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Development and characterization of diamond tip burnishing with a rotary tool

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ABSTRACT

The effectiveness of a diamond tip burnishing method with a rotary tool, which is proposed by the authors and can be applied to the flat and curved surfaces of cuboid workpieces, is investigated. A proposed hybrid-type parallel mechanism with spherical 5-degree-of-freedom range and force control system was used as a burnishing machine. A diamond tipped tool, rotated by a high-speed motor spindle, was used as a burnishing tool. A stainless steel and a hardened cold work tool steel surface were targeted, respectively. The burnishing characteristics of the proposed method were evaluated in terms of the appearance and profile of burnishing marks, surface profile, residual stress and hardness of the burnished surface layer, surface roughness, and glossiness of the burnished surface. The advantages of the proposed method were clarified by comparing its performance with that of the conventional method, which does not rely on the tool rotation. The burnishing marks on the stainless steel workpiece, obtained using a single tool feed (without the cross feed) using the proposed method were wider and deeper than those obtained using the conventional method, and the convex profiles generated by the cutter marks were satisfactorily smoothed using the proposed method. The compressive residual stress and higher hardness of the burnished surface layer of the stainless steel workpiece could be obtained as well. In the case of the hardened cold work tool steel workpiece, the burnishing marks obtained using the proposed method were also not similar to those obtained using the conventional method. The feed rate of the burnishing tool affected the burnished surface profile only when using the proposed method, and the burnished surface profile could be controlled by the tool feed rate. The burnishing force, too, strongly affected the burnished surface profile. The proposed method allows obtaining high-quality burnished surfaces, with smooth profiles, low surface roughness, and high glossiness, even for relatively hard materials.

1. Introduction

The process of diamond tip burnishing produces a superior finish on a surface by rubbing and compressing the target surface using a sliding burnishing tool, which causes minute material flows on the surface layer. The diamond tip burnishing process offers a higher level of efficiency than other removal processes, such as grinding and polishing. Konefal et al. (2013) described how the process of diamond tip burnishing can also be expected to improve the abrasion resistance and fatigue strength of a target surface layer as a result of work hardening and creation of a compressive residual stress. Given this, significant attention has been devoted to studying the characteristics of this process. Luo et al. (2006) theoretically investigated the contact mechanics between a burnishing tool and a workpiece, and conducted experiments using a cylindrical surfaced PCD tool and an aluminum alloy workpiece. Nestler and Schubert (2015) clarified the influence of machining parameters and the radius of a diamond sphere on the surface profile and residual stress of the burnished surface layer, for the surface of an aluminum alloy workpiece. These investigations demonstrated that the contact pressure between a burnishing tool and a target surface strongly affects the workpiece surface properties. Thus, a burnishing tool has a built-in spring or a hydraulic mechanism that allows to maintain a constant burnishing force regardless of any

Abbreviations: AISI, American Iron and Steel Institute; DOF, degree-of-freedom; HV, Vickers hardness; PCD, poly crystalline diamond.

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Nomenclature

CF	Cross feed (μm)
f	Tool feed rate (mm/sec)
F_b	Burnishing force (N)
G_l	Glossiness
N	Spindle revolution (rpm)
R	Diamond tip radius (mm)
R_a	Arithmetic mean roughness (μm)
v_s	Sliding speed (m/min)
w_m	Burnishing mark width (μm)
α	Inclination angle of burnishing tool (deg.)
σ_r	Residual stress (MPa)

dimensional errors and topological variations of the pre-machined workpiece surface. Korzynski et al. (2011) developed a slide burnishing method using a cylindrical-ended burnishing tool with a built-in spring, for finishing a shaft workpiece. Sagbas (2011) performed analysis and optimization of surface roughness using a ball burnishing tool, with a built-in spring. In addition, Tanaka et al. (2012) developed a hydraulic burnishing tool for finishing a discontinuous target surface. However, these burnishing tools, all of which containing a built-in spring or a hydraulic mechanism, require complex design. Thus, a burnishing method that utilizes a constant burnishing force and a simple burnishing tool is highly desired.

In general, diamond tip burnishing is applied to the outer and inner circumferential surfaces of a cylindrical workpiece that is rotated at a high speed by the main spindle of a machine tool, such as a lathe. Maximov et al. (2009) developed a spherical motion burnishing method for treating circumferential surfaces of a cylindrical workpiece using a lathe. Luo et al. (2001) also clarified the effects of burnishing parameters on the surface roughness of an aluminum alloy workpiece, using an ordinary lathe with a PCD burnishing tool. In the above cases, the target surface could be slid at a high speed and over a long distance by setting a fine tool feed rate until obtaining the required level of the surface integrity. However, it is difficult to slide a burnishing tool over a target surface at a required high speed and over a long distance when flat and curved surfaces are targeted and a machine tool such as a milling machine is used for this task, because the burnishing tool or workpiece cannot be fed in a linear or curvilinear manner at a high speed. Shiou and Cheng (2008) proposed a precision surface finishing method, which introduces the polishing process after the ball burnishing process, for spherical and aspherical lens mold cavities. However, in general, it is desired to develop a simple manufacturing process that will allow obtaining high-quality flat and curved surfaces only by burnishing, and will be applicable even to relatively hard materials.

The preliminary surface integrity has been previously shown to affect the burnishing results. Korzynski (2007) reported that the preliminary surface roughness strongly affects the outcomes of burnishing. Hiegemann et al. (2014) proposed an analytical prediction method, which accounts for the preliminary surface profile, for determining the surface roughness after ball burnishing. Hiegemann et al. (2016) also proposed a novel analytical model, which uses the contact pressure for predicting the surface roughness after ball burnishing. The burnished surface integrity is also influenced by the burnishing conditions such as the cross feed and the burnishing force. Yu and Wang (1999) experimentally investigated the influence of the burnishing conditions on the burnished surface integrity of an aluminum alloy workpiece finished using diamond cutting tools. Korzynski (2007) also investigated the relationship between the burnishing force and surface roughness in the sliding burnishing using a spherical tool. Therefore, it is important to clarify the relationship between the burnishing conditions and the burnished surface integrity when the newly burnishing method is developed. Moreover, the burnished surface is also expected to enhance the surface properties. Chomienne et al. (2016) evaluated the residual stress of the martensitic stainless steel surface finished by ball burnishing. Revankar et al. (2014) analyzed the hardness of the burnished surface layer in ball burnishing of a titanium alloy.

Many machine tools with parallel mechanisms have been developed for processing various curved surfaces. Ibaraki et al. (2006) proposed a calibration method that accounts for gravity-induced errors to improve the motion accuracy of hexapod-type parallel mechanism machine tools. Oiwa (2010) reviewed the parallel kinematic mechanism. Yachi and Tachiya (2010) proposed a calibration method for a parallel mechanism type machine tool using a simulation on a Stewart Platform Mechanism. Okada et al. (2014) developed a spherical 5-DOF hybrid-type parallel mechanism machine tool with a force control system for burnishing of flat and curved surfaces. Because parallel mechanisms, which have multiple degrees of freedom, in general are characterized by a high rigidity, high accuracy, and high output power, they are often applied to machining processes. As a conspicuous feature, the proposed hybrid mechanism offers the ability to control the burnishing force by a 3-component dynamometer fixed under the workpiece.

In this paper we propose a novel diamond tip burnishing method, which rotates the diamond tip burnishing tool using a high-speed motor spindle mounted on the proposed hybrid mechanism, for application to flat and curved surfaces. The high sliding speed and long-distance sliding of the diamond tip on the target surface can be achieved using this proposed method. Moreover, the burnishing tool, which has a simple structure, can be applied as a rotary tool, because no complex mechanism (such as a built-in spring or a hydraulic mechanism) is required in the proposed method for maintaining a constant burnishing force. In this study, we investigated the burnishing characteristics and efficiency of the rotary tool by resulting on a flat surface made of two types of steel, stainless steel and hardened cold work tool steel.

2. Experimental setup

2.1. 5-DOF hybrid parallel mechanism with force control system

An external view of the developed hybrid-type parallel mechanism machine tool with a rotary burnishing tool is shown in Fig. 1(a) and (b). The mechanism consists of a 3-DOF parallel mechanism and an *XY* table. As shown in Fig. 1, the parallel mechanism is composed of three link chains that are coupled to the base by a 1-DOF rotational joint $J_{1,i}$ ($i = 1$ to 3), and to the output link by 3-DOF spherical joints $J_{3,i}$ ($i = 1$ to 3). The link chains are arranged symmetrically with respect to the *Z* axis, as shown in Fig. 1. Each of the link chains has a 1-DOF translational joint $J_{2,i}$ ($i = 1$ to 3), and the position and posture of the output link are controlled by adjusting the length of $J_{2,i}$. A high-speed spindle motor is affixed to the center of the output link so that the burnishing tool "T" shown in Fig. 1 is directed toward the base.

The *XY* table, which is arranged just under the output link of the parallel mechanism, positions a workpiece mounted on the table in the *X* and *Y* directions. Thus, the mechanism shown in Fig. 1 has five spherical DOFs and superior rigidity owing to the advantages of the *XY* table. Thus, the hybrid-type parallel mechanism is suitable for 5-axis numerically controlled machining. Furthermore, because the 3-DOF parallel mechanism can control the force applied to the tool tip in the *X*, *Y*, and *Z* directions, it can adjust the contact force between the diamond tip and target surface during burnishing. The control of the burnishing force can then be performed by only controlling the upper parallel mechanism. Therefore, constant-force burnishing is achieved even for curved surfaces by using this 5-