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Role of dielectric fluid and concentrator material in microwave drilling of borosilicate glass

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ABSTRACT

Microwave drilling is electromagnetic energy-based machining process in which microwave radiation at 2.45 GHz is concentrated into a narrow region using a thin metallic concentrator. A high electric field region gets developed around the concentrator tip which ionizes the dielectric media around to form plasma. Heat released from the plasma removes the target material in the vicinity through melting and ablation. However, limited control over the heat during the plasma discharge results in thermal damage of the target material. Thermal damage is more in the materials with poor thermal conductivity. Therefore, materials like glass experience thermal damage as well as frequent cracking. Thus, control over the plasma is critical for quality output of the process. The current work presents a new approach to minimize the plasma induced defects like crack, heat affected zone (HAZ), overcut and taper during microwave drilling of borosilicate glass at 2.45 GHz and 700 W. The study was carried out while drilling 1.3 mm thick glass plate using 0.6 mm concentrator at 700 W in a domestic applicator. Effects of concentrator material, dielectric medium and immersion depth on hole characteristics were studied in terms of HAZ, cracks, taper and overcut to obtain the optimum drilling condition. Mechanism of microwave drilling in the presence of a dielectric medium has been explained. The results revealed that the dielectric constant of dielectrics and electric conductivity of the concentrator materials affect the plasma shape and intensity whereas thermo-physical properties like viscosity and thermal diffusivity affect the confinement of plasma into a narrow zone. On the other hand, it was found that higher immersion depth reduces defects like crack, thermal damage due to low-temperature gradient on the workpiece surface and better heat dissipation from the surface of the workpiece. The best result was obtained with graphite concentrator in transformer oil dielectric at an immersion depth of 35 mm.

1. Introduction

Demand for glass has increased significantly in the applications like MEMS, biomedical apparatus etc. due to its chemical inertness, low electrical and thermal conductivities, high hardness and optical transparency [1]. The components used in these applications often require precise holes; however, high brittleness and hardness of glass restrict the use of conventional processes for machining without considerable defects, especially in the micro regime [2]. Further, low electrical conductivity of glass makes it a poor candidate for machining through chemical or thermal based advanced machining methods like electrochemical machining and electric discharge machining. Thus, mechanical-action based techniques are usually popular for glass machining in spite of higher tendency for cracking. Micromachining of glass by dry plasma etching [3] and deep etching with wet hydrofluoric acid-based solution was reported [1–6]. However, problems like very low machining rate (12.9 mm/h), large lateral undercut [4], formation of pinholes during etching were found as the major concerns [5]. Electrochemical spark machining was used successfully to machine glass; however, the process yield was reported low [7]. In the recent years, liquid assisted laser processing (LALP) technique was reported to drill hole in glass. The process reduces crack and thermal damage, whereas taper in the workpiece was a concern [8].

In the recent years, microwave energy has been used to process various materials due to its rapid processing capability and eco-friendly characteristics [9]. Investigation on micromachining of conductive as well as non-conductive materials showed that microwave drilling is a promising machining process. In the year 1996, microwave energy was used to drill hole through material ablation on the ceramic material under semi-vacuum. A laser beam was used to preheat the spot to be drilled to increase the absorption of the microwave at the target spot [10]. But, the first-time effective drilling was reported in the year 2002

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Nomenclature

Symbols

P(r, T)	Average power dissipated inside the material (W)
***E*(*r*, *T*)**	Electric field vector at any local point **r** (V m^{-1})
***H*(*r*, *T*)**	Magnetic field vector at any local point **r** (A m^{-1})
T	Temperature (K)
d_1	Diameter of concentrator (μm)
d_2	Diameter of hole at entrance (μm)
d_3	Diameter of concentrator at exit (μm)
t	Thickness of the workpiece (μm)
d_{pl}	Diameter of plasma at low immersion depth (μm)
d_{ph}	Diameter of plasma at high immersion depth (μm)
p_1	Pressure at height, h_1 (Pa)
p_2	Pressure at height, h_2 (Pa)
SS	Stainless steel
Gr	Graphite
WC	Tungsten carbide

Greek letters

ω	Angular frequency (rad s^{-1})
μ''	Magnetic loss factor (H m^{-1})
ε''	Dielectric loss factor (F m^{-1})
σe	Electrical conductivity (S m^{-1})
σi	Ionic conductivity (S m^{-1})

by Jerby et al. [11] on materials like concretes, ceramics etc. They concentrated microwaves into a small hotspot with the help of a drill bit (extendable monopole antenna). The material beneath the concentrator got ablated or softened due to the formation of the hotspot. Following the softening, a drill bit was inserted into it mechanically to create a 'hole' [11]. It was reported that in this process, temperature in the hot spot region rises rapidly which caused cracking near the hotspot and heat affected zone (HAZ) on the glass. Defects could, however, be minimized by pre-and post-heat treatment as observed during drilling of 0.5 mm diameter hole in 1 mm thick soda lime and borosilicate glasses [1–13]; but detailed characterization results of the holes were not reported.

Cracking is a common phenomenon while thermal processing of glass. Crack development and its propagation during micromachining of various glasses had drawn the attention of many researchers. However, it is difficult to identify the exact condition for initiation of cracks and their propagation during machining. In the year 2015, the photoelasticity approach was used to characterize the cracks developed during microwave drilling of glass [14]. It was reported that the residual stresses assist in propagation of a crack in the glass. It was further identified that the variation in stresses from tensile to compressive near the hole boundary generates cracks in the heat affected zone. The rapid increase in temperature causes thermal stresses around the hole to rise beyond the critical stress of glass which causes cracks to propagate in the glass. Later, the interface between concentrator and workpiece was changed by applying different solid and liquid precursors such as wax, engine oil etc. [15]. It was found that the characteristics of cracks around the hole got changed due to the application of the precursors. The precursors help in minimizing the thermal shock in glass during machining by making the energy transfer gradual from plasma sphere at the machining zone to the glass surface. Precursors like perspex and glycerin were reported more efficient in controlling crack and minimizing heat affected zone. It was also reported that precursors having less viscosity caused partial surface damage due to sputtering.

Allcock et al. [16] reported that crack formation and its propagation on laser heated glass was due to in-plane tensile residual stresses on the surface during ablation and cooling which is dependent on temperature gradient on the surface of the workpiece. Thus, higher temperature gradient will result in larger stress. Lautre et al. [15,17] reported that glass cracks frequently while drilling in the air due to high in-plane tensile residual stress. It was found that if the workpiece is kept submerged in water, water helps in reducing the temperature gradient which, in turn helps in minimizing crack and heat affected zone during drilling [18]. It was reported that residual stresses get changed from tensile to compressive due to underwater laser irradiation [19]. Water did not help only in reducing the defect but also enhanced ablation rate during laser drilling of silicon in water; it was reported that high-pressure plasma is generated due to confinement of plasma in water [20]. Plasma in water induces very high pressure and generates shock wave for a longer duration as compared to air. Longer duration of shock wave has significant effects on the mechanical response of the workpiece immersed in water [21].

Thus, it implies that the medium in which the workpiece is immersed has significant effect on the quantum of energy absorbed by it. The absorption of energy will then be largely dependent on the characteristics of the medium used. Consequently, application of a suitable medium can help in attenuating the directed energy in the processing zone. This has the potential to influence the phenomenon of glass cracking during thermal processing. Therefore, the objective of the present work is to investigate the effect of using different media in the machining zone to minimize cracks and thermal damage during microwave drilling of borosilicate glass. Experimental trials were carried

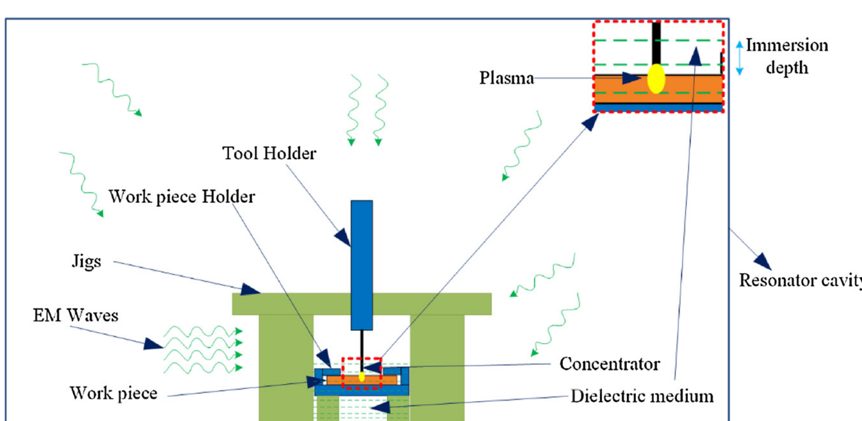

Fig. 1. Schematic diagram of the microwave drilling set up (inset: enlarged view of the machining zone).

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