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# Microwave Drilling of Ceramic Thermal-Barrier Coatings

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**The microwave drill is a novel process for creating shaped holes in nonconductive materials. Its inherent material selectivity makes the microwave drill ideally suited for the controlled removal of ceramic coatings from underlying metallic substrates. In this paper, it is shown that the microwave drill process can drill through ceramic thermal barrier coatings (TBCs) to uncover an array of simulated cooling holes. The concept, apparatus, and procedure for successful drilling are described, and the potential for use in the production of advanced gas turbine components is discussed.**

## I. Introduction

In advanced gas turbine engines, the flow path temperatures can approach or exceed the melting point of the metal superalloys that comprise the turbine components. To enable the metal components to survive these temperatures, turbine designers employ a combination of internal component cooling, surface film cooling, and a ceramic thermal barrier coating (TBC).[1,2] For example, a typical turbine airfoil has an internal cooling cavity that is formed during casting of the airfoil. Surface film cooling emerges from holes that are drilled through the airfoil wall into this cooling cavity. The TBC consists of two layers: a metallic oxidation-resistant bond coat and a thermally insulating layer of yttria-stabilized zirconia (YSZ), a ceramic chosen for its low thermal conductivity and high melting point. The ceramic layer is typically deposited using air-plasma spray (APS) or electron-beam physical vapor deposition (EB-PVD).

If the film cooling holes are drilled before deposition of the TBC, the ceramic layer can constrict or cover the holes, significantly reducing the film cooling effectiveness. This blockage is common when the design requires a thick ceramic layer or when the TBC is deposited using APS. To avoid constriction, the cooling holes can be drilled after TBC deposition. For example, lasers have been used successfully to drill through both the ceramic and metal layers.[3,4] One disadvantage of laser drilling is that the process does not distinguish between the metal and ceramic. Therefore, if the component requires recoating with TBC after drilling, the laser must be realigned precisely with the covered cooling holes, an arduous task if the cooling hole pattern is complex.

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## II. Microwave-Drill Concept

Recently, a microwave-drill technique has been introduced for cutting and drilling into hard, nonconductive materials.[5] This novel method is applicable in particular to ceramics[6] such as YSZ. The microwave-drill process has an inherent feature of materials selectivity, enabling for instance a distinction between ceramics and metals. It has the potential, therefore, for being able to drill through the ceramic layer of a TBC without affecting the underlying metallic substrate. The objective of this study was to apply the microwave-drill technique to the removal of TBC from the opening of simulated cooling holes.

The microwave-drill concept[5] is based on the localized thermal runaway effect induced in a dielectric material by a coaxial open-end microwave applicator. When the applicator is brought into contact with a ceramic, the microwave-dissipated power density is concentrated near the contact point. A local hot spot is created. If the thermal conductivity of the ceramic decreases and its dielectric coupling increases as the temperature rises, the absorption rate of the microwave power in the hot spot is accelerated. The local temperature rises rapidly to the melting point of the ceramic. A hole is then drilled by inserting the drill tip

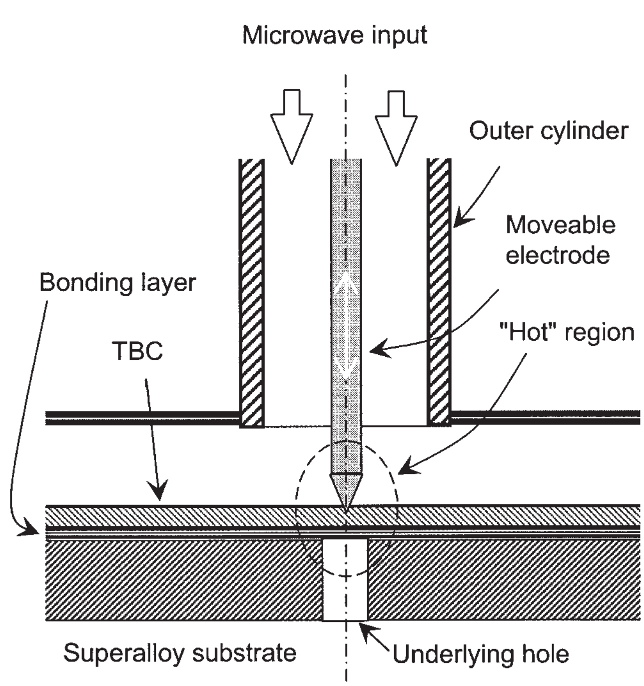


**Fig. 1.** An illustration of the experimental microwave-drill device for TBC.

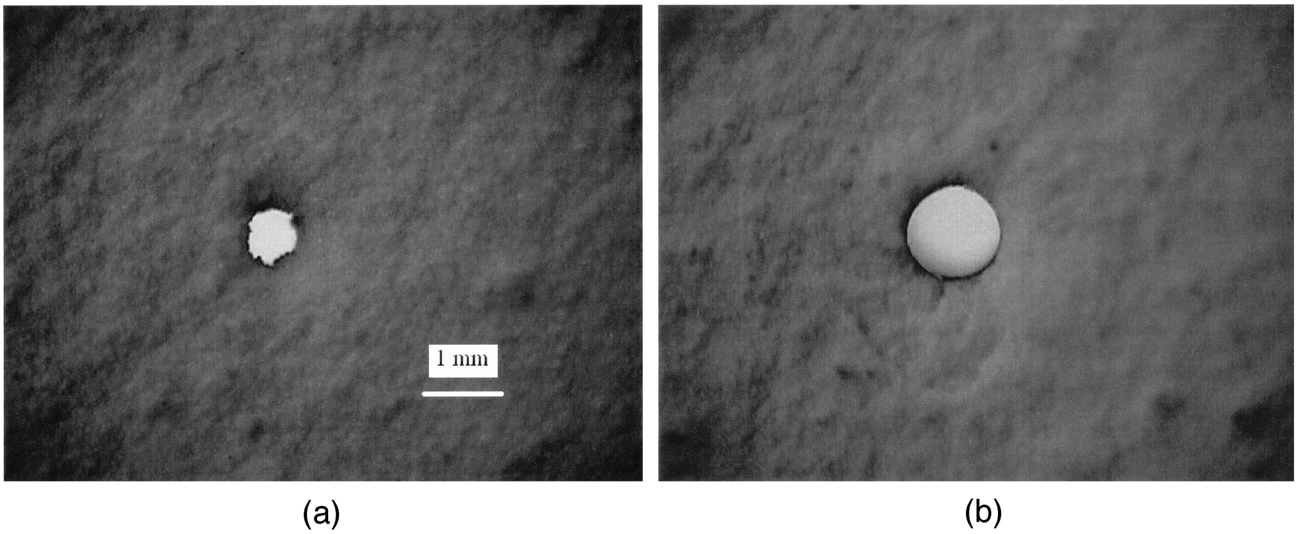


**Fig. 2.** Optical macrograph: Top views before (a) and after (b) exposure of an underlying 1.27-mm-diameter hole through a dense TBC by the microwave drill.

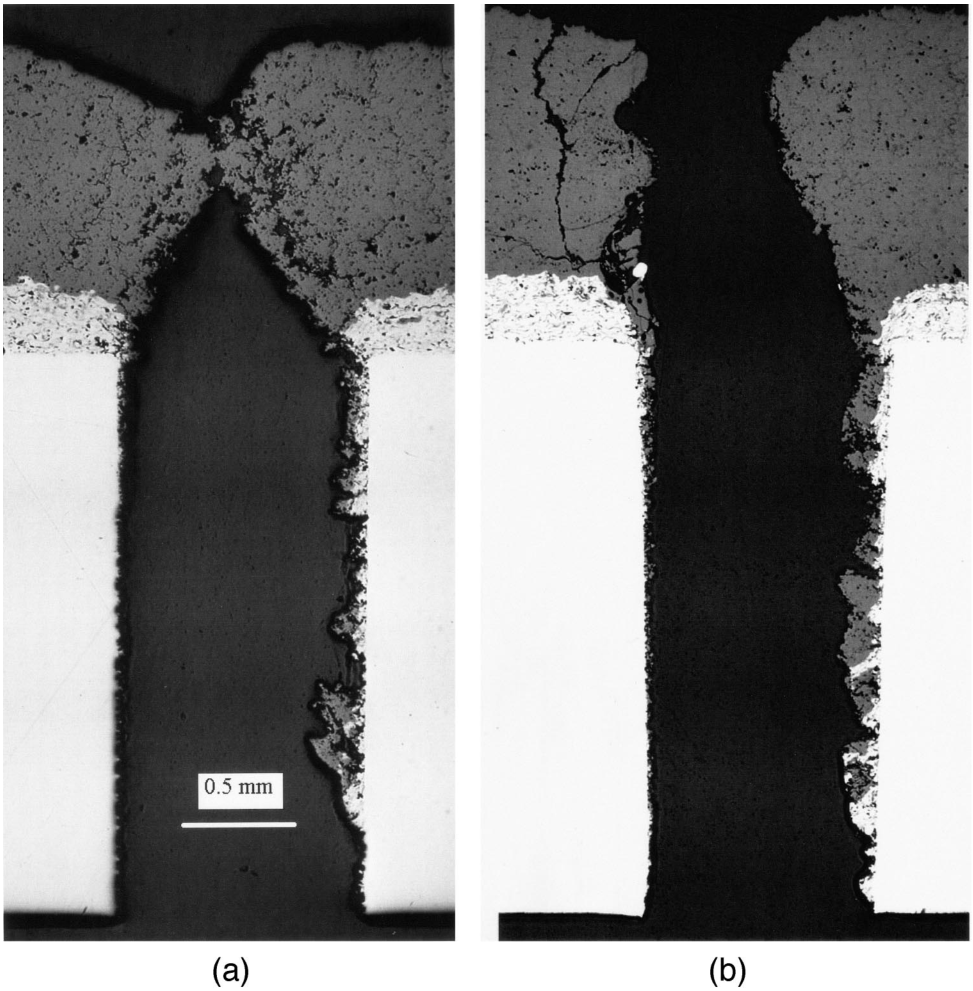


**Fig. 3.** Optical micrograph: Cross sections in coated Hastelloy X plates as sprayed (a) and after exposure (b) of a 1.02-mm-diameter hole by the microwave drill.

into the molten pool. When the applicator is brought into contact with a metal, the microwave energy is reflected and little or no localized heating is obtained. Thus, the process has the inherent feature of materials selectivity.

## III. Experimental Procedure

The microwave drill adapted for the TBC experiment is illustrated in Fig. 1. It consists of an external microwave source and a coaxial structure through which the microwave power is fed to the drilling region. The movable tungsten center electrode of the coaxial waveguide acts as both a near-field monopole antenna and a drilling bit. During the drilling process, the drill bit is pushed through the molten TBC to expose the underlying cooling hole. The near-field operation enables drilling holes in diameters much smaller (by $<10^{-2}$) than the microwave wavelength.

The microwave-drill experimental setup consists of a power-tuned magnetron (2.45 GHz), an isolator, a reflectometer (a directional coupler with calibrated detectors for transmitted and reflected powers), an E-H tuner, and a transition from the rectangular wave guide to the coaxial microwave drill (Fig. 1). A controlled gas inlet (argon or air) provided the cooling for the coaxial structure. A power level of 0.5 kW or less was sufficient for TBC microwave-drilling experiments.

For the feasibility study, metal Hastelloy® X plates (3.2 mm thick) were predrilled with through-thickness holes oriented normal to the plate. The nominal diameters of the underlying holes were 0.76, 1.02, and 1.27 mm, similar to those used for film cooling. Two APS TBCs were deposited onto the predrilled plates: One TBC consisted of a 0.25-mm layer of NiCrAlY bond coat layer followed by 0.76 mm of a porous YSZ microstructure and is representative of a conventional APS TBC system. The other TBC consisted of ~0.35 mm of APS NiCrAlY bond coat followed by 0.76 mm of a dense APS YSZ layer similar to that designed for improved TBC properties.[7]

## IV. Experimental Results

After ignition, the TBC microwave-drilling process typically lasted less than 5 s. In some cases, the ignition of the microwave drilling process caused an excitation of plasma in the slight gap between the drilling bit and the TBC surface. This starting breakdown assisted the microwave-drilling process by providing preheating to the drilled region, thus accelerating the absorption of microwave power.

More than 50 drilling attempts were made, of which more than 70% were successful. Successful results for the dense TBC are shown in Figs. 2 and 3. Figure 2(a) shows the top view of a 1.27-mm-diameter hole partially covered by the TBC. Figure 2(b) shows the same hole after the ceramic had been removed by the microwave drill. Note the smooth circular exit hole created by the drill. Figure 3(a) shows a cross section of a smaller hole (1.02 mm) fully covered by the TBC. Figure 3(b) shows a cross section in another 1.02-mm-diameter hole exposed by the microwave drill. The ceramic at the perimeter of the drilled hole is dense and cracked. This recrystallized YSZ indicates the lateral extent of the molten pool created during the drilling operation. Note that the drilling was stopped after reaching the surface of the metal plate: Thus, the drill did not remove the TBC lying deep within the hole. In all holes examined, the microwave drill process did not affect the microstructure of the underlying substrate.

In general, the microwave-drill operation yielded better results in the porous TBC than in the dense TBC shown in Figs. 2 and 3. Note that the multilayer structure of the TBC differs significantly from the dense materials used in previous microwave-drill studies, complicating the physical interpretation of the microwave-drilling mechanism in a TBC as compared with dense YSZ. The coupled effects involved in this system and process require further study. Drilling failures were caused by mechanical flaws (misalignment, excessive force, and remained debris, etc.) that could be eliminated with improved machinery and technique. None of the failures was caused by a physical-principle obstacle related to the microwave-drilling mechanism itself.

## V. Discussion

The feasibility of the microwave drill for TBC has been shown. The selective microwave drilling affected only the ceramic layer and not the underlying metal. The microwave-drill technology is less expensive than the laser-based drill, but less accurate as well, and it seems to be suitable for TBC holes in the millimeter-diameter range.

In future microwave-drill systems, advanced features could be added to use the information embedded in the reflected wave, as an active sensor. This could be used to detect the underlying geometry, the local temperature, and the state of the material in the hot spot during the microwave-drilling process. As the drill tip nears the underlying metal, the reflection of the dissipated energy varies. The magnitude of this reflected energy can be detected and used to guide the drilling procedure. An adaptive impedance-matching mechanism can also improve significantly the efficiency of the microwave-drilling process. Since the net microwave energy needed to melt a hole of the type presented above is on the order of tens of joules, a fast impedance-matching apparatus may speed up the microwave-drilling period by an order of magnitude, to less than a second per hole. Alternatively, it may allow reducing the input power significantly and enable the microwave-drill miniaturization by employing solid-state technologies available in the <100-W power range. Such compact, low-cost, solid-state microwave drills can be integrated into large microwave-drill arrays.

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