D. Technology for Producing Small Holes in Advanced Materials

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Objectives

- Explore methods for producing ultra-small holes (<50µm) in advanced materials for fuel injector nozzles.
- Evaluate carbide-based cermets and high-temperature ceramics as candidate materials.
- Devise methods to produce precisely a desired pattern of holes having a well-controlled size and shape.
- Investigate methods to fabricate fuel injector shapes or inserts having ultra-fine holes.

Approach

- Form holes in situ during the sintering process by incorporating various pore formers in the green (unsintered) body while it is being shaped.
- Use nickel alloy wires in nickel aluminide-bonded (Ni_3Al-bonded) titanium carbide (TiC) to form holes during sintering.
- Embed into gelcast ceramic materials combustible organic fibers that will vaporize during sintering at high temperatures.
- Gelcast ceramic materials around metal wires that can be removed from the green body prior to sintering, leaving a hole in the part.
- Evaluate thermalplastic coextrusion as a method to form a complex hole-forming pattern in ceramic materials.

Accomplishments

- Produced holes of 108, 76, 51, and 26 µm in diameter in a TiC-Ni_3Al cermet composition.
- Formed 8-hole arrays of ~50-µm-diam holes in gelcast alumina and zirconia ceramics.
- Formed fuel injector nozzle shapes containing an array of fine holes in alumina and zirconia ceramics by gelcasting in a plastic mold with metal wire inserts.
- Fabricated a 6-hole array of 30-µm-diam holes in alumina ceramic using thermalplastic coextrusion.

Future Direction

- Fabricate a precision mold to gelcast ceramic fuel injector nozzles.
- Evaluate joining methods for producing hybrid steel-/ceramic-tip fuel injector nozzles.

- Assess the durability of advanced ceramics in the diesel engine combustion environment.

Introduction

To meet the ever-growing demand for improved efficiency and reduced emissions, future fuel injection systems will require improvements in both design and materials. The objective of this project is to explore new methods for forming ultra-small (<50-μm) holes in advanced materials. Carbide-based cermets (ceramic/metallic composites) and high-temperature ceramics are candidate materials to be used in this study. They have the desirable properties of high strength, high modulus, and low density compared with steel. In addition, they are corrosion resistant and, because of their high hardness, are resistant to wear and erosion.

Currently, fuel injector nozzle holes in steel are 150 to 200 μm in diameter. This size is at the limit for machined holes. One of the major challenges to using advanced materials for improved nozzles is the lack of capability to manufacture very fine holes in the densified material by conventional machining processes. To overcome this limitation, this project will explore methods for the in situ fabrication of holes during the sintering step that is a normal part of the fabrication process for advanced materials. Various techniques for incorporating fugitive pore-formers will be investigated. These pore-formers will be incorporated in the unsintered (green) body during the forming process and will be removed before or consumed during the sintering step to leave precisely-controlled pores (holes) in the densified material. If successful, this technique will not only allow the formation of simple holes but also add the potential to form holes having variable geometries.

Approach

It has been observed in past studies of the cermet Ni_3Al-bonded TiC that metal particles in the unsintered powder compact can leave voids in the sintered part because the metal is drawn into the carbide particle array by capillary action when the metal becomes molten. This tendency will be exploited in the present study to intentionally form holes in predetermined locations. Nickel alloy wires of the appropriate size will be located in the unfired material to form fine holes in the sintered part.

Two ceramic materials were selected for investigation in this project, alumina (Al_2O_3) and zirconia (ZrO_2). To form holes in the ceramics, fugitive pore formers will be incorporated in gelcast ceramic green bodies. Gelcasting is a method of forming powdered materials into complex shapes. Organic monomers are added to an aqueous slurry of the ceramic powder. When a polymerization reaction is initiated, the organic molecules and the slurry are transformed into a solid (gelled) body. By casting the slurry in a mold and then gelling it, a complex-shaped part can be formed. One approach to forming holes in the gelcast ceramic part is to place fibers in the mold that are trapped in desired locations in the gelled part. These fibers are burned away during the sintering process, leaving holes in the densified part. The fibers can be synthetic polymers (e.g., nylon, polyethylene), natural fibers (cotton, silk), or even graphite.

The second approach to forming holes in gelcast ceramic parts is to locate fine metal wires within the casting mold. Like the fibers, the metal wires are trapped in the gelled part. But rather than being burned out, the wires can be withdrawn from the green body prior to sintering. Very fine holes that are formed in the green part can be retained in the sintered ceramic.

Another method being evaluated for forming holes in ceramic materials is the use of coextrusion to form complex arrays of holes on a very fine scale. The coextrusion process involves blending powder materials in a thermalplastic resin and then assembling segments of the filled resin to form a desired pattern. Each segment can contain a different filler material. In the present study, the segments contain either alumina ceramic or carbon powder, and the segments are arranged to form a hexagonal array of carbon-filled “holes” in an alumina matrix. The assembly is then extruded to reduce the cross-sectional area while retaining the segment pattern. The coextrusion can be repeated until the desired reduction of the segment pattern is achieved.

Results

A powder compact of Ni_3Al and TiC containing small lengths of nickel wire was prepared; several

different diameters of nickel wire were incorporated in the specimen. At the firing temperature used to sinter the compact, the nickel became molten and was drawn into the surrounding powder matrix by capillary action, leaving a void where the wire had been. After sintering, the sample was sectioned, polished, and examined by optical microscopy. Elongated holes were observed in the otherwise dense body. The holes had measured diameters of 108, 76, 51, or 26 µm, depending upon the initial size of the nickel wire embedded in the sample. One of the holes in the cermet is shown in the scanning electron microscopy (SEM) micrograph in Figure 1.

Fine holes that were produced in a gelcast alumina ceramic sample by incorporating organic fibers were examined by SEM. An example is shown in Figure 2, where the hole is intersected at an oblique angle by the polished surface of the sample. The hole is approximately 30 µm in diameter. One interesting feature is that the surface roughness of the hole is at a scale defined by the grain boundary curvature of the individual crystallites that form the sintered ceramic. These crystallites average 2–3 µm in diameter. The curvature forms shallow grooves at the grain boundaries that are no more than 100 nm deep. This is an extremely fine surface finish that should minimize turbulence in fluid flowing in such a hole.

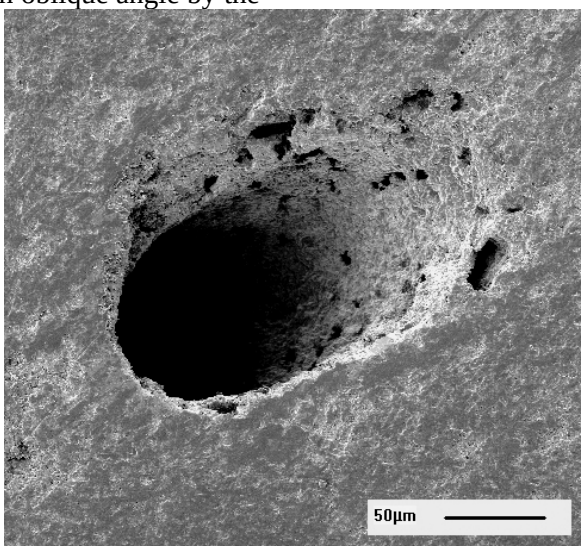

Figure 1. SEM micrograph of a 76-µm hole formed in an Ni_3Al–TiC cermet material.

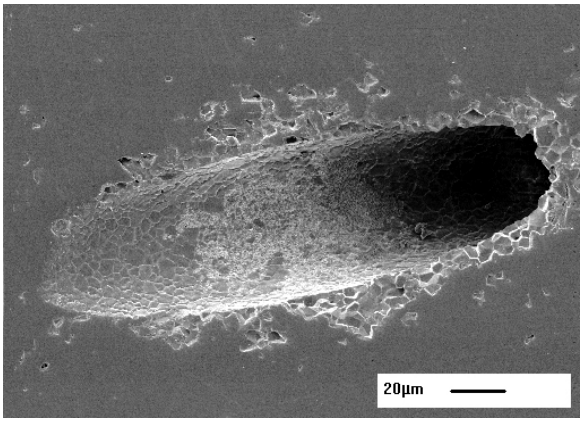

Figure 2. SEM micrograph showing the fine surface finish on a 30-µm hole formed by embedding an organic fiber in gelcast Al_2O_3.

A mold design was developed for gelcasting ceramic material in the shape of a fuel injector nozzle. The plastic mold was designed with removable wires in fixed locations to produce a controlled array of holes in the gelcast ceramic. An optical micrograph of the 8-hole array in the unfired part is shown in Figure 3. The sintered part is shown in Figure 4, along with a steel fuel injector nozzle that was used as the model for making the mold.

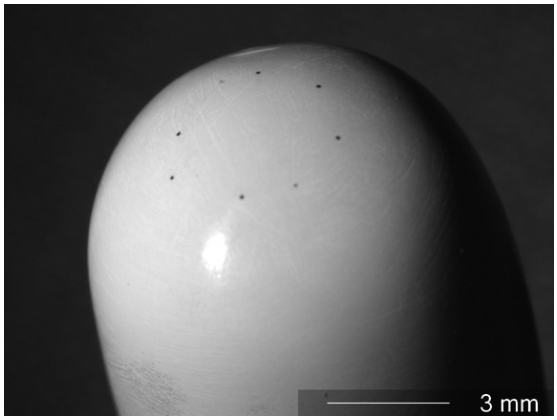

Figure 3. Optical micrograph of an 8-hole array formed on the tip of a fuel injector nozzle shape by incorporating removable metal wires in gelcast ZrO_2.

Figure 4. Gelcast and sintered ZrO_2 fuel injector nozzle shape (left) containing an array of eight holes in the tip. A steel nozzle is shown at right.

A coextrusion process was used to fabricate rods of unfired alumina ceramic containing a hexagonal array of fugitive hole-formers. Figure 5a shows two extruded rods approximately 50 mm long and 5 mm in diameter. The hole-forming array runs through the entire length of the rods. A thin disk was cut from the length of one of the rods; the optical micrograph in Figure 5b shows the cross-sectional view of the hole-forming array on the disk. Disks were fired at a high temperature to sinter the ceramic and burn away the fugitive material in the holes. After firing, the disks were about 4 mm in diameter as a result of sintering shrinkage, and the holes were about 32 µm in diameter. One of the holes is shown in the SEM micrograph in Figure 6. These disks could be used as inserts in a steel housing to form a hybrid fuel injector nozzle with ultrafine holes.

Conclusions

Fine holes of various sizes were produced in a Ni_3Al–TiC cermet material by incorporating fine nickel wires in the powder compact prior to sintering. Holes as fine as 26 µm in diameter were produced using this method.

SEM examination of holes produced in gelcast Al_2O_3 by trapping organic fibers in the casting and then burning them away during the sintering process revealed an exceptionally smooth surface finish on the holes that were formed.

A mold was designed to produce a controlled array of holes in gelcast ceramics having a fuel injector nozzle shape. A circular array of eight holes was formed in the tip of the nozzle shape.

Coextrusion was shown to be a viable forming method for producing an array of fine holes in Al_2O_3 ceramic.

Figure 5. (a) Coextruded alumina rods 50 mm × 5 mm containing a hexagonal array of hole-formers. (b) Cross-section of a coextruded alumina rod showing the hole-forming array.

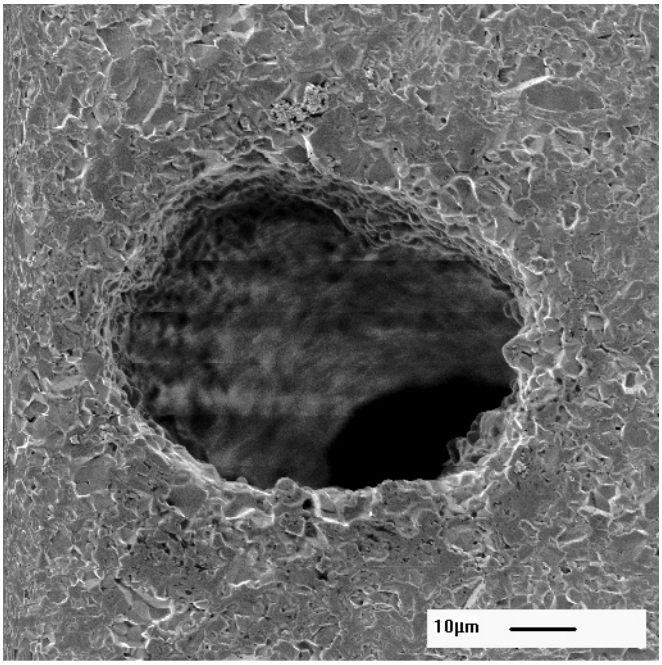

Figure 6. SEM micrograph of a hole in the coextruded alumina after sintering.