Performance of Monopole Concentrator during Microwave Drilling of Perspex

Nitin Kumar Lautre[1*], Apurbba Kumar Sharma[2], Pradeep Kumar[3], Shantanu Das[4]

[1,2,3]Department of Mechanical and Industrial Engineering, Indian Institute of Technology Roorkee, Roorkee, Uttarakhand, India -247667.

[4]Reactor and Control Division, Bhabha Atomic Research Center, Mumbai, Maharashtra, India.

E - Mail: [1*]nfl_123@rediffmail.com, [2]akshafme@gmail.com, [3]kumarfme@iitr.ac.in, [4]shantanu@magnum.barc.gov.in

Abstract

The applications of microwaves in engineering has been fast expanding, one such area is micromachining and micro-fabrication. A series of experiment with different types of concentrator (steel, copper and nichrome) wascarried out. Different machining conditions like variable power, location and movement were considered. The drilled hole shows development of three differentheat affected zones (HAZs). The performance of the process was evaluated in term of the residue diameter, HAZ diameter and the hole diameter. Energy Dispersive Spectroscopy (EDS) and field emission scanning electron microscope (FESEM) were used to assess the zone and damage of the monopole concentrator used as drilling tool. The drill bit damage in its length was controlled with careful selection of process parameters. An optimum processing condition was determined experimentally, for minimum residue generation, minimum HAZ and minimum oversize of drilled holes. The depth of through hole in perspex material was maintained constant at 2 mm.

Keywords: Microwave, Drilling, Concentrator, HAZ, EDS, FESEM.

1Introduction

Microwave energy is very popular in the area of food processing industry. Over the years it is being attempted to expand the scope to process materials, unfavourable to microwaves. The effectiveness of the process is based on the effective interaction of the microwaves with characteristically different materials. Application of microwaves is thus being explored in melting, drying, sintering, joining, cladding, casting and drilling.

Most of the earlier works were focused on microwave drilling of ceramics and metals (Jerby et al., 2004). Wylie et al. (2006) drilled hole on masonry using tungsten bit. The drilling was performed through waveguide in a microwave safe chamber at 800 W. However, drilling of low melting point transparent material (e.g. perspex) using microwave energy is yet to be well investigated. Conventional drilling on the other hand has a critical role of designing, manufacturing and setting up of the drill bit. Most of the conventional drilling of perspex related material is related to proper parameter design and selection of drill bits. As diameter of drill reduces in size the length of the drilling also reduces which poses limitation on the aspect ratio of the holes to be drilled. The frictional heat generated between tool and the delaminations of perspex are very common problem encountered in conventional drilling.

Some of the work, on perspex drilling is attempted with laser ablation. However, the method has inherent problems of creating non-cylindrical holes from entry to exit. Other problems include high cost, wide and complex parametric settings, variation in effect of penetration per pulse and low aspect ratio of the drilled holes. Berrie and Birkett (1980) have used CO_2laser to drill and cut the perspex specimen at 400 W. Tokarev et al. (2000) performed drilling on polymers with multipulse eximer UV laser. Truong et al. (1994) have studied the dielectric properties of polymer composites at microwave frequencies ranging from 2 to 18 GHz. Masmiati and Philip (2007) obtained good quality holes on polymers through selection of significant laser parameters by applying design of experiment tool. Davim et al. (2008) showed the complex 2D cutting of perspex by CO_2laser by varying power and cutting velocity. The HAZ formation was in the range of 0.12 to 0.37 mm, on a specimen of 6 mm thick perspex. There was an additional advantage of producing burr free holes, low surface roughness and good process repeatability. The laser power was in the range of 250 to 650 W and cutting velocity varied from 1.5 – 3.5 m/min. Abdulnabi et al. (2011) drilled hole in perspex of 2.5 mm thick at 5 W using 1064 nm diode laser. It uses 1 W for about 2.5 s for generation of good quality hole without any assist gas. Romoli et al. (2011), machined perspex using CO_2laser for miniaturized microfluidic devices. The controlling laser parameters were incident power, scanning speed and spot diameter. It is clear from the drilling work on perspex using thermal ablation that the work is limited to laser processing. The process being practiced most widely, suffers several deficiency while in operation. However, the use of microwave energy for drilling hole as a potential technique can be explored in order to reduce the complexity and defects. Microwave drilling is found capable of providing high aspect ratio holes when not much choice for drilling microholes through thermal ablation of low melting point material is available.

This paper presents results of a series of experimental details with three microwave reflective concentrators. The experiments are performed at different power setting within a range of 90 – 900 W, at 2.45 GHz frequency (wavelength of 122.4 mm). The performance of microwave drilling is categorized on the basis of three distinct regions formed post drilling on the perspex specimen. The factors affecting the performance are analyzed under microscopy.

2 Selection of concentrator and work specimen

The selection of monopole concentrator is based on the theory of generation of sparks. Simultaneously, while generating sparks, heat is generated; this attracts the microwaves inside the cavity resonator. The most common suitable microwave reflective materials for concentrator were common conductive metals (Lautre et al., 2014). The transmission losses in these materials are measured by Maxwell (1947) in waveguide and through measurement of resonant cavity Q-factor. The attenuation of some of the popular material at 2.45 GHz microwave frequency is shown in Figure 1. Steel, nickel and copper were found with good attenuation and better availability. Aluminium faces the problem of formation of extra oxide and results in easy deformation of the bit. Gold and silver are expensive and more reflective in microwave process. In the present work steel, copper and nichrome were selected as drill bit concentrator.

Copper faces the problem of formation of oxide and porosity at elevated temperature. Lazarus (2013), found at about temperature of 275 ^{O}C, copper oxide reaches tenacity and restricts further oxidation. Nickel avoids carbide formation and dissolves carbon at elevated temperatures. Alloying is found to be an option to reduce the oxidation as observed in nichrome concentrator. The property of better reflectivity of steel and nichrome constitutes a suitable material for the drill bit. The diameters of the drill bit used are 0.8 mm and are clutched in a jig. The jig provides an extra weight of 15.56 g to propel the tool through the work specimen.

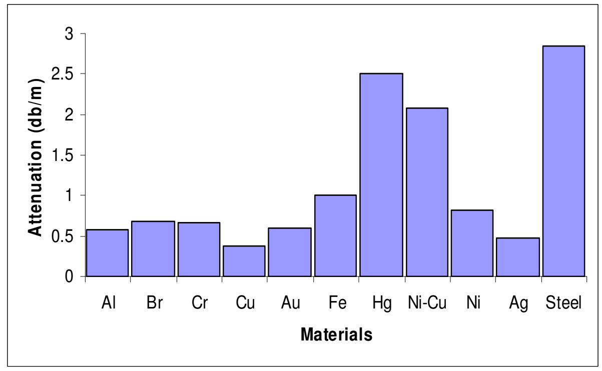


Figure 1 Relative attenuation of different material

The perspex ($C_5O_2H_8$)nas a thermoplastic work material has abundant applications in various industries. The application ranges from food processing to supporting parts manufacturing to micro equipment fabrications. Perspex is a favorable replacement for glass in terms of its strength, weight and durability. Truong et al. (1994) had showed the unique electrical and optical properties of perspex, which paved its way to be used in optics and microelectronics application. The dielectric parameters permittivity (real and imaginary) and loss tangent of perspex, increase with conductivity. Even the rate of degradation is observed to be occurring at a very small temperature range (197 to 227 ^{O}C, Berrie and Birket, 1980). The activation energy was found to be varying from 28 to 32 kcal/mole. The low thermal diffusivity of perspex helps to disperse the heat slowly in material. It does not hinder microwaves to form the hot spot at the bit tip. The other physical properties of perspex are shown in Table 1.

Table 1 Different properties of perspex

Property	Value	Unit
Melting/ Boiling point	160/ 200	^{O}C
Density	1.19	g/cm^3
Rockwell Hardness	102	M Scale
Tensile/ Flexural strength	75/ 116	MPa
Elongation	4	%
Flexural Modulus	3210	MPa
Poisson Ration	0.39	--
Thermal diffusivity	0.0006	cm^2/s

The other commonly used and widely used thermoplastic is polyethylene. The blocking of radiation by liquid phase and energy degradation in most of the polyethylene creates problems. The properties like inertness, no hydrolysis, high absorption (0.92) of infrared frequencies and good machined quality favor selection of perspex over other thermosets as per Romoli et al. (2011). It is shown by Holland and Hay (2002) that, the perspex remains in the solid glassy state till reaching the temperature of 115 ^{O}C. Table 2 shows the changes occurring in perspex when subjected to heating. Low heat capacity and low heat conductance of perspex support the rapid temperature rise.

Table 2 State change in perspex with temperature

Temperature (^{O}C)	Perspex state
< 27	Solid
115 - 160	Moldable
> 350	Thermal cracking
<380	No polymerization
>460	Vaporization

3 Experimentation

A line diagram of the setup for microwave drilling is shown in Figure 2. It houses a magnetron which produces microwaves in a microwave safe cavity. The work support is of refractory brick and acts as a microwave absorber. In addition, it also provides a dummy load, so that microwaves do not get returned or reflected back to the magnetron. The interaction of reflective and transparent material is fine tuned in terms of their volume, bit feed, microwave power and time. The tool head was specially made conical (Figure 7(a)) to have maximum possible skin depth at the tip. The tip helps to form a plasma ball of hot region to remove material and continuously attract the microwaves at the tip.

Hill and Marchant (1996) expressed the hot spot as a material specific property caused due to microwave irradiation. The hot plasma is temperature dependent that can be due to a small temperature rise, and sufficient to attract microwaves. Small edge or corner and the higher thermal absorption at elevated temperature help to retain the hot plasma. The setup volume and relative positioning of drilling zone was well simulated in COMSOL Multiphysics software (version 4.4.0.195), as per the approach highlighted by of Lautre et al. (2013). The drill tip was placed over the perspex. The workpiece was freely supported on the refractory brick. The bit feed is gravity controlled and the weight adjustment was done on the jig appropriately. The time of microwave impingement on the perspex specimen is less than a minute. The power was varied from 90 W to 900 W in steps (180 W, 360 W and 600 W). The perspex specimen was cleaned in acetone before placing in the setup. The wear of the monopole bit was recorded under field emission scanning electron microscope (FESEM).

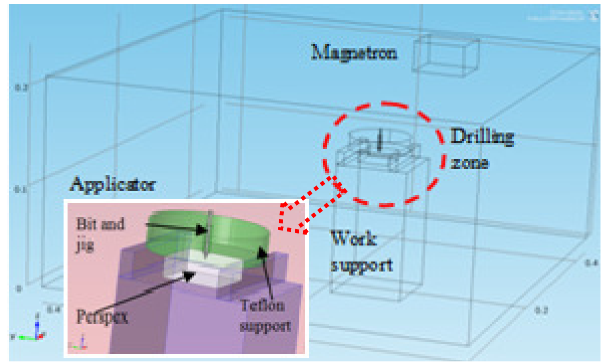


Figure 2 Scheme of the experimental setup used for microwave drilling (inset: Aspect of drilling zone)

Continuous hot spot was created at the bit tip on the perspex. The temperature of this irradiated spot shoots up with thermal runaway to melt the perspex. The melting results in degradation of perspex to monomer after reaching its boiling temperature. The behaviour of microwave in the cavity is dependent on various settings. Many a time, the experimental trials result in burning of perspex or tool. It can be further prevented by fine tuning the experimental and design parameters through practical observations and simulation.

4 Results and discussion

Microwave drilling generates three unique regions of heat affected zone (HAZ), on the perspex workpiece, as schematically shown in Figure 3. The regions are due to hole formation (H), residue pileup (P) and HAZ (Z). Theseregion forms a circular or near circular profile, of which residue pileup is found least circular.The residue ejection in drilling is well explained by Kudesia et al. (2002). The melt ejection is due to the vapor pressure created inside the cavity. The residue material being softer than the work specimen usually forms porous material, as shown in Figure 4. The larger spherical pore shows lower molecular weight, lower viscosity, lower density and vice versa. Nayak et al. (2008), claims that the formation of bubble and its bursting results in development of pores. The bubble formation is dependent on the oxygen component of the perspex. The release of CO, CO_2gases as small molecules leads to higher porosity.

On the monopole bit, the electric losses take place due to current flowing in the metals. Copper material gets oxidized very frequently and increases the electric loss at high frequency. A small diameter copper tool bit very often gets adhered to perspex due to its oxidation. The molten material gets accumulated in the pores of copper bit. The adhesion of polymer with perspex is higher for copper than steel and nichrome bit. Copper of small diameter is not found suitable for perspex drilling as it becomes softer after getting heated. Thus, the copper bit disturbs the drilled geometry.

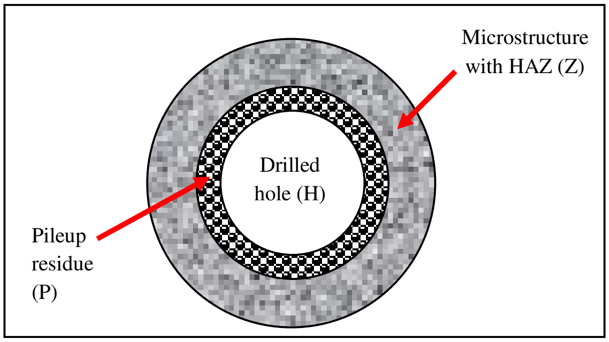


Figure 3 Different region generated after microwave drilling on perspex specimen

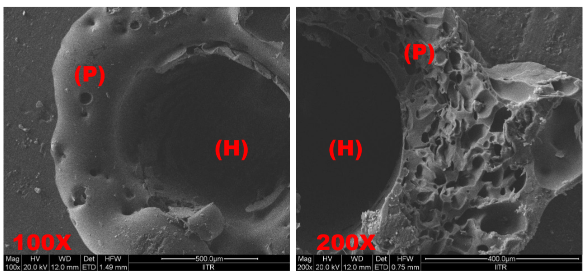


Figure 4 Enlarged views of microwave drilled holes

The holes drilled by steel and nichrome bit are shown in Figure 5. The holes drilled by steel bit are better than that of nichrome bit. The surface damage and burning were observed more with nichrome bit. Vaporization of perspex by hot plasma is very effective with steel bit. It results in formation of small residue pileup region on the perspex surface. The HAZ and average hole diameter variation at different microwave power is shown in Figure 6. The drill overcut by steel bit increases with the applied power. The relative variation of drilled hole is not much with increase of power levels. The average HAZ diameter is lowest corresponding to drilling power of 180 W. The residue diameter is always found in between the hole and HAZ diameter for small perspex thickness of 2 mm. The porous residue also appears almost circular around the drilled hole.

The result with nichrome bit shows high overcuts in comparison with the steel bit. The HAZ variation is not much even at different power level. This may be due to the heat conduction and high resistivity of the bit. The overcut was found to be minimum at 180 W and the drilled holes were constant at other power level. Mani et al. (2013) used 3 mm thick perspex to ensure a glass transition temperature over a small portion. It was focused to control the heat transfer rate accordingly, for minimum HAZ. In the present setup, the heat transfer rate is controlled with power setting; with steel monopole bit, it seems possible to control the hole and HAZ variation with proper power settings.

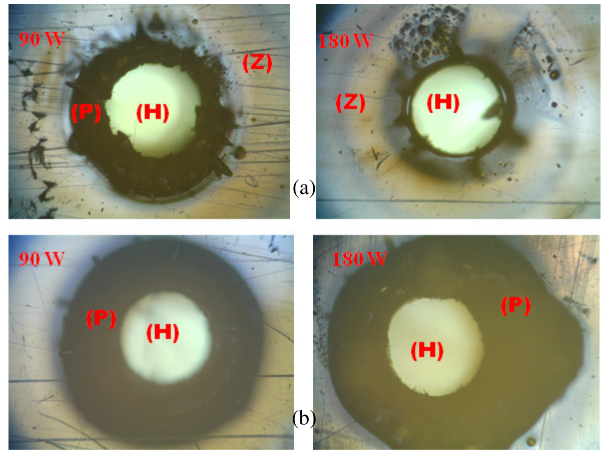


Figure 5 Microwave drilled holes with (a) steel and (b) nichrome bit at 50X magnification

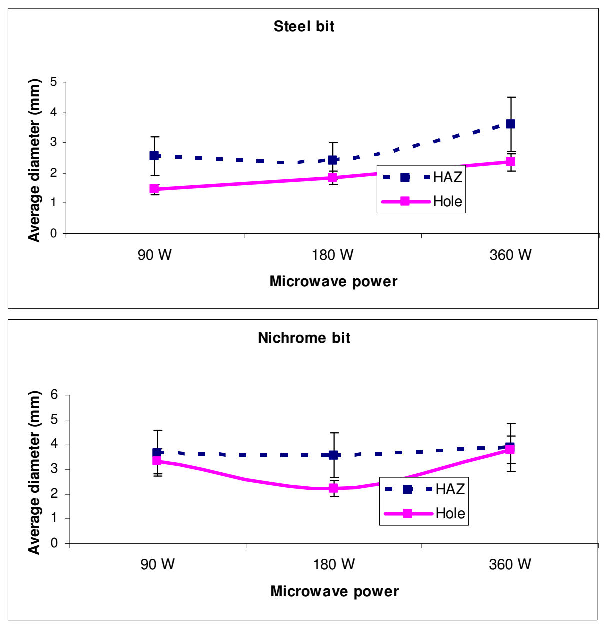


Figure 6 Average variation in size of HAZ and hole for drill diameter of 0.8 mm

As proposed by Hill and Marchant (1994), a typical 'S'-shape relationship exists between power and temperature in microwave heating. The relation is considered as multivalued power function due to role of thermal runaway and thermal rundown. The increase of microwave power to a critical power is steady state and thereafter it shoots up drastically and vice-versa. It imposes sudden rise of temperature and creates heat imbalance in materials. The dependence of thermal absoptivity and permittivity for microwave bit is in cubic power to the temperature. The inappropriate setting of power results in blunting or burning of monopole bit due to rapid temperature rise is shown in Figure 7. The blunt tool (Figure 7 b)) shows the trace of linear wear from the tool tip.

The monopole bit also suffers damage along its length and at the other end of the bit. For a copper monopole, the damage is shown in Figure 8. The spalling observed over the length is due to the oxidation of bit. Random burnout at the other end of bit is also observed, in case of ceasing of the hot plasma formation at the drill tip. In order to prevent burnout at the other end, the bit is clutched in reflective jig, which divert the microwaves by reflection.

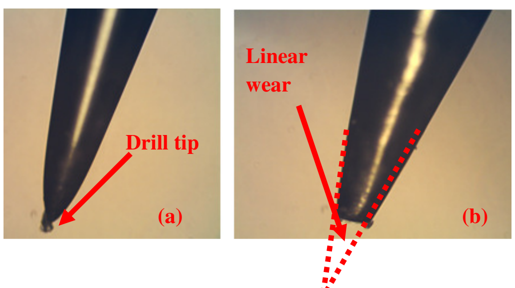
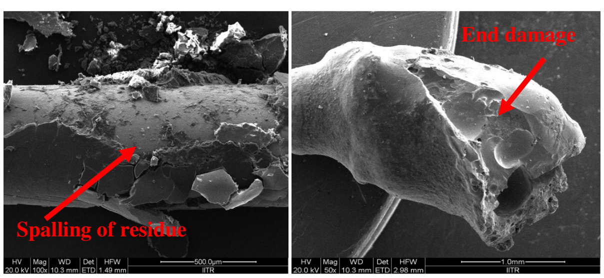


Figure 7 Stainless steel tool tip (a) before and (b) after drilling



(a) (b)

Figure 8 Damage noticed at (a) middle and (b) other end of the monopole copper concentrator

The interaction of bit with perspex starts with solid phase boundary. At elevated temperature, it interacts with molten liquid and vapors as per the state of hot plasma. At low microwave energy, the burnt drill bit tip gets transformed to spherical porous material. In case of low gravity feed the perspex gets welded to the monopole easily, as shown in Figure 9. The EDS analysis confirms the adhesion of perspex over the porous spherical tip. The starting perspex specimen contained carbon 63.74% and oxygen 35.57 %. The lump of the perspex around the tip has about 44.88% carbon and 54.69% oxygen. There is reduction in carbon content and increase in oxygen content due to oxidation assisted from surroundings and formation of CO_2.

The trials were carried out in the ambient atmosphere. The dielectric loss of air is low with high Q factor at high microwave energy. Air does not interact much with microwave but helps in oxidation of the process. The EDS spectrum of residue shows addition of foreign materials to perspex. These materials are found settled around the hole due to small wear of monopole bit as shown in Figure 10. The presence of small percentage of chromium (0.58%) and iron (0.40%), signifies the wear of alloyed bit. The residue has small drop in carbon (59.51%) and small addition of oxygen (39.51%). The rate of oxidation may be prevented in residue region by the reflection of settled nanoparticles from the wear of the bit.

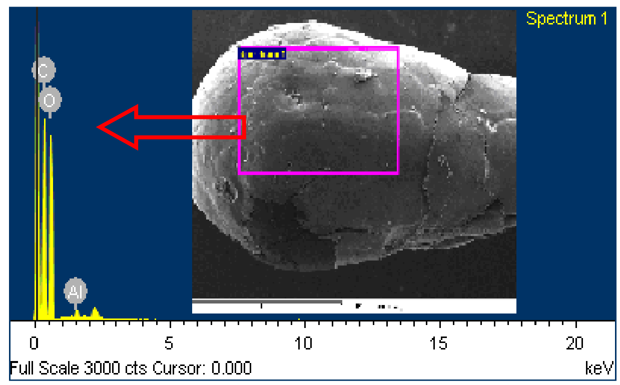


Figure 9 Bit tip covered with perspex

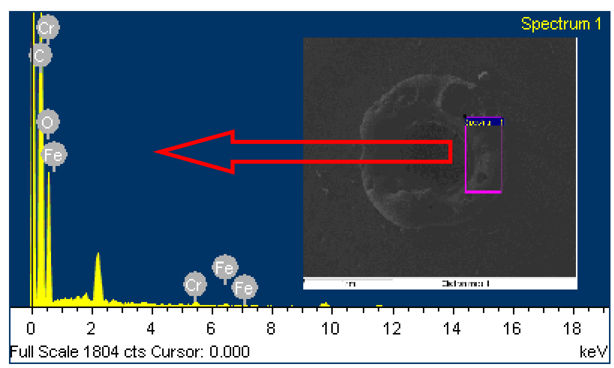


Figure 10 Typical EDS of residue

It is clearly seen from the experimental results that the residue material and HAZ is less for nichrome bit, but the overcut is beyond acceptable limit. The desired quality of hole largely depends on proper selection of microwave reflective material. The steel material monopole, act as a suitable bit to generate hot plasma and interact with microwave till the finish of the drilling process.

5 Conclusions

Microwave drilling on microwave transparent perspex is performed using three different drill bits. A through hole in the perspex of 2 mm thick was successfully drilled with microwave irradiation. Monopole steel bit was observed to be better than copper and nichrome bits. The performance of the bits was measured in terms of three different zones generated on perspex surfaces. Steel bit at 180 W was generating relatively minimal overcut, residue and HAZ. The ejected material was found to be porous. Addition of oxygen and traces of bit wear particles were present in the residue diameter.

The variation in HAZ generated by nichrome bit was almost uniform with varying power level.The nichrome bit, on the other hand, had provided large overcut, but appeared suited for large size hole drilling. The damage noticed on monopole bit was in terms of linear wear, burning at the hot spot, burning at other end of hot spot, sticking of perspex residue at the tip and oxidation of the bit. The drill bit damage over its length is found controllable with proper process parameter selection.

The microstructural changes in perspex were compared with variation in weight percentage of carbon and oxygen. The oxidation was predominant with the interaction of microwave energy. The applied microwave power affected the HAZ directly with steel monopole bit. This study revealed the interaction of characteristically different material under microwave by thermal ablation. The results, confirm that, the microwave drilling can easily be realized using the monopole concentrator and the process has enormous scope to compete with the conventional and laser drilling processes upon maturity.

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