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Sphere forming mechanisms in vibration-assisted ball centreless grinding

Weixing Xu [a,b], Dandan Cui [c], Yongbo Wu [b,*]

[a] *Laboratory for Precision and Nano Processing Technologies, School of Mechanical and Manufacturing Engineering, The University of New South Wales, NSW 2052, Australia*
[b] *Advanced Machining Technology Laboratory, Department of Machine Intelligence and Systems Engineering, Akita Prefectural University, Akita 0150055, Japan*
[c] *School of Mechanical & Mining Engineering, The University of Queensland, Queensland 4072, Australia*

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ABSTRACT

This paper aims to clarify the sphere forming mechanisms in vibration-assisted ball centreless grinding, a new technique for effectively processing balls using ultrasonic vibrations. Based on a comprehensive analysis of the ball rotation motion, geometrical arrangement and stiffness of the whole grinding system, a reliable mechanics model was successfully developed for predicting the sphere forming process. Relevant experiments conducted showed that the model had captured the mechanics and the major sphere forming mechanisms in ball centreless grinding. It was found that the ball whole surface can be well ground with a high accuracy, while efficiency is much enhanced compared with that in the traditional methods. The ball rotational speed which is controlled by the ultrasonic regulator has a great impact on final sphericity, and the speed controlled by the ultrasonic shoe dominates the whole processing time. To achieve a stable and high precision grinding, the ball needs to rotate rhythmically, and the wheel feed per step and the ball location angle should be controlled in a critical range.

1. Introduction

Spherical components are widely used in many engineering applications, such as balls in bearings [1–3], spherical silicon in photovoltaic energy conversions [4,5], contact probes in inspection devices and other precision products [6,7]. To meet the growing demands of high level functional performance, not only the dimensional and geometric control of the balls is strict, but the requirement towards the ball materials is stringent, such as silicon nitride (Si_3N_4), silicon carbide (SiC), aluminium oxide (Al_2O_3) and zirconia (ZrO_2), which are advanced and normally combine with high elastic modulus, hardness and corrosion resistance, low density, friction and thermal expansion coefficient [8]. However, just the abovementioned superior properties bring challenges to the fabrication of advanced balls. As for the processing method, there are mainly two types available: V-groove lapping (VL) and magnetic fluid polishing (MFP). Apparently, the VL methods can be a bit diverse, such as concentric VL, eccentric VL and variable-radius VL, but the balls are normally constrained by the V-shaped groove and revolve around the pad to remove materials [9,10]. However, the machining cycle usually requires a long considerable time (6-16 weeks) because of the low material removal rate [3,9–11]. To improve the machining efficiency, MFP was then proposed, which is based on the magneto-hydrodynamic behaviour of a magnetic fluid, and can lower the grinding force and improve the final ball accuracy; nonetheless it is environment-unfriendly and the cycle time also lasts for 20—30 h [1,12,13].

In an attempt to reduce the processing time, the authors have developed a novel grinding technique with the aid of ultrasonic vibration, named vibration-assisted ball centreless grinding [14,15]. This technique is based on the concept of the ultrasonic vibration-assisted centreless grinding of cylindrical components [16–19]. Two kinds of ultrasonic vibrations are applied to the ball, and by adjusting the directions of the vibrations, the ball can be controlled to rotate in two directions to achieve a full spherical surface grinding [14,15]. It has been shown that this technique can significantly shorten the processing cycle in grinding of advanced balls. However, the sphere forming mechanisms are still unclear, which has significantly hindered the optimisation and practical application of the new ball grinding technique. The objective of this work is to remove the above barrier through a detailed mechanics analysis to understand the science behind ball centreless grinding, thereby establishing the essential fundamentals.

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[*] Corresponding author.
E-mail addresses: weixing.xu@unsw.edu.au (W. Xu), dandan.cui@uq.edu.au (D. Cui), wuyb@akita-pu.ac.jp (Y. Wu).

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Nomenclature

PZT	piezoelectric ceramic
AC	alternative current
VL	V-groove lapping
MFP	magnetic fluid polishing
a_0	apparent wheel depth of cut at the beginning of spark-out
a_i, a_m	true depth of cut in the *i*th/*m*th half-revolution in spark-out
A_s, A_r	applied vibration amplitudes on shoe and regulator, μm
d_w	ball diameter, mm
E_r	roundness of the measured cross-section, μm
E_s	ball sphericity error, μm
f_s, f_r	applied vibration frequencies on shoe and regulator, kHz
F_n, F_t	normal and tangential grinding force
F_x, F_y	grinding force in *x*- and *y*- directions
F	pressure force on stoper, N
k	machining elasticity parameter of the grinding system
n_g	grinding wheel rotational speed, rpm
n_{wz}, n_{wx}	ball rotational speed around *z*-axis and *x*-axis, rpm
N_1, N_2	ball revolution number before and after spark-out process
R_g	grinding wheel radius, mm
T	grinding period time, s
T_A	time for ball rotates one revolution around *z*-axis, s
T_{off}	relay switch off time during wheel feed-in, s
T_{on},	relay switch on time during wheel feed-in, s
T_s	vibration velocities on top of shoe and regulator, m/s
v_s, v_r	vibration velocities on top of shoe and regulator, m/s
V_{fr}	grinding wheel feed rate, μm/s
α_0	ball initial location angle, °
$\alpha(t)$	ball location angle at time *t*, °
δ	wheel feeding step, μm
Δ	wheel feeding depth, μm
ρ_0	ball initial radius, mm
$\rho(t)$	ball radius at time *t*, mm
$\rho_A(t)$, $\rho_B(t)$, $\rho_C(t)$	ball radius at contact points A, B and C after grinding for time *t*
ϕ	blade angle
O_g (X_{Og}, Y_{Og}, Z_{Og})	coordinates of grinding wheel centre
O_w (X_{Ow}, Y_{Ow}, Z_{Ow})	coordinates of ball centre
A (X_A, Y_A, Z_A)	coordinates of grinding point A
B (X_B, Y_B, Z_B)	coordinates of contact point B
C (X_C, Y_C, Z_C)	coordinates of contact point C
D (X_D, Y_D, Z_D)	coordinates of contact point D

2. Principle and modelling of ball centreless grinding

2.1. Principle

Fig. 1 illustrates the processing principle of the vibration-assisted ball centreless grinding, in which the ball is placed underneath the grinding wheel and above a ultrasonic shoe with a location angle of α, and constrained by a blade, an ultrasonic regulator and a stop. The grinding wheel rotates at a speed of n_g and feeds in at a speed of V_{fr}. The material removal starts as the wheel interferes with the ball. Once the required stock removal Δ has been attained, the wheel feeding will stop followed by a dwell to allow "spark-out". During grinding, the ball"s rotation around *z*-axis is controlled by the elliptic vibration from ultrasonic shoe, which is a typical centreless grinding operation for high precision roundness forming [16–19]. With an additional well-controlled rotational motion around *x*-axis by ultrasonic regulator, the whole surface of the ball can be well ground to generate a spherical shape. To do this, a stop is arranged to work under a pressure of *F* to provide sufficient control force through friction between the ball and regulator. Suppose the ultrasonic shoe and regulator vibrate at frequencies of f_s and f_r, and amplitudes of A_s and A_r, their corresponding vibration velocities, v_s and v_r, can be described as

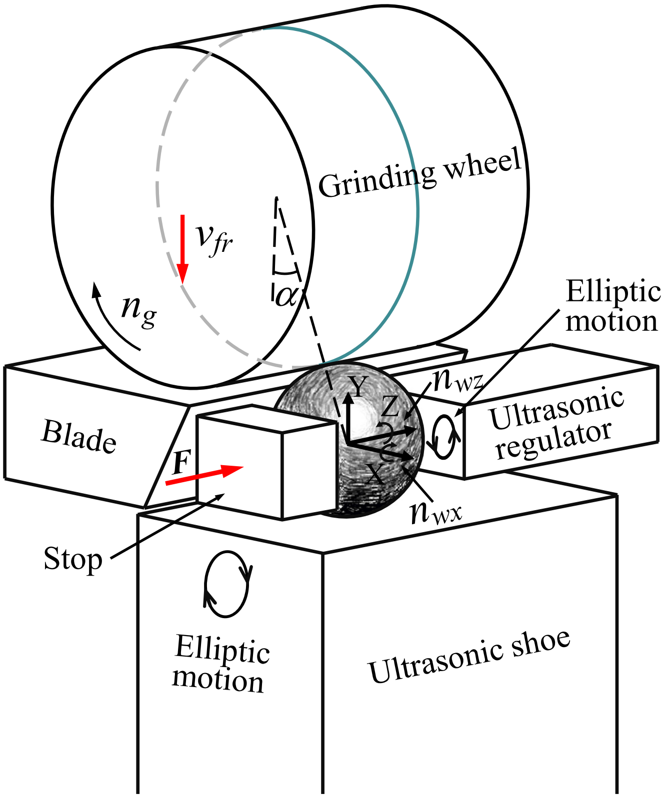

Fig. 1. An illustration of vibration-assisted ball centreless grinding.

$$\begin{cases} v_s(t) = 2\pi f_s A_s \sin(2\pi f_s t) \\ v_r(t) = 2\pi f_r A_r \sin(2\pi f_r t) \end{cases} \tag{1}$$

For a precision control, the tangential velocities of the ball rotation around *z* and *x*-axis are the same as the maximum vibration speeds of the ultrasonic shoe and regulator, respectively [14,15]. Therefore, the ball rotational speed around *z*-axis and *x*-axis becomes

$$\begin{cases} n_{wz} = 2\pi f_s A_s / d_w \\ n_{wx} = 2\pi f_r A_r / d_w \end{cases} \tag{2}$$

where d_w is the ball diameter.

2.2. Modelling

Fig. 2 shows the geometrical arrangement of the ultrasonic shoe, blade, regulator, stop, ball and grinding wheel in ball centreless grinding after machining for time *t*, by which the ball location angle and radius at the grinding point A become $\alpha(t)$ and $\rho(t)$, respectively, from their initial values of α_0 and ρ_0. The blade