# Drilling into Hard Non-Conductive Materials by Localized Microwave Radiation

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## Abstract

The paper describes a novel method of drilling into hard non-conductive materials by localized microwave energy (US patent 6,114,676). The *Microwave Drill* implementation may utilize a conventional 2.45GHz magnetron, to form a portable and relatively simple drilling tool. The drilling head consists of a coaxial guide and a near-field concentrator. The latter focuses the microwave radiation into a small volume under the drilled material surface. The concentrator itself penetrates into the hot spot created in a fast thermal runaway process. The microwave drill has been tested on concrete, silicon, ceramics (in both slab and coating forms), rocks, glass, plastic, and wood. The paper describes the method and its experimental implementations, and presents a theoretical model for the microwave drill operation. The applicability of the method for industrial processes is discussed.

## 1. Introduction

Drilling holes is a fundamental operation in almost any industrial or construction work. Advanced drilling technologies are being developed for hard non-metallic materials (i.e. ceramics, concrete, marble, silicate, etc.) [1]. Mechanical drills satisfy most of the needs, but their operation causes loud noise, vibrations, and dust effusion, and is not always effective. Hence, other drilling technologies are utilizing ablation or thermal effects to produce holes. These include mostly lasers [2,3], but also jets,

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flames, plasmas, and electro-erosion tools. Other drilling methods use ultrasonic devices [4], water jets, and hydraulic presses.

Microwaves are used for a variety of industrial, scientific, and medical (ISM) applications [5], but not for drills. Their industrial applications include heating and drying, as well as advanced material processing such as ceramic sintering [6]. However, Microwaves have been proposed also for destructive applications, such as crushing of stones, mining, and concrete demolishing [5,7]. These apparatus use 2.45GHz magnetrons (~12cm wavelength) to generate volumetric heating in the material to be crashed. The long wavelength has inhibited more delicate remote drilling operations by microwaves. This paper introduces a novel method for drilling into hard non-conductive materials by localized microwave energy [8].

## 2. The Microwave-Drill Concept

A key principle of the microwave-drilling concept is the concentration of microwave energy into a small spot, much smaller than the microwave wavelength itself. This is done by a near-field microwave concentrator, which is brought to contact with the material to be drilled, as shown in Fig. 1.

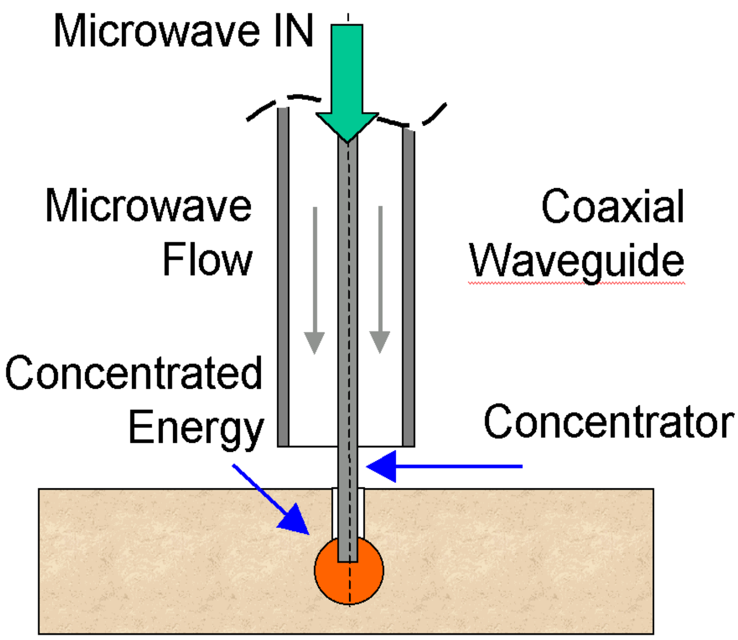



**Fig. 1. A simplified principle scheme of the microwave drill.**

The microwave energy localized underneath the material surface generates a small hot spot [9] in which the material becomes soften or even molten. The concentrator pin itself is then inserted into the molten hot spot and shapes its boundaries. The hole can be shaped other than circular. Finally, the concentrator is pulled out from the drilled hole, and the material cools down in its new shape. The process does not require fast rotating parts, and it makes no dust and no noise.

The microwave drill is effective for drilling and cutting in a variety of hard non-conductive dielectric materials, but not in metals. The latter reflect the radiation and therefor are almost not affected by the microwave drill. Hence, the microwave drill enables a distinction between different materials, and in particular between dielectrics and metals.

Specifically, the microwave drill can be implemented to make holes and grooves in dielectric coatings on metallic substrates (thermal barrier coating (TBC) for instance). Furthermore, it can expose existing holes in the metallic substrate coated by the ceramic, with no damage to the underlying metallic substrate.

The microwave drill can be implemented in relatively simple instruments, consuming moderate electrical powers. However, safety and RF interference considerations may limit its free public usage. Hence, the microwave drill concept is proposed first for embedded tooling in industrial manufacturing processes.

## 3. Microwave Drill Apparatus

The experimental laboratory setup for the microwave drill consists of standard Richardson's components, including switched power supply for magnetron (0-2kW adjustable), a 2.45GHz magnetron, an isolator, a reflectometer with incident and reflected power indicators, and an E-H tuner. The laboratory setup includes also a specific transition from a WR340 waveguide to the coaxial microwave drill, and a chamber in which the microwave-drill is installed.

The microwave-drill head used in this setup is illustrated schematically in Fig. 1. This is basically an open-end coaxial waveguide with a movable center electrode (which sustains high temperatures). In this setup the drilling process is controlled and operated manually (automatic impedance tuner and remote-controlled actuators are being installed in an advanced laboratory setup).

Another, more practical version of the microwave drill is shown in Fig. 2. The telescopic coaxial concentrator is fed directly by the 600W, 2.45GHz-magnetron. Two actuators provide the impedance matching. This tool is much more compact than the laboratory setup, but is not less effective.

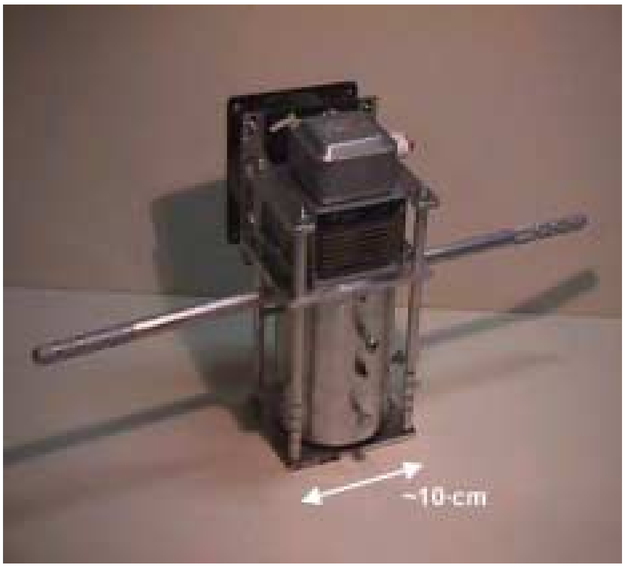



**Fig. 2. The microwave-drill tool version.**

## 4. Experimental Demonstrations

The creation of a hot spot (undesired in most applications) is essential for the microwave drill operation. Fig. 3 shows a hot spot generated by the microwave drill in a glass plate before penetration.

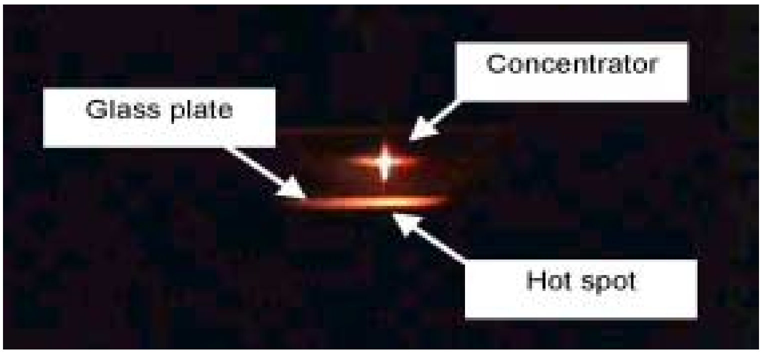
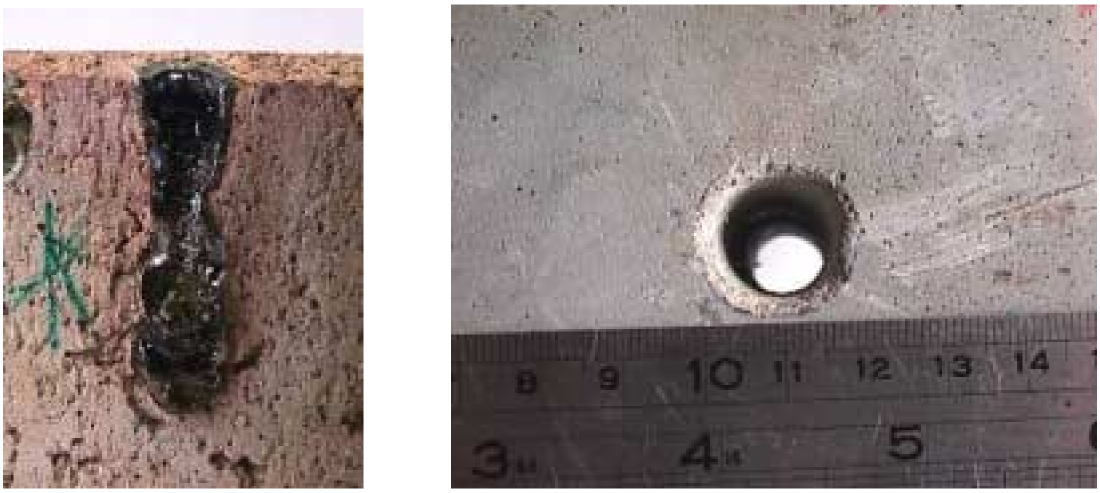



**Fig. 3. Hot spot generated by the microwave drill in a glass plate.**

The microwave drills have been tested on a variety of materials and hole sizes. Typically, a 600W microwave-drill can penetrate easily into a concrete slab to form hole of ~2mm diameter and ~2cm depth within less than a minute. The debris are densified to the wall, evaporated, or converted to a glossy material. A widening of this basic hole requires a further microwave radiation to soften or to melt the remaining volume bound in the required (larger) diameter. Fig. 4a shows a cut in a drilled concrete slab, which reveals the glossy material formed around the concentrator pin in an extensive radiation. This fragile debris can be easily removed mechanically to enlarge the drilling diameter. The hole can be deepened in successive cycles of microwave radiation and mechanical removal of the molten or soften debris. Fig. 4b shows a 13mm diameter, 10cm depth hole made in four cycles of the microwave drilling in a concrete slab.




**(a)** **(b)**

**Fig. 4. Microwave drilling in concrete: (a) A cut in an extensively radiated slab, and (b) a 13mm-diameter 10cm-depth hole made in a concrete slab by a cyclic microwave-drill operation.**

In silicon wafers, the microwave drill has performed 1mm-diameter holes without cracks. The accuracy of their shapes is not satisfying yet, but these preliminary results provide a proof of principle for this process. Similar results are obtained in glass plates, but more careful operation is needed there to prevent cracks.

The microwave drill penetrates also into low-purity alumina and other industrial ceramics. The microwave drill was used also to insert nails into an alumina plate. These nails were originally the concentrator pins, left inside the ceramic after their insertion, and remained bonded to it.

Ceramic coatings on metals (thermal barrier coating, TBC), have been penetrated successfully by the microwave drill. The microwave radiation does not affect the underlying metal, and the ceramic structure around the hole is not damaged

The microwave drill is found useful for other cutting and marking operations in addition to drilling and nailing.

The operation of the microwave drill is characterized in general by two useful features. One is a natural tendency of the microwave radiation to concentrate in a small spot in the vicinity of the concentrator pin. The dimension of the affected zone is much smaller than a wavelength, and it hardly exceeds few millimeters. The other feature is the tendency of the microwave drill to reach an impedance matching. The power acceptance is typically increased with the temperature, and the impedance matching becomes easier as the process evolves.

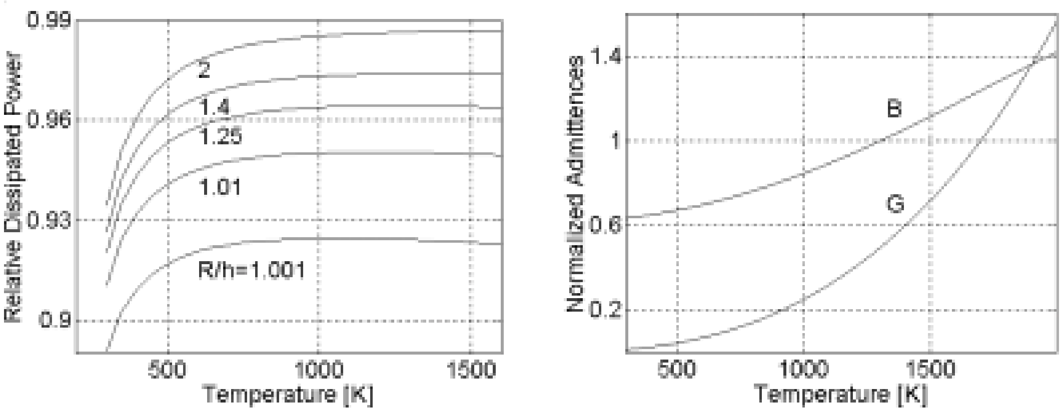
## 5. Theoretical Analysis

A simulation of the microwave drill operation requires a simultaneous solution of the wave equation and the heat equation. This should take into account the non-uniformity evolved in the medium due to the temperature dependence of its parameters. The microwave power density is larger near the drill concentrator, and therefore the temperature tends to be higher in this vicinity. The rapid spatial and temporal temperature variation affects the dielectric properties of the material, and forms a distributed cavity around the concentrator. This non-uniform distribution affects the microwave propagation, and increases the stored radiation energy in this hot cavity. Consequently, a thermal runaway effect occurs rapidly in front of the microwave drill concentrator, and a hot spot is generated there.

Numerical FDTD simulations related to the microwave drill operation are presented in one- and two-dimensions in Refs. [10] and [11], respectively. The latter includes a simulation of the concentrator inserted into the drilled material, and it shows the thermal-runaway effect in front of the microwave drill concentrator.

A simplified analytical model of the microwave drill operation assumes a coaxial open-ended applicator with an extended inner conductor immersed into a lossy dielectric material. The temperature dependence of the dielectric parameters should be available, but the heat equation is simplified to include only the blackbody radiation, the dominant effect at high temperatures. The complex impedance of the microwave drill (i.e. of a monopole antenna in a lossy dielectric) is found vs. temperature assuming steady-state conditions. Unlike [11], this simplified analytical model neglects the spatial non-uniformity evolved in the dielectric material.

The simplified microwave-drill model utilizes analytical expressions for the spatial radiation distribution of a monopole antenna in a lossy dielectric medium, derived in Ref. [12]. These result in a slightly off-axis power distribution profiles near the antenna. The drilled medium is characterized by a temperature-dependent complex dielectric parameter. Using the dielectric parameters given in Ref. [13] for pottery clay, Fig. 5a shows the relative absorbed power in small spherical volumes around the antenna, vs. temperature. At high temperatures, the lossy material near the antenna absorbs most of the microwave energy. Fig. 5b presents the corresponding normalized admitance (Y=G+jB) of the monopole-antenna vs. temperature. At the beginning of the drilling process the antenna responses mostly as a reactive load, but as the temperature increases it becomes more resistive. This semi-analytical description coincides with the experimental observations of the improved impedance matching during the temperature increases.




(a) (b)

**Fig. 5. Analytical calculations of the temperature dependence of (a) the relative absorbed power in spherical volumes of radius R around the antenna, and (b) the real and imaginary components of the monopole-antenna admitance (G and B, respectively) . The material is pottery clay, and the monopole length is h=3mm.**

## 6. Discussion

The microwave drill presented in this paper has shown capabilities to create holes in concrete, ceramics, silicon, basalt, and glass, as well as plastics and wood. As compared to mechanical drills, the microwave-drill has a quiet and clean operation. It does not contain any fast rotating part, and its operation is dust-free. Laser drills, however, are essentially more accurate and they can produce much smaller holes, but they must evaporate the removed material, whereas the microwave drill only melt or even just soften it (letting the penetrating concentrator to shape the hole). The latter is therefore much cheaper, in both equipment and operation costs.

Concerns of safety and RF interference are real difficulties that impede the promotion of the microwave-drilling technology. These difficulties could be alleviated by proper screening and appropriate operating procedures.

The microwave drill can be operated not only as a stand-alone tool, but also in combinations with other instruments, for instance mechanical machining tools. This may lead to a new concept of *microwave-assisted machining*.

The microwave drill concept can be extended to other operations [8], such as cutting, nailing, milling, and jointing. Furthermore, the microwave drill enables a distinction between different materials, and certainly between ceramics and metals. Specifically, the microwave drill can be implemented to make holes in ceramic or plastic coating on metallic substrates (including in thermal-barrier coating). And, in principle, one may conceive that the advanced microwave drill will have a ”radar” feature, enabling to ”sense” the underlying material conditions in self-controlled processes.

The basic microwave-drill is a relatively simple apparatus and it is expected to be a low-cost tool for specific industrial applications. In view of the above mentioned materials and experimental results, various schemes of the device can be considered for several identified applications. These include industrial drilling and cutting machines for electronics, ceramics, and wood industries; drills for construction works (mainly drilling, nailing, and insertion tools for concrete), and high-power microwave drills for geological surveys, oil and gas productions. However, the microwave-drill concept presented in this paper is yet in a premature stage of development, and it requires now extensive interdisciplinary - scientific, technological, and commercial- efforts[1] in order to become a valid and useful technology.

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[1] Potential partners who might be interested in collaboration in any of these aspects, are kindly requested to contact the crresponding author.

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