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Experimental Investigation of Ultrasonic-Assisted Milling of Soda Glass Using Factorial Design of Experiments

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Abstract

Soda glass is a difficult-to-machine material widely used in industry. In this work, ultrasonic-assisted milling (UAM) of soda glass is investigated and compared to conventional milling (CM). Statistically designed experiments are conducted with and without cutting fluid at different levels of the spindle speed, feedrate, depth of cut, and tool particle-concentration. The significant factors and their interactions are identified by modelling the process parameters and the corresponding responses in terms of cutting forces and moment. Results show a reduction of axial cutting force and moment at higher spindle speed and lower feedrate and depth of cut. The application of ultrasonic vibration-assistance and cutting fluid demonstrates a significant effect on the axial cutting force and moment.

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Keywords: Ultrasonic-Assisted Milling (UAM); Soda Glass; Cutting Force; Moment; Ultrasonic Vibration; Cutting Fluid.

1. Introduction

Machining of hard and brittle materials is gaining importance due to its growing utilization in many industries such as electronics, optical, and bio-medical fields. These materials such as glass, ceramics, zirconia, alumina … etc. are considered as difficult-to-machine materials because of their superior characteristics such as high strength, hardness, brittleness, thermal resistance, corrosion resistance, and wear resistance. Therefore, a need arises to develop a low-cost and high-efficiency un-conventional machining process that is applicable to glass. At this point, ultrasonic-assisted machining is an effective method for its capability to machine such materials when compared to conventional processes [1–4].

Ultrasonic-assisted milling (UAM) combines the material removal mechanism of grinding, milling kinematics, and ultrasonic assistance, Fig. 1(a). This process is so-called in reference to the milling kinematics, however, it is sometimes called ultrasonic-assisted grinding (UAG) as the material removal is based on the abrasion mechanism of diamond particles bonded on a rotating tool which is ultrasonically vibrated parallel to its axis. In conventional milling (CM), there is a continuous contact between the cutting tool and the workpiece surface during the whole machining process, while in UAM, an interrupted contact is occurring due to the ultrasonic vibration, Fig. 1(b).

Ultrasonic vibration applied to the machining process leads to the reduction of the cutting forces and tool wear, production of better workpiece surface finish, and longer tool life as well. Zhang et al. [5–7] compared the performance of rotary ultrasonic face milling (RUFM) with the conventional diamond milling of K9 optical glass. The results presented that the relationship between cutting depth and ultrasonic amplitude would significantly reduce the cutting force, tool wear on the end face, and extend the life of diamond tools. Moreover, RUFM process would effectively reduce the surface damage depth as the chipping size generated from RUFM are smaller than that in conventional diamond milling. Fang et al. [8] reported that rotary ultrasonic milling of K9 optical glass produced less tool wear than conventional milling in lateral direction of the cutter under the same cutting conditions. Additionally, it was concluded that cutting hard and brittle

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materials with a larger depth of cut and a lower feedrate was better compared to high speed cutting of metals as the radial cutting force is more sensitive to the variation of feedrate than depth of cut. Lv et al. [9,10] found that the superposition of an ultrasonic vibration on the diamond tool compared to CM reduces the cutting forces significantly and, at the same time, slightly increases the surface roughness during machining of glass BK7 and K9. Compared to conventional grinding of silica glass, in ultrasonic grinding, forces decline up to 50% and the surface quality is improved [11]. Dambon et al. [4] emphasized that increasing of ultrasonic amplitude during side grinding of optical glass N-BK7, lead to a significant decrease of cutting forces and increase of the material removed, however, the amount of tool wear considerably increases. In UAM, few studies are reported regarding the interaction between abrasive grains and bond. The bonding type, grain size, and grain structure play a prevalent role on the tool performance and the features of the machined parts. In this regard, the influence of different tool variables, including bond type and diamond grain concentration, on the tool wear during UAM of optical glass N-BK7 was studied [4]. It was reported that during UAM, increasing the bond hardness of the tool and reducing the diamond grain concentration lead to cutting force reduction and increased tool wear. Hence, grinding tools with low grain concentration and high bonding hardness were recommended for roughing, while, those with high grain concentration and low bonding hardness for finishing.

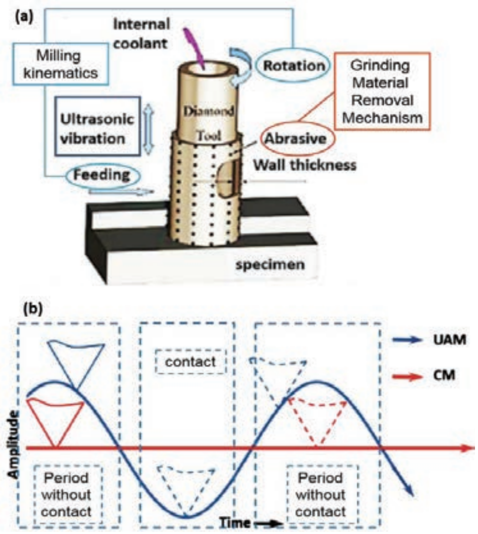

Fig. 1. (a) Ultrasonic-Assisted Milling; (b) Abrasive trajectory with and without ultrasonic

Research in the field of UAM of hard-to-machine materials is mainly focused on studying the effect of the control variables of UAM on the measures of process performance with limited application of design of experiments techniques as mentioned by El-Taybany et al. [12]. Moreover, there are limited investigations covering the interaction effects of the process variables on the process performance [12–16] .

In this work, a series of experiments were conducted using ultrasonic-assisted milling of soda glass, a hard/brittle material. A systematic design of experiments was used to reveal the relationship between the control variables and their interactions from one side and to statistically analyse the measures of the process forces from the other side. The aim of this exploratory work is to investigate the behaviour/trend of the process variables on the process performance. For this reason, a relative wide range of process variables were considered in order to determine the ones among them showing significant direct and/or interactive effects over the process performance. For each process variable, two levels, representing the two extreme applied values of the factor, were assigned in order to evaluate the general trend and the effect of the process variable. In future detailed work, more levels for the effective process variables, as the result of the current work, will be considered for deeper investigations.

2. Experimental Work

2.1. Experimental conditions

Figure 2 schematically illustrates the experimental setup. The workpiece material used in the present research is soda glass with dimensions of 40x30x6 mm^3.

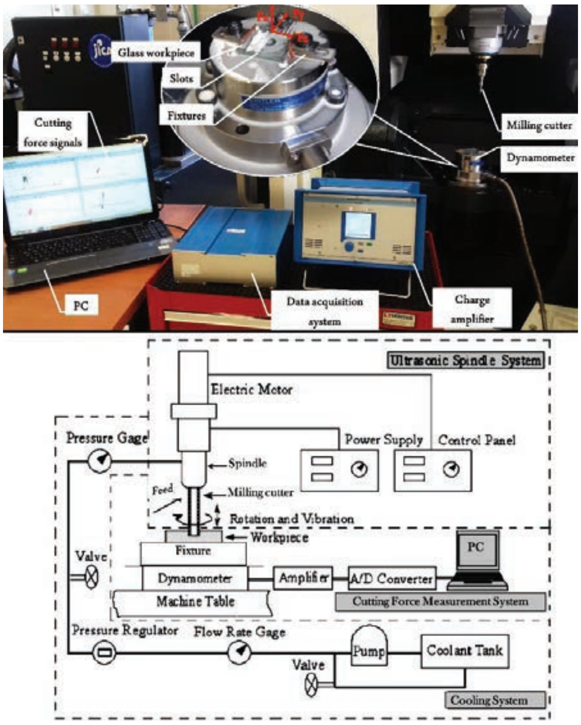

Fig. 2. Schematic diagram of experimental setup

Prior to the formal machining tests, a facing process was done for all the specimens to ensure their flatness. Diamond abrasive end milling cutters (SCHOTT Ltd Corp., Germany) with outer diameter of 4 mm and wall thickness of 1 mm were used for slotting. The end mills were redressed every five slots.