Defect Minimization in Microwave Drilling of Glass Using Dielectrics

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Abstract

Microwave drilling is achieved by concentrating microwave radiation in the proximity of the target material with the help of a thin metallic concentrator, also called a drill. The incident microwave radiation then causes ionization of the surrounding air giving rise to formation of plasma at the tip of the concentrator. Thus, the material in the vicinity of the concentrator gets either melted/ablated leaving behind a crater. A continuous feed of the material/tool causes drilling of the target. However, due to thermal shock, poor thermal conductor and brittle material like glass exhibits frequent cracking during the machining. This paper presents a technique for minimizing defects like overcut, taper, cracks during microwave drilling of borosilicate glass at 2.45 GHz. A few materials, like coconut oil, EDM oil, Transformer oil etc., with different dielectric properties were used at the tip of the concentrator (tungsten carbide) to make the plasma confined to a narrow drilling zone. This makes energy transfer more effective and rapid. Consequently, damages on the target material get reduced significantly. It has been found that as the emergent depth of the concentrator into the dielectric was increased, defects like taper, overcut got decreased in all dielectric media. The best result was obtained in case of transformer oil; but the drilling time required was relatively more. The study was carried out while drilling 1100 micrometer thick glass plates using 600 micrometer drills at 900 W in a domestic microwave applicator. The holes were characterized in terms of taper, overcut and crack.

Keywords: Microwave, Glass, Dielectrics, Defect, Emergent depth.

1. INTRODUCTION

Electrically non-conducting materials like glass are becoming increasingly popular in semiconductor and microelectronics industries, biochemistry and medical fields, particularly in the manufacture of micro fluidic devices because of their inertness, optical characteristics and biological inactiveness respectively. Some promising applications for glass in the micro-electro-mechanical Systems (MEMS) field are micro accelerometers, micro reactors, micro pumps, and in medical devices are flow sensors, drug delivery devices. So, while glass is often a strong material choice, the machining of glass for those applications poses a set of unique challenges like crack free machining and heat affected zone (HAZ) free thermal processing.

Prior to 1996, microwave energy at 2.45 GHz was mainly used for heating and sintering purposes but for the first time, microwave energy was used in the year 1996 to drill hole through ablation of workpiece material [1]. But for the first-time effective drilling was reported in 2001 by Jerby et al. [2]. The authors concentrated the microwave radiation at the tip of the near-field concentrator. Due to localized concentration of microwave, plasma was generated at the tip of microwave drill, also known as concentrator (small monopole antenna) and a hot spot was created at the material's surface just beneath the concentrator and the concentrator was made to penetrate into the hot spot while simultaneously ablating the material [3]. In the process, a hole in the workpiece gets created along the path of the concentrator. The smallest hole of 0.5 mm was reported to be drilled in approximately 1-mm-thick soda lime glass plate; however, accuracy and imperfection were matter of concern. Another study however reported that with the pre-and post-heat treatment of glass, crack can be avoided [4]. Later, in 2002, a theoretical model for coupling thermal-electromagnetic phenomena was developed during microwave drilling in alumina and mullite. It was observed that the electromagnetic waves modified the dielectric properties of the material which is temperature-dependent, and formation of a hot spot takes place beneath the tool tip [5]. It was reported that the temperature increases gradually up to a certain level after which a sudden increase in temperature takes place which causes a local hot spot and melting of the material beneath the tool tip that enables penetration of tool. In the year 2004, Jerby et al. had shown selectivity of the microwave drilling process by drilling a hole only in the ceramic layer of the ceramic thermal barrier coating without affecting the metal [6]. In the year 2006, microwave drilling in bovine trabecular and ovine tibias of bone was reported by E. Jerby et al. by using microwave power of 150–200 W within 2–5s [7-8]. In the year 2012, Titto et al. developed a setup using spring-loaded rugged steel tool and cement-coated drilling fixture. Holes were drilled in materials like aluminum, copper, mild steel, animal bone and glass at 600–900 W but no nailing was reported although quality was not good [9-10]. Titto et al. also tried to drill hole with copper drill bit which was attached to the end of the coaxial cable. They reported that coaxial system was appropriate for only low power application [9]. In 2014, Lautre et al. used a Litz wire coax as a monopole which acted like a drill bit and reported drilling blind hole on perspex material [11].

Lautre et al. reported drilling of micro holes in perspex using a nickel coated steel wire of diameter 0.45 mm as a drilling tool in the microwave applicator at 2.45 GHz, 700 W in 60 s using gravity feed method. Drilling of micro-holes on perspex of diameter 0.5 mm up to a depth of 5 mm with 0.5 mm overcut was reported [14]. Later, drilling on soda lime glass plates (thickness: 1.2mm) was reported in which the movement to the copper drill (ϕ800 μm) was due to gravity [13]. It was reported that microwave processing of glass is a challenging task as thermal stresses are generated during the drilling process that eventually causes cracking. In order to reduce the thermal stresses in the drilling zone, it was also attempted to change the interface of the drilling zone by applying different surface

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precursors and hence to minimize cracking. It was observed that cracking due to the thermal shock on the glass specimen got reduced due to suitable application of a dielectric precursor. The best result was obtained with glycerin and perspex precursors in terms of crack control with minimum HAZ because the liquid precursor attenuates the heat energy prior to reaching the glass specimen. The precursor acts as a microwave absorber and reduces the induced thermal stress in the drilling zone, however, less viscous precursors cause damage to the surface to be drilled due to microwave sputtering and plasma heat [12]. Typical simulation studies using COMSOL Multiphysics 4.4 revealed that the tool with the conical tip of 14° included angle and 3.49 µm skin depth could generate a plasma sphere of ϕ28.1 µm. They noticed thermal imbalance at the HAZ as the prime reason for circular crack around the tool; the linear radial crack on the other hand occurred due to relatively cool tool surface at the interior of HAZ [13,15].

In the above research work, drilling with the help of tool electrode were carried out in the air. Due to this, thermal energy produced due to discharge at tool tip doesn't get concentrated at the tip of tool. Brittle material like glass exhibits frequent cracking during the machining in air due to thermal shock, poor thermal conductor. These defects can be minimized by using a few materials, like coconut oil, EDM oil, Transformer oil etc., with different dielectric properties at the tip of the concentrator (tungsten carbide). Due to this, the plasma gets confined to a narrow drilling zone. This makes energy transfer more effective and rapid. The objective of the present work therefore is to find out whether use of few materials, like coconut oil, EDM oil, Transformer oil etc., with different dielectric properties at the tip of the concentrator (tungsten carbide) can minimize the defects like crack, thermal damage, taper, overcut etc.

2. EXPERIMENTAL SET UP

A 900 W domestic microwave applicator (model: LG Solar DOM) was used to perform the drilling experiments. The drill tool material used was tungsten carbide with diameter 600 µm and cylindrical tip. Fig. 1. shows the schematic of microwave drilling. The size of borosilicate glass plate was 76x26x1.2 mm. Four different liquids: - Coconut oil, Transformer oil, EDM oil, Palm oil were used as dielectrics liquids. The thermo-physical properties of different dielectric liquids are shown in Table 1. In this experimental set up, drill is held in pen vice and is kept just above the work piece with the help of jig. Here, the tool is dipped in the different dielectric liquids up to a certain depth, called as emergent depth. making energy transfer rapid and efficient.

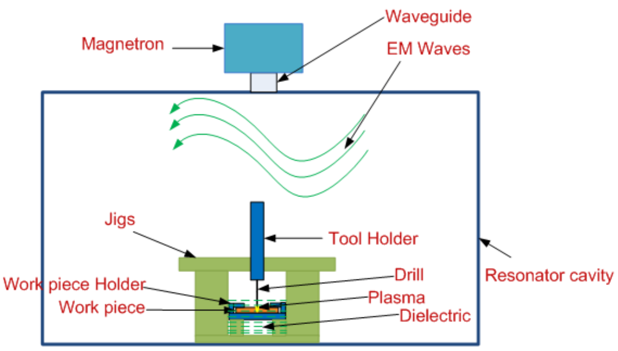

Fig. 1. Schematic diagram of microwave drilling

Table 1: Properties of different dielectrics used [16-22]

Dielectrics:	Transformer oil	EDM oil	Coconut oil	Palm oil
Density(kg/m^3)	873	769.29	937.16	864.42
Prandtl No.	291.04	22.12	137.76	618.86
Specific Heat (J/kgK)	2382	2010	2100	1848
Thermal Conductivity (W/mK)	0.110	0.149	0.5	0.1726
Absolute Viscosity (Ns/m^2)	$13.44*10^{-3}$	$1.64*10^{-3}$	$32.8*10^{-3}$	$57.8*10^{-3}$
Flash Point (^0C)	140	126	295	323
Dielectric Constant	2.1	1.8	2.9	1.8

3. MATERIAL REMOVAL MECHANISM

Material removal mechanism of microwave drilling has been shown in Fig. 2. In the presence of electromagnetic field, the free electrons on the electrode surface get concentrated at the tip of tool which results in increase in charge density. If the electric field intensity increases beyond the ionization potential of dielectric medium, ionization of surrounding dielectric medium takes place which is seen as plasma discharge. When these plasma discharge takes place near the vicinity of workpiece, a part of the material of the workpiece gets ablated and some part where temperature is not sufficient to ablate get melted. In this set-up, tool is given the gravity feed. After the material beneath the tool is ablated or melted, tool penetrates into work piece and creates a hole.

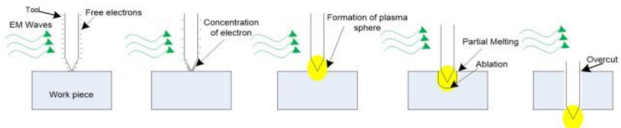

Fig. 2. Material Removal Mechanism

4. RESULTS AND DISCUSSIONS

4.1. Surface integrity

Fig. 3. shows hole drilled in borosilicate glass using different dielectrics at different conditions. Fig. 3A. shows hole drilled using coconut oil as dielectric fluid. There are circular cracks

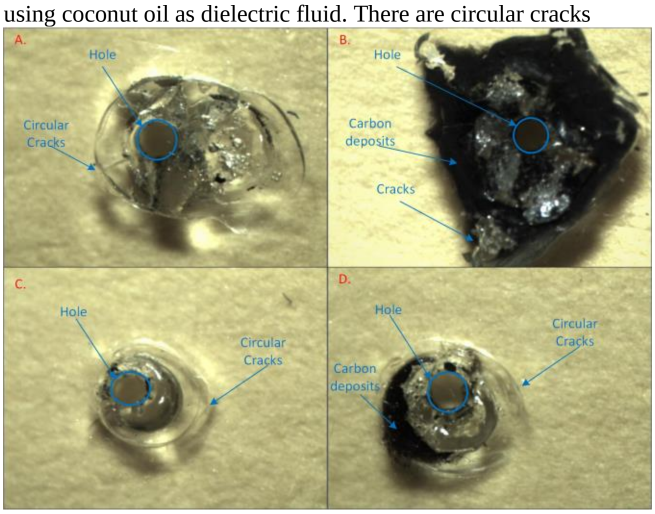

Fig. 3. Hole drilled in borosilicate glass immersed in A. coconut oil B. EDM oil, C. Transformer oil at an emergent depth of 25 mm and in D. Palm oil at an emergent depth of 5 mm when exposed to microwave for about 5 sec.

present around the hole but it has almost negligible carbon deposits around hole as compared to hole drilled using EDM oil as dielectrics shown in Fig. 3.B. which shows severe carbon deposits at its surface. There are also some carbon deposits around the hole drilled using palm oil as dielectrics shown in Fig.3D. This happens because these all oils contain hydrocarbons and hydrocarbons in EDM oil and palm dissociates easily at the machining condition thus marring down its surface integrity. In case of transformer oil, cracks are very less around the hole shown in Fig. 3C. as compared to others dielectrics due to its better heat dissipation capacity from the surface of the workpiece. Circularity was observed to be better in all dielectrics. In case of palm oil, if the emergent depth is increased beyond 5 mm, surface of hole quality deteriorates severely and if exposed for longer period, the glass plate breaks. This happens because palm oil has low dielectric constant and low specific heat capacity value. As the time of exposure increases, temperature of oil increases rapidly and thus value of dielectric constant decreases. Due to decrease in the value of dielectric constant, microwave energy at tool tip increases significantly.

4.2. Thermal damage

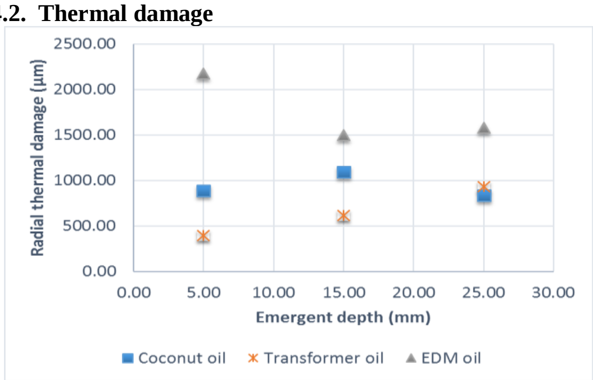

Fig. 4. Comparison of thermal damage during drilling in different dielectric medium

From the Table 1, we can see that Prandtl number of EDM oil is low. Due to low value of Prandtl number, thermal diffusivity is high consequently heat transfer through conduction dominates and thermal conductivity of EDM oil is lower than the glass. Heat energy produced due to plasma doesn't get transferred from source location to other region easily through oil. Rather, most of the heat transfer does take place through glass and causes thermal damage. It is seen from Fig. 4. that radial thermal damage in case of EDM oil is more as compared to other dielectrics. As the emergent depth increases, microwave energy available at tool tip decreases and hence thermal damage tends to decreases. As transformer oil has the highest specific heat among dielectrics attempted as well as higher prandtl number, heat transfer from the surface of workpiece will be more efficient due to better heat absorbing capacity of liquid and stronger natural convection. Hence, thermal damage is least as compared to the others.

4.3. Radial Overcut

In case of transformer oil, overcut at the entrance decreases as the emergent depth increases as shown in Fig. 5. As the emergent depth is increased, microwave has to travel more distance before reaching to the tool tip. Therefore, plasma energy density decreases and also with the increase in the emergent depth, shape of plasma becomes more confined. Hence the radial overcut decreases with the increase in emergent depth. But in case of coconut oil, overcut at entrance and exit decreases as the emergent depth increases and beyond 15 mm, it again starts to increase in case of coconut oil as shown in Fig. 5. Decrease in overcut up to 15 mm is due to confinement of plasma to the tool vicinity region and decreased plasma energy density. But after increasing the emergent depth beyond 15 mm overcut increases because of increased plasma energy density. Plasma energy density may increase because as the temperature of the dielectric fluid increases, dielectric constant decreases and hence more microwave energy at the tip of tool.

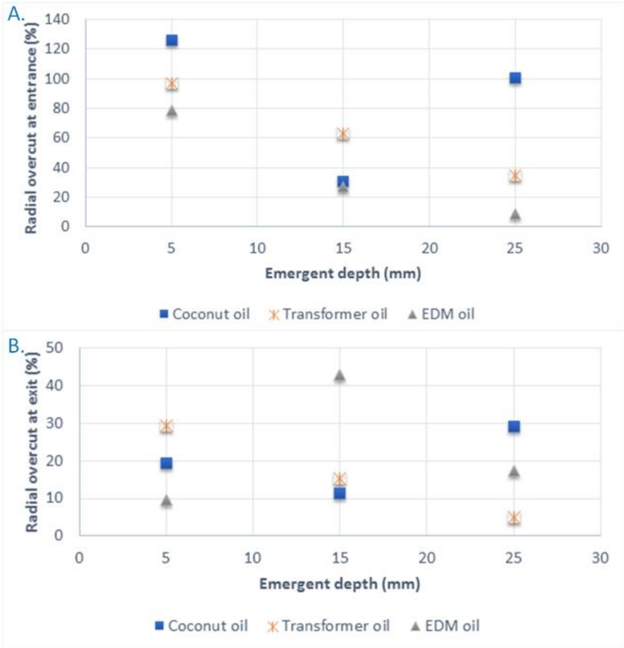

Fig. 5. A. Variation of radial overcut at entrance and B. radial overcut at exit as a function of emergent depth

In case of EDM oil, overcut at entrance decreases with the increase in emergent depth but overcut at exit increases up to 15 mm and then decreases beyond 15 mm. Increase in overcut at exit may be due to decrease in dielectric constant of EDM oil due to increase in temp. of dielectrics due to its heating by microwave. But after 15 mm again overcut decreases because of dissociations of hydrocarbon present in oil. Dissociated hydrocarbons gets mixed with oil and thus increases the dielectric constant. Due to increase in dielectric constant of dielectrics, microwave energy at tool tip decreases and thus overcut decreases. Compared to all, overcut at entrance is the lowest in case of EDM oil as EDM oil has the lowest viscosity among all. The least viscosity enables EDM oil to reach the machining zone faster and helps in effective flushing.

4.4. Taper

The increase in entrance diameter of the hole at lower emergent depth has a greater effect on the hole taper than the exit diameter due to high machining rate initially. As the top surface of the work material is exposed to the discharges for a longer period of time, more material is removed compared to the bottom layer. The hole taper decreases with the increase in emergent depth as shown in Fig. 6. because higher the emergent depth, lesser will be microwave energy available at the tip of

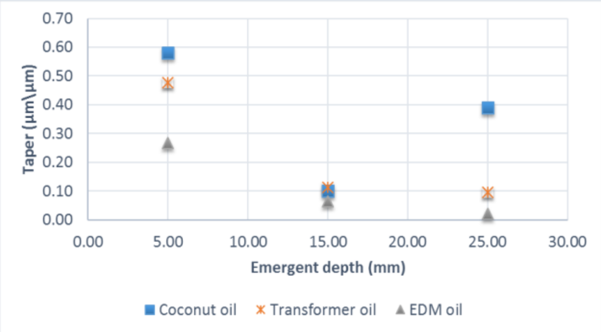

Fig. 6. Variation of hole taper with emergent depth

intensity plasma sphere which results in low overcut as shown in Fig. 5.

5. Conclusions

The following conclusions can be drawn from the present study:

- Higher the value of specific heat as well as Prandtl number of the dielectrics, better is the hole quality due to better heat dissipation from the surface of the workpiece.
- As the emergent depth is increased, defects like overcut, taper etc. decreases due to decreased plasma density and confined plasma sphere
- Thermal damage is the least in case of oil having higher Prandtl number as heat transfer from work piece surface takes place efficiently.
- Higher the value of specific heat of oil, lesser is the overcut and taper.

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