MICROWAVE DRILL APPLICATIONS FOR CONCRETE, GLASS AND SILICON

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ABSTRACT

A microwave drill employs concentrated microwave energy to perform thermal drilling into hard, non-metallic materials. Besides drilling, microwave drill technology enables the insertion of pins and nails, as well as the performing of melting, cutting and jointing operations. This paper describes the underlying principle of the microwave drill and its experimental implementation, and presents various applications of microwave drill technology in various materials: concrete, glass, silicon, ceramics and basalt. The phenomena of thermal-runaway and hot spot generation by the microwave drill are simulated by a coupled thermal-electromagnetic numerical model.

1. Introduction

Microwaves are widely used in communication and radar systems. In addition, microwaves have a great potential, though not yet fully realized, in industrial, scientific, and medical (ISM) applications [1, 2]. Current industrial applications of microwaves include heating, drying, and material processing, such as ceramic sintering and microwave chemistry. The utilization of microwave energy for physically destructive purposes such as the crushing of stones, mining, tunneling, and concrete demolition has also been proposed [1, 3].

Recently published research reports the ability of microwave drills [4, 5] to create relatively delicate holes and cuts, down to 0.5 mm in diameter. The fact that these dimensions are much smaller than the microwave wavelength itself (12 cm at 2.45 GHz, for instance) is due to the characteristics of the near-field operation of the drill. This relatively new field of sub-wavelength microwave drilling has potential applications in various industries (e.g., electronics, ceramics, automotive, avionics and space), and in geological and construction work. This paper reviews the theory behind the microwave drill and presents its possible use with various materials.

2. The Microwave Drill Principle

The core principle of the microwave drill is to concentrate the generated microwave energy into a small spot, one that is much smaller than the microwave wavelength. This "focusing" effect is achieved by bringing a small monopole antenna into contact with the material to be drilled, as illustrated in Fig. 1. The microwave energy tends to localize underneath the material's surface in a thermal-runaway process. This generates a small hot spot [4] where the material becomes softer or even molten. The near-field antenna is then inserted into the molten hot spot to form the contour of the hole (thereby allowing the hole to have non-circular shapes, depending, naturally, on the shape of the antenna).

Depending on the application's purposes, the antenna's pin is then either pulled out after having formed the drilled hole, or left inside to stick out as a nail. This direct pin insertion procedure was found feasible for diameters of 0.5 - 5 mm, and up to 3 cm in depth. For larger diameter holes, e.g., in the order of 1 cm, or for deeper holes, the outer cylinder of the coaxial structure is made as a hollow reamer that is inserted into the hole and slowly rotated. In this manner, the device includes a mechanical means to remove any debris.

However, the microwave drill concept has some inherent limitations. From a technical standpoint, the method is not effective with metals (which reflect the microwaves) or with low-loss

materials (such as sapphire, which is transparent to microwaves). Radiation safety and electromagnetic interference (EMI) considerations may limit the availability of microwave drills in the consumer market. Therefore, these devices will probably see their main use in automated production lines in industrial plants where the safety environment can be controlled.



Figure 1. An illustration of the microwave drill's operating principle: the localized microwaves emitted by the antenna create a hot spot in the drilled body. The antenna pin is inserted as a drill bit into the softened hot spot. For larger diameters (~1 cm), the outer cylinder serves as a hollow reamer to shape and deepen the hole as it slowly rotates.

3. Experimental Applications for Concrete

The microwave drilling concept as described above has been tested successfully on sundry materials: concrete, glass, silicon, basalt, and various ceramics. The microwave drill operation is silent and gentle, and it produces no vibration. Several prototypes of microwave drills for concrete have been developed, including a 0.5-5-mm diameter, 3cm deep microwave drill and nail-gun, a 12mm diameter, 20cm-deep microwave drill, and a concrete crusher that can pulverize a 5 cm-wide band (not presented here).

Figure 2 shows the first microwave drill prototype for use on concrete. The telescopic coaxial structure is fed directly by the 600W, 2.45 GHz-magnetron's output. Two electrical actuators function as stubs to maintain impedance matching.



Figure 2. A microwave drill prototype for producing 0.5-5 mm diameter holes, or to serve as a nail gun.

In the drilling mode, the drill bit (0.5-5 mm diameter) is immediately withdrawn from the concrete after forming the hole. In the nailing mode (in which, the same tool operates like a nail gun to insert pins, nails or screws in a single-stage process) the drill bit-antenna is detached and left protruding from the hole. Figure 3 shows a 3 mm diameter pin inserted 3 cm deep into a concrete brick. Nails inserted by using this technique have resisted extraction by forces up to 30 kg in strength.



Figure 3. A pin inserted 3 cm into concrete using the microwave nail gun shown in Figure 2.

The pin insertion speed with respect to the effective microwave power was measured using a laboratory microwave drill setup, which included a power-adjusted magnetron, directional couplers, and an impedance-matching tuner. Figure 4 shows the measured insertion speeds for a 2.4-mm diameter pin for various power levels. The maximum insertion speed of a bit over 1 mm/sec was realized at 0.7 kW of effective microwave power. Further increases in power caused breakdowns in the microwave drill tube and reduced the insertion speed.



Figure 4. Measurement of the microwave drilling speed for a 2.4 mm-diameter pin in concrete.

Figure 5 demonstrates the portable microwave-drill prototype for producing 12-mm-diameter, 20-cm-deep holes in concrete. In addition to the microwave feeder shown in Fig. 1, the outer tube of the coaxial structure functions as a mechanical hollow reamer. It is able to remove debris and shape the hole as it slowly rotates. The drill's light weight (weight <5 kg) allows it to be operated on a stand, or held against a wall or ceiling by a single person. Its power consumption is 1 kW (110/220 VAC or 12/24 VDC). The safe operation of this microwave drill is ensured by a two-layer shield that reduces the microwave leakage to meet the established safety standard (<1mW/cm2).



Figure 5. The microwave drill prototype used to produce 12-mm-diameter, 20-cm-deep holes in concrete (shown without the outer cover and handles).

Figure 6 shows a 12-mm-diameter, 10-cm-deep hole in concrete made by the microwave-based drill shown in Figure 5. The device is able to drill a hole of this diameter at a rate of 1-2 cm/minute.



Figure 6. A 12-mm-diameter, 10-cm-deep hole made in concrete by the microwave drill of Figure 5.

4. Microwave drilling into glass

A laboratory microwave drill setup similar to the one used to obtain the results shown in Figure 4 was then used to drill into different types of glass. Figure 7 shows ~1.6-mm and ~2.4-mm diameter holes, and arrays of four 0.5-mm diameter holes in ~1-mm thick borosilicate and soda-lime glass. The main objective in these experiments was to prove the feasibility of making holes in these types of glass using the microwave drill without producing cracks (it required careful pre- and post-heating stages). Less attention was paid to the accuracy of the holes' shapes; an obvious imperfection caused by the manual punching action is observed in the perimeter's edge. These 0.5-mm diameter holes represent the smallest diameter borings achieved to date by a 2.45-GHz (122-mm wavelength) microwave drill.



Figure 7. Microwave-drilled holes in 1-mm thick borosilicate and sodalime glass.

Preliminary tests of other microwave drill-derivative devices designed for applications involving glass and glass products have demonstrated the feasibility of glass cutting, tube sealing, and surface shaping. Figure 8 represents a glass ampoule sealed by the microwave drill. Sealing such as this one has sustained test pressures of more than 7 atm.



Figure 8. A glass ampoule sealed by a modified microwave drill device.

5. Local Microwave-Heating Applications for Silicon

The microwave drill's rapid thermal-runaway process and the near-field interaction combine to limit the area of the affected zone to a much smaller size than the radiation wavelength. The heating mechanism of the sub-wavelength microwave can be exploited for assorted mechanical and thermal small-scale processes including local heating and melting, drilling, cutting, and bonding. The microwave drill has recently been studied as a means to produce direct localized heating of silicon in various schemes. Although these preliminary experiments were done with a relatively large electrode (0.5-mm-diameter), the results demonstrate the feasibility of performing several localized thermal processes, including the:

- (a) Local heating of silicon at a rate of $\geq 200^{\circ}$ C/second, up to its melting point.
- (b) Point-contact bonding of silicon to silicon, and silicon to glass (Figure 9).
- (c) Indentation and drilling in silicon.
- (d) Localized doping of silver and copper into silicon (Figure 10).



Figure 9. Silicon bonded to glass using the microwave drill. The two images (a, b) show both sides of the spot-welded, silicon-glass-silicon sandwich.

The relevant scientific and technological underpinnings for these findings and for other current research are provided in large part by studies involving the microwave processing of silicon and related materials, as provided by Thompson and Booske [6] among others. Current methods for silicon bonding include both direct and indirect techniques. The direct wafer bonding (DWB, or fusion bonding) is performed by pressing two silicon wafers together at high temperature. Indirect methods of intermediate layer bonding include adhesive bonding, eutectic and glass-frit bonding. The intermediate films deposited can be made of gold, glass, or resin. The recent interest in microwave-assisted silicon bonding is motivated by several reasons. These processes offer an alternative to other power-device applications that produce a thick epitaxial growth layer of crystalline silicon on silicon. Silicon wafer bonding has also become a key technology in micro-electromechanical system (MEMS) manufacturing (for applications such as automobile fuel injection systems, biomedical micro-fluidic devices, smart sensors, power devices, solar cells, optical components, communication systems and data storage).

A thermal process for ion implantation in silicon using high-power microwave radiation was reported by James et al. in 1990 [7]. Microsecond microwave pulses at 2.86 GHz were used to rapidly heat the near-surface region of arsenic-implanted silicon. Surface melting occurred at incident pulse powers of 3 MW. More recently, Ref. [8] presents studies on the effect of microwave radiation on boron activation, and Ref. [9] examines athermal photonic effects on the diffusion and activation of boron

during microwave rapid thermal processing. The microwave drill applications proposed here add the feature of *directly* localized heating for various silicon processes, such as doping.



Figure 10. Secondary ion mass spectroscopy (SIMS) measurements of silver doped into an n-type silicon wafer (0.37 mm thick) by the microwave drill. Contact potential difference (CPD) measurements made by atomic-force microscopy (AFM) reveal a potential difference of 0.32 Volt (evidence of a "junction") created by the microwave drill's doping effect.

6. Theoretical Model

Analysis of the microwave drill's operation involves studying the overlapping effect of the electromagnetic (EM) waves and their resulting thermal effects [10-12]. The EM waves emitted by the microwave near-field antenna and the power absorbed by the material in this region are described by Maxwell's equations for a lossy medium. Assuming a cylindrical symmetry as shown in Figure 1, these equations are reduced to

$$\frac{\partial E_r}{\partial t} = -\frac{1}{\varepsilon_0 \varepsilon'} \left[\frac{\partial H_{\varphi}}{\partial z} + \sigma_d E_r \right], \tag{1a}$$

$$\frac{\partial E_z}{\partial t} = \frac{1}{\varepsilon_0 \varepsilon'} \left[\frac{1}{r} \frac{\partial}{\partial r} \left(r H_{\varphi} \right) - \sigma_d E_z \right], \tag{1b}$$

$$\frac{\partial H_{\varphi}}{\partial t} = \frac{1}{\mu_0} \left[\frac{\partial E_z}{\partial r} - \frac{\partial E_r}{\partial z} \right],\tag{1c}$$

where E_r and E_z are the radial and longitudinal electric field components, respectively, H_{φ} is the azimuthal magnetic field component, and σ_d is the conductivity associated with the dielectric losses, $\sigma_d = \omega_0 \varepsilon_0 \varepsilon''$ where $\varepsilon = \varepsilon_0 (\varepsilon' - j\varepsilon'')$ is the complex dielectric coefficient.

The dissipated power density is

$$P_{d} = \omega_{0} \varepsilon_{0} \varepsilon'' \left\langle \left| \mathbf{E} \right|^{2} \right\rangle, \tag{2}$$

where $\langle ... \rangle$ denotes the root-mean-square (RMS) time average at each point in the radiated volume.

The heat equation describes the temporal and local temperature variations caused by microwave energy absorption. Assuming a cylindrical symmetry, the heat equation is written in the form

$$\rho_m c_m \frac{\partial T}{\partial t} = \nabla \cdot \left(k_t \nabla T \right) + P_d , \qquad (3)$$

where ρ_m , c_m , and k_t are the material's density, specific heat and thermal conductivity, respectively, and T is the local temperature. The temperature dependence of the medium properties (ρ_m , c_m , k_t) as given in the material specifications is incorporated in this analysis. These variations in the material properties during the microwave heating process affect the spatial non-uniformity evolution of the temperature profile, and therefore are key factors in the analysis of the thermal-runaway phenomenon.

The microwave drill operation is simulated by a finite-difference time-domain (FDTD) code solving Eqs. (1-3) in a two time-scale approach [10]. The resulting temperature profile after 8 seconds of 800W microwave drilling in mullite, for instance, is presented in Figure 11 [12]. While the hot spot exceeds 1,300°K it remains confined within a 2-3 mm radius.



Figure 11. An FDTD simulation result of the temperature profile evolved in front of the microwave drill in mullite (5-mm insertion, 800W power for 8 seconds).

The simulation demonstrates the creation of a molten region in front of the microwave drill, into which the device is inserted mechanically to deepen the hole in the drilling process. The simulation also yields the input impedance of the microwave drill, and its reflection coefficient toward the microwave source [12].

7. Summary

Microwave drills can be incorporated into a variety of instruments and tools. To date, these devices have demonstrated the capabilities to create holes in concrete, ceramic, glass, silicon, basalt, granite, and similar materials. Unlike mechanical drills, the microwave drill's operation is quiet and clean. It does not use quickly rotating parts, nor does it cause mechanical friction or vibration, and it complies with safety standards. The current objectives of the microwave drill project at Tel Aviv University are aimed at increasing the drilling speed, to conclude the human-engineering design, and to test the tools in real conditions in various industries. Larger microwave drills for deeper and wider holes are being designed, as well as miniature drills for more delicate applications, such as MEMS.

A unique advantage of microwave drills is their silent operation. This makes them ideally suited for use in construction work in sensitive areas where loud noise and vibration need to be avoided (e.g., residential and office areas, schools, hospitals, etc.). The microwave drill technology is able to use components found in domestic microwave ovens, thus it should be possible to provide low-cost tools for construction and maintenance work. Development of microwave drill technology will also be directed towards more specialized industrial applications (for instance, drilling, cutting, and jointing in the glass industry). The microwave drill technology may provide unique capabilities for advanced manufacturing processes.

The microwave drill was found to be applicable with various ceramic materials [13] such as lowpurity alumina, zirconia, mullite, and glass ceramics. The selectivity feature of the microwave drill was found useful for punching cooling holes in ceramic thermal-barrier coatings (TBCs, which are used to protect jet-engine blades) in order to expose the underlying cooling holes without damaging the metallic substrate [14].

The microwave drill concept has been applied for localized heating experiments of silicon plates. A local heating rate of $>200^{\circ}$ C/second was attained, up to the melting point. Additional feasibility experiments have shown that the microwave drill enables various localized thermal processes in silicon including jointing, welding, doping, and drilling.

Advanced features are being developed for more complicated drilling scenarios. These include sensing abilities to enable distinguishing between different materials in the drilled structure. The microwave drill will then also act as "radar" which will be able to "sense" the underlying material's condition in a self-controlled process. The microwave-drill concept is further developed also for medical applications, and in particular for drilling in bones [15].

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