International Journal of Machine Tools & Manufacture 50 (2010) 737–740

Contents lists available at ScienceDirect

International Journal of Machine Tools & Manufacture

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

An integrated tool for five-axis electrorheological fluid-assisted polishing

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ARTICLE INFO

Article history:
Received 30 July 2009
Received in revised form
7 April 2010
Accepted 9 April 2010
Available online 27 April 2010

Keywords:
Electrorheological fluid
Polishing
Integrated electrode tool

ABSTRACT

A five-axis electrorheological fluid-assisted polishing equipment is presented for the finishing of curved surfaces in this paper. An integrated electrode tool is specially designed to make the abrasive particles in the electrorheological fluid concentrate around the tool end when the electric field is applied and it is suitable to polish not only the conductive material such as tungsten carbide but also the non-conductive material such as optical glass. The polishing experiments for curved surfaces of tungsten carbide and optical glass are conducted to confirm the validity and suitability of the developed five-axis equipment with the designed integrated electrode tool and to reveal the influence of the process parameters on the workpiece surface roughness in electrorheological fluid-assisted polishing.

1. Introduction

Polishing, as a post-process, is usually essential for the optical lens and the moulding dies to obtain a mirror-like surface with high form accuracy and low surface roughness after shape making.

Unlike conventional polishing methods such as fixed abrasive polishing with grinding wheel and loose abrasive polishing with a soft pad holding the abrasive particles in the polishing area, different field-assisted polishing methods, such as magnetic abrasive polishing [1,2], magnetic fluid polishing [3,4], magnetorheological polishing [5,6] and electrophoresis polishing [7], are proposed to concentrate the abrasive particles in the polishing area by the effect of the magnetic field or that of the electric field. The performance of field-assisted polishing is between those of fixed abrasive polishing and loose abrasive polishing.

Electrorheological (ER) fluid is a functional fluid with the property that its viscosity can vary with the applied electric field intensity. Kuriyagawa and coworkers [8,9] firstly proposed the concept of mixing ultra-fine abrasive particles (diamond, GC or WA) in an ER fluid and employing the ER effect to gather and stabilize the abrasive particles in the vicinity of the tool tip for the polishing of optical lenses and moulding dies. Kim et al. [10,11] extend the ER fluid-assisted polishing method to the polishing of silicon wafer chip. Zhang et al. [12,13] develop the empirical models for evaluation of the effects of the process parameters on material removal depth and surface roughness in ER fluid-assisted polishing and propose an approach to predict the effective area in which the abrasive particles concentrated in the vicinity of the tool tip result in effective material removal from the workpiece. Lu et al. [14] use Fe_3O_4 magnetic particles as solid particles of ER fluid in ER fluid-assisted polishing of optical glass. Now two different modes of ER fluid-assisted polishing are generally adopted for conductive material and non-conductive material, respectively (see Fig. 1 in Ref. [12] and Fig. 3 in Ref. [9] for the details). In the ER fluid-assisted polishing of conductive material such as tungsten carbide, the needle-like tool and the conductive workpiece are directly used as electrodes. And in the ER fluid-assisted polishing of non-conductive material such as optical glass, an auxiliary electrode in circular shape is needed to surround the glass surface to be polished when the needle-like tool electrode is positioned in the centre to form a circular type electric field. For these two modes of ER fluid-assisted polishing, the mixture of abrasive particles and ER fluid is supplied to the gap between the tool and the workpiece and the gap is kept at several microns. The application of the fluid-assisted polishing is limited to the flat surfaces at this stage. Little work is reported about the ER fluid-assisted polishing of curved surfaces. The existence of auxiliary electrode limits the extension of ER fluid-assisted polishing to the curved surfaces of non-conductive material.

This paper develops a five-axis ER fluid-assisted polishing equipment with an integrated electrode tool not only for the finishing of the conductive curved workpiece but also for the finishing of the non-conductive curved workpiece. The set-up of an integrated tool for the five-axis ER fluid-assisted polishing equipment is described in Section 2. Then the polishing experiments for the curved surfaces of tungsten carbide and optical glass are performed with the designed integrated electrode tool on the developed five-axis equipment in Section 3. A summary of findings is given in the concluding section.

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doi:10.1016/j.ijmachtools.2010.04.003

2. An integrated tool for ER fluid-assisted polishing

An ER fluid-assisted polishing equipment with *X*, *Y*, *Z*, *B* and *C* axes is developed in this paper. The workpiece fixture is mounted on a rotating table, which can move along *X*-axis and along *Y*-axis driven by a Panasonic AC servo motor and rotate about *Z*-axis (*C*-axis). The stroke for the *X*- and *Y*-axis is 200 mm. An integrated electrode tool is specially designed and mounted on another rotating table, which can move along *Z*-axis driven by a Panasonic AC servo motor and rotate about *Y*-axis (*B*-axis). The stroke for the *Z*-axis is 140 mm. TURBO PMAC2-PCI made by Delta Tau is used for the five-axis motion control of the equipment. The software is programmed by Visual Basic for automatic polishing path planning and motion control. The structure of the integrated electrode tool is illustrated in Fig. 1(a). Two copper plates connected to the slip rings are separated by the insulating rod to form parallel type electrodes when electricity is supplied to them via slip rings. The spacing between the two parallel copper electrodes is set at 6 mm in this paper and it is adjustable when necessary. Fig. 1(b) gives the photograph of the ER effect of the integrated electrode tool. The measured extent of ER effect from the boundary of the electrode plates within which the ER fluid becomes sticky can reach 14 mm. The nearer the gap between the tool and the workpiece is, the stronger the electric field intensity is and the more abrasive particles are concentrated to polish the workpiece. And the polishing area of the integrated electrode tool is obviously larger than that of the needle-like electrode tool when the tool moves along the polishing path on the workpiece.

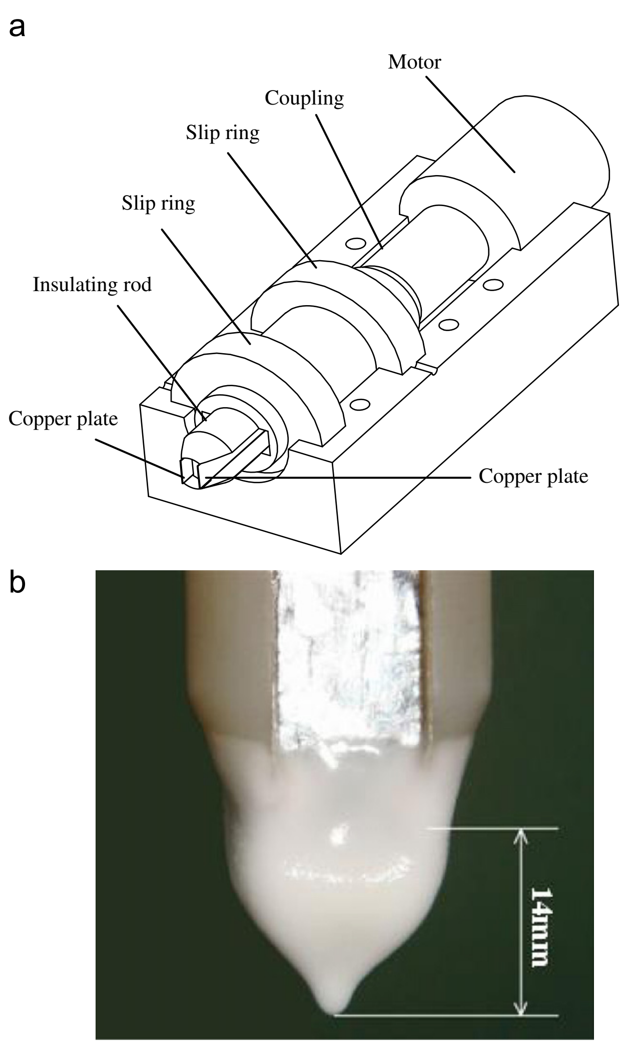

Fig. 1. The integrated electrode tool.

3. Experiments for conductive and non-conductive materials

The experiments of ER fluid-assisted polishing are conducted for conductive and non-conductive materials with the integrated electrode tool on the developed five-axis equipment in this paper. The conductive workpiece material is tungsten carbide and the non-conductive workpiece material is optical glass. The ER fluid used in the experiments is composed of starch particle as the disperse phase and silicone oil as the continuous phase. The abrasive particles mixed into the ER fluid are diamond with grain size W10 for polishing of tungsten carbide and Al_2O_3 with grain size W5 for polishing of optical glass. Considering the rotation of the integrated electrode tool and the polishing efficiency, the gap between the tool and the workpiece is set at 1 mm in the experiment. The surface roughness of the wokpiece before and after polishing is measured by a WYKO NT 1100 optical profiling system. The curved surfaces of non-conductive workpieces are ground to Ra 18 nm before ER fluid-assisted polishing. The experimental results of the surface roughness changing with the varying process parameters of the applied electric voltage *U*, the spindle rotational speed *n*, the mixing ratio for abrasives in ER fluid η and the polishing time *T* are shown in Figs. 2–5 for polishing the curved surfaces of non-conductive optical glass. Fig. 5 also gives the surface roughness changing with the varying polishing time *T* for polishing the curved surfaces of conductive

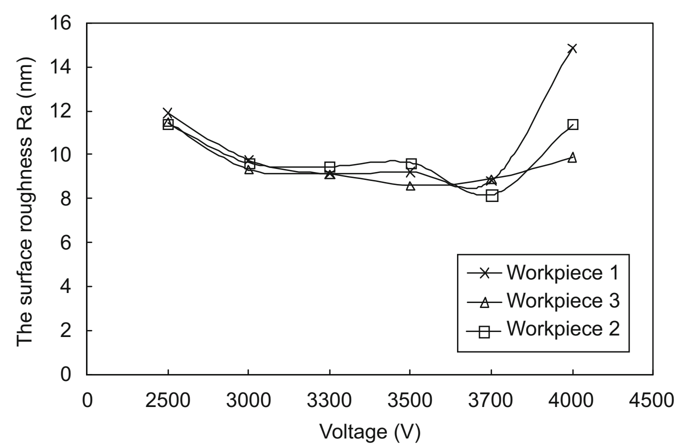

Fig. 2. Experimental results for the surface roughness vs. voltage. $n=4000$ rpm, $T=10$ min, $\eta=15$ wt%.

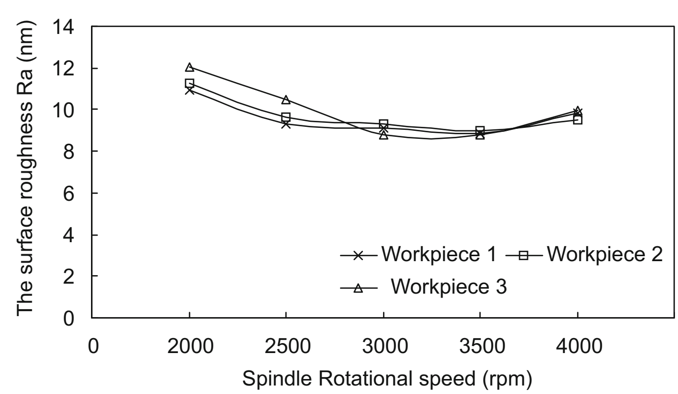

Fig. 3. Experimental results for the surface roughness vs. spindle rotational speed. $U=3000$ V, $T=10$ min, $\eta=15$ wt%.