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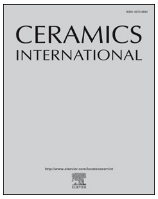

Regression analysis of surface roughness and micro-structural study in rotary ultrasonic drilling of BK7

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A R T I C L E I N F O

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A B S T R A C T

Ceramic materials have tremendous demand in manufacturing sectors. However, poor machinability impedes their widespread applications on an industrial scale. BK-7 falls in the same category and is normally processed by ultrasonic machining. But nowadays rotary ultrasonic machining is overtaking the ultrasonic machining for processing difficult to cut materials because of its superlative material removal mechanism. Current study aims to improve the surface quality of BK7 by studying the effect of input factors on surface roughness during rotary ultrasonic machining. Response surface methodology has been used to observe the effect of input variables — spindle speed, feed rate and ultrasonic power — on surface roughness (SR). Thereafter, central composite design was employed to estimate the regression coefficients of quadratic model for surface roughness. Fitness of developed quadratic model was checked by ANOVA test, which also revealed that all the model terms of input factors were significant except feed and speed interaction. Feed has the maximum impact over surface roughness descended by moderate impact of power and spindle speed. The study was further reinforced on observing the surface integrity of processed surfaces using scanning electron microscopic images. Mixed flow of material was observed to occur at lower feed rate and higher levels of rpm and ultrasonic power.

1. Introduction

In recent years, ceramics have emerged as high performance engineering materials. BK-7 glass is one such material having numerous applications in every industrial sector especially in automobile, optic, electronic and biomedical industries. It possesses excellent combination of optical, thermal, mechanical and chemical properties such as wide transmission range, low thermal coefficient of expansion, chemical inertness, high wear resistance and high hardness etc. Moreover, its structure is homogeneous and almost free from inclusion impurities and bubbles. Therefore, BK7 is used extensively in making micro-electro mechanical system (MEMS) components, image sensing devices, microfluidic devices, electronic substrate, headup display, etc. Other crucial applications include fabrication of lenses, prisms and mirrors for scanner, digital cameras, projectors, laser and optic devices [1–4].

However, machining of BK7 is always a challenging task as its high hardness, non-conductive nature and low fracture toughness account for poor machinability. Traditional machining of BK7 results in excessive tool wear, poor surface characteristics, high cutting forces and high processing cost etc. [5]. Even non-traditional machining methods like laser beam machining and abrasive jet machining, which were developed especially for difficult to cut materials like glasses and ceramics, suffer from thermal damage, stray cutting, poor surface roughness and low material removal rate [1,6]. These difficulties were resolved by ultrasonic machining (USM) to some extent making it a primary choice for machining hard and brittle material [7].

In 1964 a new concept was originated by Percy Legge where machining was performed between vibrating tool and rotating workpiece [8]. This approach termed as “rotary ultrasonic machining” (RUM) was found to deliver superior performance than USM because abrasives were directly coated on tool tip, whereas in USM abrasives are mixed with carrier fluid and supplied between vibrating tool and stationary workpiece. Hammering and throwing of these abrasives beneath the tool tip cause the material removal [7]. In RUM abrasives abrade, erode and hammer the workpiece surface to remove the material [9]. In USM abrasive trajectory is random whereas in RUM it follows a definite trajectory. Instability in initial machining set-up and limited research restricted adaptation of RUM on industrial scale. Nowadays perpetual efforts are being made by researchers to explore full potential of RUM. It is showing a great potential for machining all categories of materials with the benefits of enhanced material removal rate, less cutting force, better tool life and higher geometrical accuracy [10].

Plenty of research works have been carried out in the field of RUM for knowing about its capabilities. Wang et al. performed grinding

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Nomenclature

RUM	Rotary ultrasonic machining
USM	Ultrasonic machining
CFRP	Carbon fiber reinforced plastic/polymer
RUG	Rotary ultrasonic grinding
RUEM	Rotary ultrasonic elliptical machining
RUD	Rotary ultrasonic drilling
CCRD	Central composite rotatable design
MEMS	Micro-electro mechanical system
SR	Surface roughness
RSM	Response surface methodology
ANOVA	Analysis of variance
SEM	Scanning electron microscope
S	Spindle speed
F	Feed rate
U	Ultrasonic power
CI	Confidence interval
PI	Prediction interval
CF	Cutting force

variant of RUM on CFRP with different tool geometries. Tools with flat tip and two slots generated minimum cutting forces (CF). Surface finish was also reported to get better with decrease in abrasive size and abrasive concentration [11]. Jing et al. performed rotary ultrasonic grinding (RUG) on silicon nitride to reveal the impact of process variables on surface morphology. Fractal dimension— that directly affected surface roughness— was found to be increasing first with increasing feed, spindle rpm and cutting depth. But with further increase it was found to be decreasing [12]. Ning et al. drilled CFRP and found rotary ultrasonic drilling (RUD) superior to conventional drilling with lesser cutting forces and reduced surface roughness (SR) [13]. Cong et al. observed rotary ultrasonic drilling to give superior performance when process was carried under cutting fluid rather than cold air. Use of cutting fluid yielded lower tool wear, SR and burning ratio due to reduction in cutting force and torque [10]. Geng et al. attempted rotary ultrasonic elliptical machining (RUEM) on composite material under dry condition. In comparison to conventional grinding, RUEM improved the surface integrity with less tool wear and lower SR [14]. Wang et al. formulated a mathematical model for brittle and composite materials that accurately predicted the critical value of cutting force below which RUD yields superior performance [15]. Anwar et al. investigated the hole quality, surface integrity and tool wear while performing RUD on titanium alloy. All the responses were significantly influenced by input variables namely spindle rpm, tool diameter, feed and ultrasonic power [16]. Li et al. devised a CF model with 85% prediction accuracy that is applicable for rotary ultrasonic face milling of composite material (C/SiC) [17]. Wang et al. performed RUG on CFRP and investigated the effect of machining variables on surface roughness, cutting force and surface morphology. Higher ultrasonic power was reported to suppress the cutting forces. Lower feed and higher rpm yielded superior surfaces due to less damage in terms of voids and fiber pull out [18]. Fernando et al. inferred RUD superior to percussive drilling for machining rock materials. Not only the surface finish was improved but also penetration rate was high, which led to substantial reduction in drilling time [19].

Literature review revealed that several studies have been attempted on processing of BK7 glass [16,20–25]. However, most of them have used rotary ultrasonic grinding (RUG) variant in which abrasives experience different loading condition in comparison to rotary ultrasonic drilling (discussed in detail in Section 3.4). The difference in loading

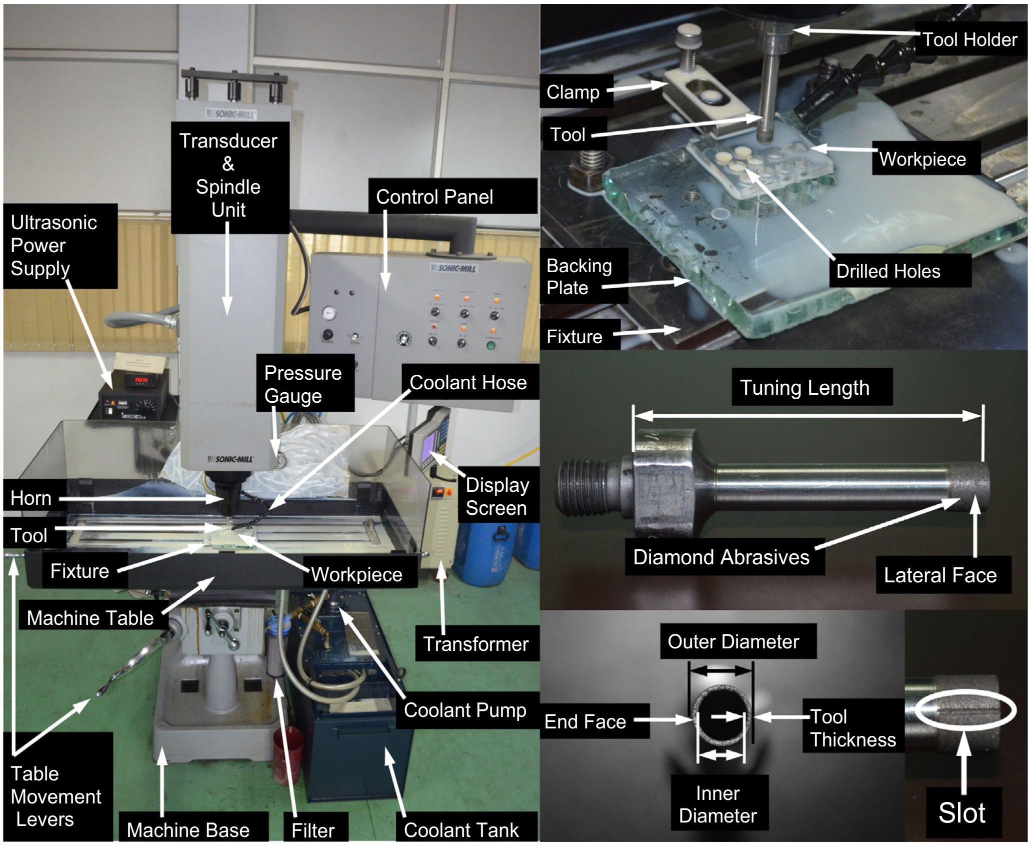

Fig. 1. Experimental set-up of rotary ultrasonic machining (RUM).