Journal of Materials Processing Technology 225 (2015) 151–161

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

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

A photoelasticity approach for characterization of defects in microwave drilling of soda lime glass

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ARTICLE INFO

Article history:
Received 17 October 2014
Received in revised form 20 May 2015
Accepted 26 May 2015
Available online 28 May 2015

Keywords:
Glass drilling
Microwave
Concentrator
HAZ
Cracks
Photoelasticity

ABSTRACT

Need for drilling micro holes has been on rise in many miniature applications including biotechnology. Micro machining of such features is difficult to realize, particularly on difficult-to-machine hard and brittle materials like soda lime glass. Defect characterization with precision in micro-nano scale is even more challenging. Conventional approaches appear inadequate in such cases while fabrication as well as in characterization. In the present work, holes of 900 μm diameter were drilled on soda lime glass using a novel thermal-based approach called ‘microwave drilling’. It uses the phenomenon of thermal ablation with plasma heat created by the applied microwave energy through a tool. The energy was applied in the range of 90–900 W at 2.45 GHz in a multi-mode applicator. The glass specimens were subjected to high localized heat, which also caused some defects like cracking and deformation due to melting in the drilling zone. A photoelasticity approach was employed to characterize these defects. A setup was developed using a polarizer and a CCD camera to obtain the birefringence patterns. The patterns were analyzed to assess the defects. The microwave drilling process was also simulated and the stress-temperature relationships were studied. Simulation results substantiated the experimental observations. Details are discussed with evidences.

1. Introduction

Microwave drilling is a relatively new approach to drill micro holes in different materials. An approach to microwave drilling was proposed and studied by Jerby et al. (2000, 2002, 2004, 2005, 2009) to get established. In this process, Al-Shamma et al. (2001), Shayeganrad and Mashhadi (2009), Jerby et al. (2009) used an electromagnetic wave at 2.45 GHz to create a hot plasma ball at the tip of a tool. Meir and Jerby (2012a) recently highlighted the role of drill tool to interact with microwave and generate plasma, also at the same time maintain the intensity of plasma as per the power input. Microwaves are continuously attracted toward hot plasma due to the availability of free electrons around the plasma. Jacob et al. (1995) emphasized on the need of microwave material interaction and promotes the microwave specific effect over the normal dielectric material heating. Whereas, Meir and Jerby (2012b) showed the applications of localized microwave heating (LMH) of dielectric material in conjunction with the importance of concentrated plasma at the tool tip to thermally ablate the target material, to create a cavity, identified as drilled hole. Conventional drilling, on the other hand, by its virtue has some limitations in drilling micro holes. Various difficulties experienced in conventional drilling include more mechanical movement (rotary and linear), challenge in balancing torque and thrust, use of complex bits, tool workpiece friction, delamination of workpiece, burr formation, development of micro cracks, strength requirement of the drill bit at that scale, rigid clamping requirement of tool and workpiece, complex tool preparation, etc. On the other hand, laser drilling especially, the ultra short pulsed laser drilling, apart from water jet drilling, is by far the most popular process for drilling of micro holes in glass specimen. Recently, an attempt was made to drill micro holes of diameter 0.4 mm to 1.2 mm through laser drilling by Wang et al. (2014). Laser drilling is sophisticated, in general, induces high energy thermal stresses, causes hole taper, has limited aspect ratio and costly to operate at the micro regime.

Abbreviations: ASTM, American society for testing and materials; B, brewsters; CCD, charge coupled device; FEM, finite element analysis; GaP, gallium phosphate; GHz, giga Hertz; HAZ, heat affected zone; HRA, rockwell hardness on scale-A; LED, light emitting diode; LMH, localized microwave heating; Na_2O, sodium oxide; R, retardation; RGB, red–green–blue; SBR, stress birefringence; SCA, spectral content analysis; SiO_2, silicon oxide; VGA, video graphic array.

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http://dx.doi.org/10.1016/j.jmatprotec.2015.05.026
0924-0136/

Nomenclature

Symbols

D	Distance between two fringes
F	Material fringe value
G	Distance between grid array
K	Stress optic constant
n	Order of the fringe
N	Fringe order
S	Distance between work specimen and image grabber
t	Thickness
$\tan\delta$	Loss tangent
L × B × H	Length × breadth × height
ϵ_r	Dielectric constant
μ	Refractive index
σ	Stress
λ	Wavelength

In both the processes, formation of heat affected zone (HAZ) is however predominant. In conventional drilling, the HAZ was due to friction between the tool and the workpiece; whereas, in laser drilling it was due to the generated heat. A better control of HAZ in laser leads to better quality of micro holes; whereas in conventional drilling, it leads to cracking in the work material like glass. Unlike conventional drilling, laser is also a contactless dry drilling, which induces less mechanical stress as compared to thermal stresses.

Micro holes in glass are required in many applications. These include light biotechnology, weight optics, about 0.8 mm holes in solar panels, wafer chucks, bus bars, etc. Glasses are found better than the metallic materials in terms of their low thermal expansion, less chemical reactivity, high transparency and high rigidity. However, fabrication of precise and high quality micro holes in glasses is a big processing challenge. The microwave drilling is a thermal-based drilling approach being investigated in the recent times by few researchers like Jerby and Dikhtiar (2000), Jerby et al. (2004), George et al. (2012), and Lautre et al. (2014a,b, 2015). The ablation of work material in microwave drilling does take place mainly because of two stage interactions. These interactions are of the tool material with the microwave radiation, which produces plasma and consequently the interaction of the plasma with the workpiece material. The ability to control these interactions primarily decides quality of the drilled hole. At the same time, Alhekail (2001) emphasized on ensuring that the interactions are performed in an enclosed atmosphere (applicator). While considering microwave material interaction, there are basically three different types of materials – transparent, absorptive and reflective. Upon irradiation, different types of interaction take place with characteristically different type of work material. Fini and Breccia (1999) showed the importance of microwave–material interaction and a few consequences. In microwave drilling, the interactions inside the applicator play a crucial role in performance of the process and quality of the drilled holes. In most of the cases, the work piece experiences a high thermal stress during the interaction with the plasma and gets fractured. The stress analysis due to microwave plasma heat thus becomes an important aspect to prevent the occurrence of cracks and hence material failure.

The method of photoelasticity is being effectively used for study of fracture. The method is used to analyze the surface measurement after the occurrence of the fracture. A photoelastic effect is observed when the stressed glass specimen is kept under light emitting diode (LED) light source (considered $\lambda = 0.565\ \mu m$ for calculation) and screen through a linear polarized lens. The stressed region shows a distorted rainbow like effect depending upon the residual stresses induced in it. Khanna et al. (2004) used an open mode stress field equations to model the isochromatic fringe patterns according to orthotropic stress-optic law. A different method of separating principal and normal stresses is modeled through single boundary pixel. Ashokan and Ramesh (2009) showed the relationship of isochromatic line in terms of the principal stress difference while the isoclinic line in terms of principal stress direction. A 3D photoelastic method was tried by Aben et al. (2000) for two different cases of weak birefringence and constant principle axes, to find the complete stresses. The authors have identified the problems of implementation and application of the photelasticity method in determining the whole field stress. A phase shifting method was used by Ramji and Ramesh (2008), to find the isoclinic lines through plane polariscope (phase shift between electromagnetic component in 2D is zero) and isochromatic lines through circular polariscope (phase shift between electromagnetic component in 2D is $\pi/2$). In this work, the possibility of use of monochromatic and white light was highlighted along with the three methods in white light photoelasticity. The method explained were the spectral content analysis (SCA), the RGB (red–green–blue) photoelasticity and the phase shifting methods.

The use of white light photoelasticity is supported for minimum interface between the isoclinic and isochromatic lines. The white light is generated for a continuous and discrete spectrum by incandescent and fluorescent lamps, respectively. The discrete fringe order (12 fringes) as discovered by Ajovalasit et al. (2007), as more than the continuous spectrum (6–7 fringes) during all trial experiments. Later, an attempt was made by Ajovalasit et al. (2012) on a tempered glass specimen to estimate residual stresses using RGB photoelasticity approach. A crack tip stress field of thin glass was measured with charge coupled device (CCD) of pixelated array, through instantaneous photoelasticity. The stresses were further determined from the phase map of retardation by Sakaue et al. (2008). The study has revealed that it was difficult to predict the direction of the quenching cracks with the approach.

In general, residual stresses are claimed for stationary and equilibrium to surrounding specimens. Residual stresses are difficult to predict; during service, they merge with other stresses to cause detrimental failures. Withers and Bhadeshia (2001) discovered that the generation of compressive residual stresses is usually due to rapid cooling. The authors attempted quantitative measurements of residual stresses on the GaP (Gallium phosphate) crystal using photoelasticity. The isochromatic lines of zeroth order retardation were determined for two different wavelengths (0.55 and 1 μm). The results identified residual and principal stress lines along the pulling direction and were confirmed with piezo-optical approach. Kotake et al. (1980) also observed the zeroth order of retardation as very independent of wavelength and its appearance is always at the same spot. Beghini and Bertini (1998) used a hole drilling method in lieu of photoelasticity to find residual stresses. In this method, strain gauges are fixed near the hole to be drilled to measure the stresses as per ASTM (American society for testing and materials) standard *E* 837-95. However, photoelasticity based method is considered more effective to measure residual stresses in the transparent brittle work material like glass, as this method eliminates the need for additional hole drilling.

In this study, the residual stresses induced in glass during microwave drilling were analyzed qualitatively using the photoelastic approach. An interaction between a reflective nichrome tool and transparent glass workpiece was established via hot plasma generated by microwaves at different input power. The cracking of glass, while drilling a hole was identified using the fringe pattern obtained through a photoelastic setup. It was attempted to correlate the results with the distortion on the glass, which are responsible for the development of cracks and eventual failure of the work material in drilling process.