A Silent Mechanically-Assisted Microwave-Drill for Concrete with Integrated Adaptive Impedance Matching

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This paper presents a prototype of a silent, remotely-operated microwave drill (MWD) for concrete. The MWD concept, based on the induced thermal-runaway instability and hotspot formation effects, is pushed here beyond the limit of quarter-wavelength drilling depth. This extension is achieved by a slow mechanical rotation (~20-rpm) of the entire coaxial structure penetrating as a hollow reamer into the softened concrete. An adaptive impedance-matching tuner is incorporated in the microwave-drill system in order to enable its automatic operation remotely. The portable MWD prototype enables a silent drilling of deep holes in concrete (>20-cm depth). However, its present drilling speed (<1-cm per minute for 12-mm diameter holes) is too slow yet for most practical applications.

Keywords: Microwave drill, hotspot, thermal runaway, concrete.

INTRODUCTION

A key principle of the microwave-drill (MWD) concept [1, 2] is the intentional concentration of microwave energy into a small hotspot (much smaller than the microwave wavelength) by a near-field microwave concentrator [3]. The localized thermal-runaway instability evolved [4] leads rapidly to softening or even melting of the hotspot region, into which the concentrator's electrode is inserted mechanically to make the hole. This MWD mechanism does not require fast rotating parts, and it makes no dust and no noise.

The MWD concept has been extended to a variety of materials and applications (such as cutting, joining, combustion, plasma generation, etc.) in a wider scope of localized microwave heating (LMH) [5]. These have been also demonstrated by a compact solid-state implementation of a miniature MWD [6]. Yet, the penetration depth of the basic MWD device is limited to a quarter of wavelength depth (~2 cm) due to the radiation pattern evolved.

Here we present a prototype of a silent, remotely operated MWD, which is capable of drilling deeper holes (of a >20-cm depth and 12-mm diameter) in concrete and masonry. This MWD system is controlled by an embedded programmable controller, which automatically operates the adaptive impedance matching and various other mechanical functions, as governed remotely by the operator.

MATERIALS AND METHODS

In the MWD prototype presented here, the microwave energy is delivered to the drilled region by a coaxial structure with a centre electrode, as shown in Fig. 1. This hybrid device functions also as a mechanical drill-bit, in addition to facilitating the localized microwave-heating effect which creates the hotspot near the contact point of the centre electrode and the material. The centre electrode is then inserted into this softened (or molten) region in the material, up to a depth limited to a quarter of a wavelength (~2 cm). This depth limitation refers to the distance between the tip of the centre electrode and the perimeter face of the outer tube of the coaxial structure.

In order to drill deeper and wider holes, this MWD prototype is equipped with auxiliary mechanical components combined as shown in Fig. 1. These operate simultaneously incorporating (I) a microwave softening, (II) a mechanical rotation, and (III) a mechanical insertion. The outer tube with helical grooves is rotating slowly (in <20 RPM) hence functioning as a hollow reamer. This rotation marked II in Fig. 1 enables us to cut in the softened concrete in the edge of the hotspot, and to deepen the hole further. The axial motion marked III in Fig. 1 inserts the coaxial structure into the drilled material. This axial motion is subjected to a sufficient softening of the material by the microwave-heated hotspot. An independent axial motion of the centre electrode marked I in Fig. 1 deepens the hotspot and inserts the drill bit further. An air flow inside the tube assists the debris removal from the drill-bit region and also cools it down.

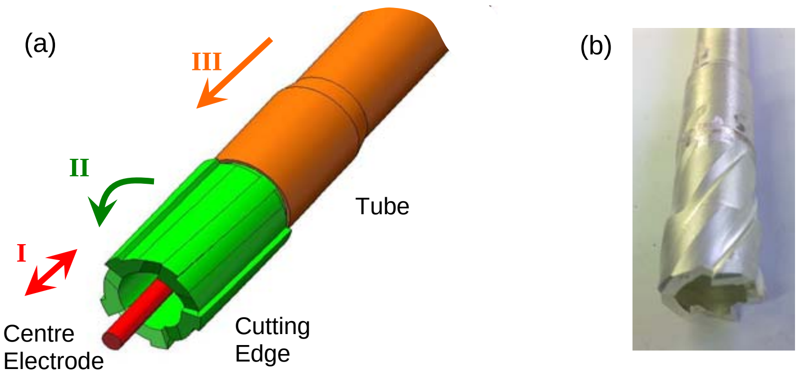

Figure 1. (a) The microwave-drill bit as a hybrid of a coaxial waveguide and a slowly-rotating (II) hollow reamer which removes the debris. The centre-electrode insertion (I) is mechanically independent of the axial progress (III) of the entire device. (b) The silver-coated outer tube (12-mm$^{\varnothing}$).

The MWD prototype incorporates also an adaptive impedance-matching capability in order to minimize the microwave reflections from the varying load. This rapid tuning is essential for the MWD operation in order to cope adaptively with the extreme variation of the load impedance, from cold (high impedance) to molten (low impedance) conditions, within a few seconds. The 3-stub tuner, incorporated with the waveguide-to-coax transition and the adaptive tuning procedure are depicted in Figs. 2a, b. The adaptive tuning and other MWD functions are executed automatically by a programmable controller embedded in the MWD system. For instance, the axial insertion motion III is dictated by a feedback loop that measures the torque applied in the rotation motion II, and enables the axial insertion below a certain torque threshold determined by the operator. This threshold also dictates the level of the material softening and consequently the level of noise emitted by the rotational reamer cutting (in a trade-off with the drilling speed). Another feedback loop controls the adaptive impedance matching in an autonomous manner, which does not require the operator's involvement in normal operating conditions.

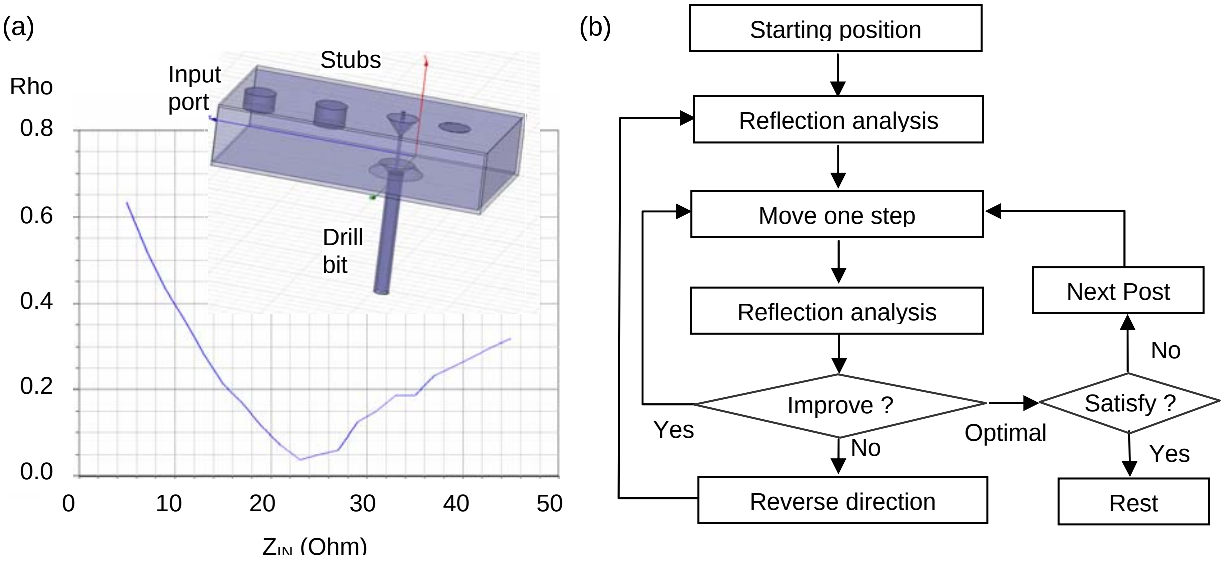

Figure 2. The adaptive impedance-matching device and algorithm. (a) The triple-stub tuner with the waveguide-to-coax transition in between the stubs, and the reflection vs. load impedance in a fixed position. (b) The tuning algorithm performed by the programmable controller and step-motors driving the stubs.

The MWD block diagram, including its microwave, electronics, and mechanical components, is depicted in Fig. 3a. The MWD prototype is shown in Fig. 3b, including the main unit, the leading rail and the operating box. The slowly-rotating coaxial drill-bit (Fig. 1) is connected to the main unit by a chuck. The 0.8 kW, 2.45-GHz magnetron tube is fed by a controllable switched-mode power supply. The hand-held control box of the MWD prototype, also shown in Fig. 3b, maintains serial communication with the main unit by another programmable controller embedded in this control box. The alphanumeric display indicates the main parameters and the actual operating mode of the silent drill, including (a) a manual or automatic mode selection, (b) a microwave power level adjustment, (c) a mechanical torque limiter in the automatic mode setting the feedback condition for the rail motor. The drilling progress is displayed numerically to the operator by the control box.

The adaptive impedance matching is activated autonomously in the automatic mode. The reflected power, displayed on the screen, is normally maintained below 5% of the transmitted power. In a case of failure, however, in the automatic impedance matching, a reset command reinitiates the matching process. In the manual mode, the rotation and the rail motors are operated directly by the control box, and the feedback loop and the adaptive impedance matching are idle.

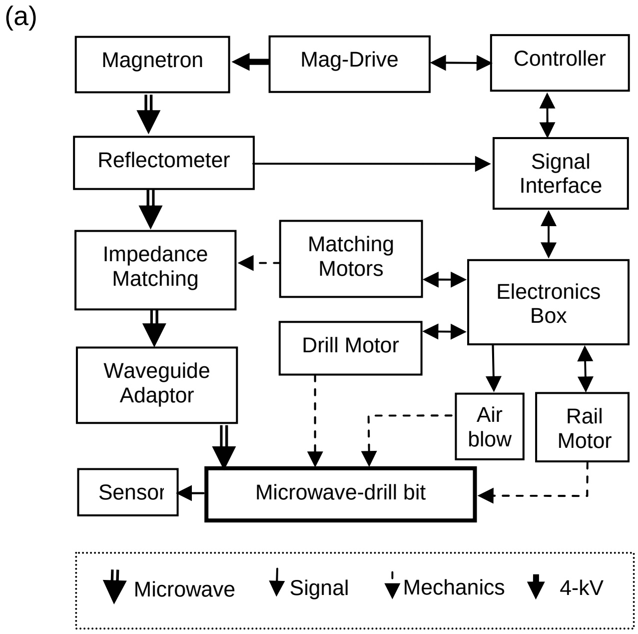

Figure 3. The system overview. (a) A block diagram of the microwave, electronics and mechanical units. (b) The microwave-drill prototype.

The common safety standard for human exposure to microwave emission from domestic and industrial microwave installations, 1 mW/cm^2, is complied with in a proper MWD operation. The leading-rail basis has to be attached firmly to the drilled body, and covered by an aluminum foil to avoid microwave leakage. Microwave leak detectors are incorporated to monitor the operator's safety.

The fixed positioning of the MWD is essential also for its stable alignment and a proper drilling operation in deep holes (in particular to reduce friction and to avoid a geometrical locking effect). An effective fixation is achieved by anchors (possibly inserted by the MWD itself in a preliminary positioning mode).

RESULTS AND DISCUSSION

The portable MWD prototype presented above operates as a stand-alone, remotely-controlled tool. The drilling operation in concrete has been proven to be silent and vibration free in a satisfying level for residential areas, even during night time hours, as well as for offices, schools and hospitals. In these silent operating conditions, the MWD enables making holes deeper than 20 cm in concrete. The average drilling speed measured in over one hundred experimental runs is ~ 0.6 cm/min. The first stage of such run is presented for instance in Fig. 4. The insets show the initial hotspot observed through the view pipe (seen in Fig. 3b) on the surface underneath the slowly rotating hollow reamer, and a typical final hole of 12-mm diameter. A stepwise progress is observed in this case, whereas in each step the hotspot is evolved first by the centre electrode in order to enable the penetration of the outer cylinder afterwards.

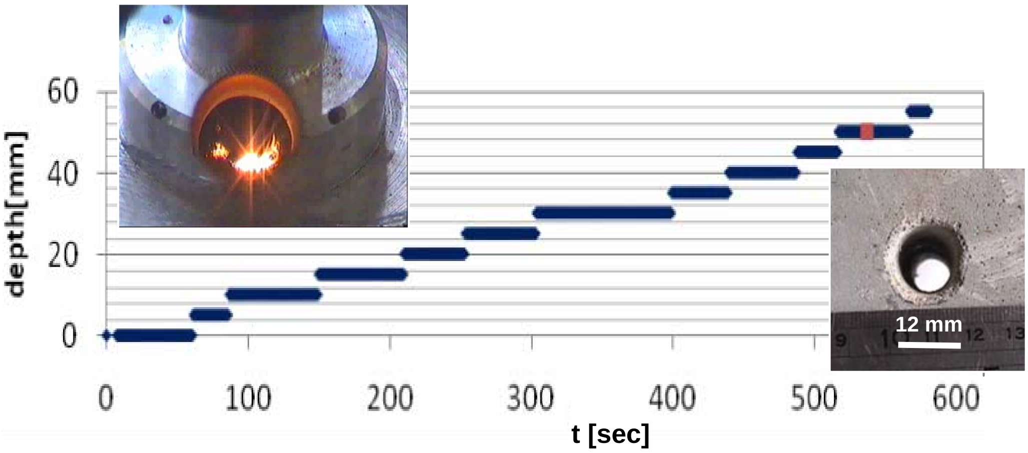

Figure 4. A typical MWD progress of drilling depth vs. time in concrete. The insets show the initial hotspot seen through the view pipe at the beginning of the operation (left), and a typical 12-mm diameter MWD hole (right).

CONCLUSIONS

While the feasibility of a silent and deep MWD operation has been demonstrated by the prototype developed in this study, the drilling speed presented (making for instance a ~20-cm deep, 12-mm diameter hole in half an hour) might be insufficient for many practical needs, except probably for delicate noise-sensitive operations. Another difficulty is imposed by the metallic rebar in reinforced concrete which may impede the MWD operation. Both difficulties may have various solutions (e.g. rebar cutting by plasma excited by the MWD in a properly modified mode, as in [7]). Nevertheless, more development is needed yet at this premature stage of the MWD technology presented in this paper for the application of silent drilling of deep holes in concrete.

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