2R_W\varepsilon}\right) \end{cases} \quad (1)$$

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