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Reinforced Ceramic Dies for Superplastic Forming Operations

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Ceramic dies have been developed to meet the need for a dimensionally stable tool, which can withstand the temperatures (425 to 950 °C) and high forming pressures (up to 7 MPa) that are required for superplastic forming (SPF), superplastic forming with diffusion bonding (SPF/DB), and hot sizing of metal parts. With the improvements that have been made to strengthen fused silica based ceramics, the performance of ceramic tools is slowly closing in on meeting the same forming complexity as corrosion-resistant steel (CRES) dies can achieve. Boeing has successfully superplastically formed jet engine wide chord fan blades using ceramic dies, and many production aircraft parts are being built with Boeing's patented ceramic die technology.

Keywords aerospace, automotive, ceramic, ceramic tooling, die forming, diffusion bonding, hot forming, manufacturing technology, rapid prototyping, rebar, reinforcement, superplastic forming, SPF, SPF/DB

1. Introduction

Superplastic forming (SPF) and hot forming of titanium are becoming highly attractive options for building monolithic structures that must be compatible with graphite-based composites. For many of these applications, the nonrecurring cost and lead time for metal tooling is the most significant factor in the economic trade studies. The current Boeing 7E7 conceptual design features more SPF titanium parts than has been considered for any other commercial aircraft. Ceramic dies present a viable alternative tooling method for all of these new opportunities and have opened up new frontiers in manufacturing.

The first use of ceramic die technology for SPF manufacturing was reported by Goodrich (formerly Rohr) (Ref 1, 2) in 1988. Goodrich's approach for SPF forming is to fabricate a slab of ceramic with the desired shape cast into the top surface of the die and place the tool into a corrosion-resistant steel (CRES) pressure vessel (Fig. 1). Driver sheets of titanium are sometimes used to form the separate net-shape titanium parts over the individual ceramic die mandrels. After forming, the formed parts are peeled away from the driver sheet, which is then cut up for reclamation. Several different ceramic blocks are placed into a forming chamber to fabricate many parts in each production run, and this resulted in important cost savings when compared with forming small clips and brackets with individual CRES dies one piece at a time.

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A popular method of SPF forming using a ceramic molding cavity set into a stronger cylindrical CRES pressure vessel was developed by Curtis et al. (Ref 3) for manufacturing Ti-6Al-4V

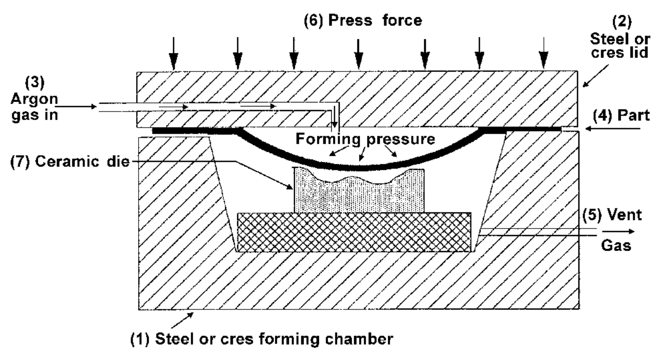


Fig. 1 Schematic of a forming chamber with a ceramic die, using a method developed by Goodrich (Ref. 2). Pressure is contained by the CRES chamber (1) and lid (2) as gas enters through the port (3). Part (4) is formed against the ceramic die insert (7) as gas is vented (5) from the interior of the die. Press force (6) is used to maintain a gas seal as presure increases.

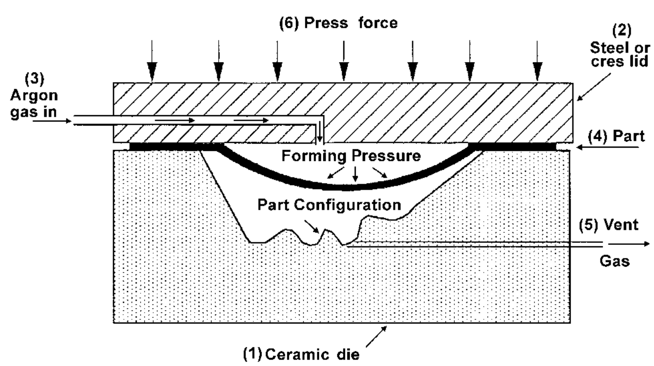


Fig. 2 Schematic of a stand alone ceramic die (1) used for superplastic forming without a CRES containment vessel. Gas enters the CRES lid through the inlet line (3) and forms the part (4) towards the part configuration, which is a shape cast into the bottom of the die cavity. The vent lines (5) that are cast directly through the wall of the ceramic.

dental implants and for superplastic forming with diffusion bonding (SPF/DB) forming of aerospace hardware by Jocelyn et al. (Ref 4) and Ginty et al. (Ref 5). In each of these cases, the ceramic die is used as the pattern for shaping the part and the CRES backing material carries the bulk of the forming stresses.

2. Results and Discussion

2.1 Stand-Alone Ceramic Dies

Ceramic die technology has been improved to meet the need for a dimensionally stable forming tool, which can withstand the temperatures (425 to 950 °C) and high forming pressures (up to 7 MPa) that are required for SPF and superplastic forming with diffusion bonding (SPF/DB) for manufacturing titanium alloy aerospace structural parts. Further, the ceramic die material has been strengthened in excess of 14 MPa (modulus of rupture, MOR) through the use of integral reinforcement rods and postcasting thermal treatments.

Stand-alone ceramic dies have been developed at Boeing (Ref 6) that do not require a forming chamber. These dies can be set onto a press platen and used in nearly the same way as steel or CRES dies. For simple shapes of SPF parts, a planar seal surface along the top of the die can be mated with a flat plate and gas is injected through inlet holes bored through the CRES lid (Fig. 2). Vent gas holes are cast through the ceramic die cavity walls to allow the trapped gas to escape as forming

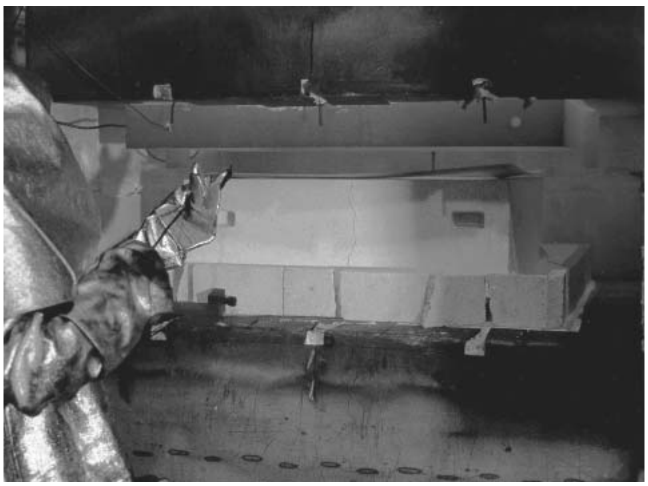


Fig. 3 An SPF press operator removing a hot part from a stand alone planar seal ceramic die. Note that the CRES lid (upper die half) is used to make a seal with lower die cavity.

Fig. 4 SPF ceramic die set with preform ribs around the periphery and indexing nubbins. The die halves are approximately 1 × 1.5 × 0.5 m high.

Fig. 5 A matched ceramic die set for hot sizing of titanium 6Al-4V. The die set is 1 × 0.75 × 1.5 m high.

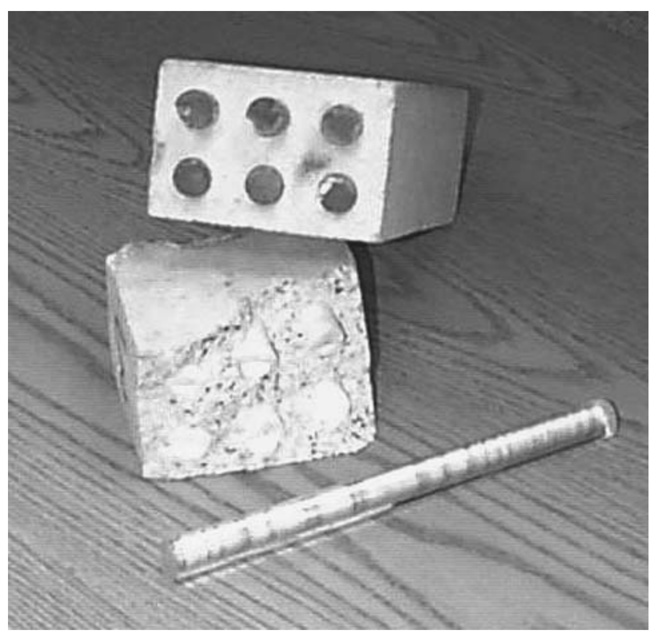
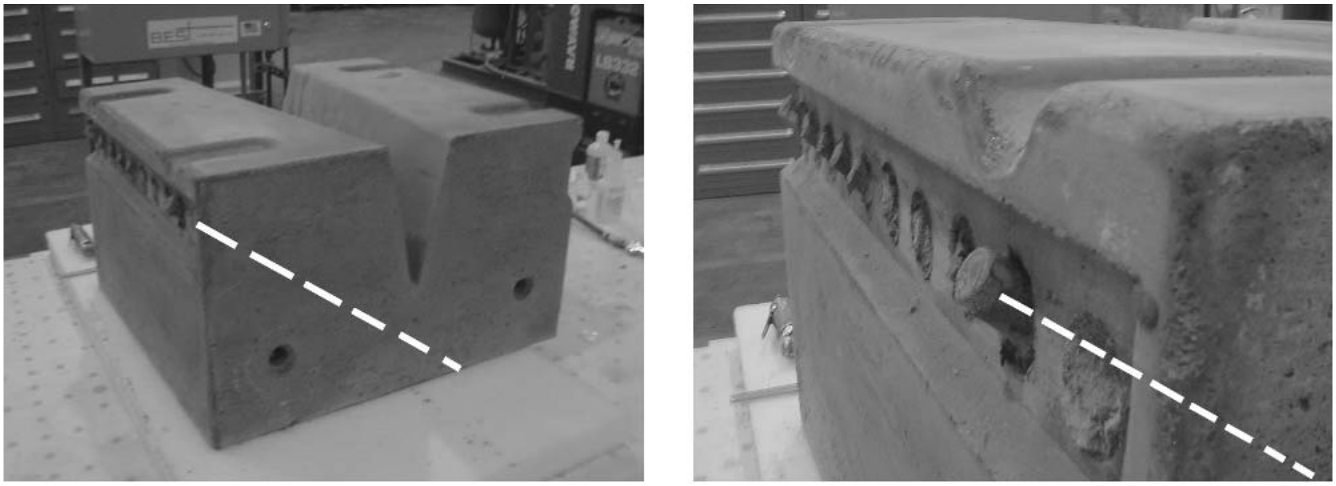


Fig. 6 Reinforced ceramic test brick shown after 3-point bend test. A 20 cm long, 20 mm diameter, quartz reinforcement rod is shown as a reference for size.



(a) (b)

Fig. 7 (a) Ceramic die lower half (in the shape of a wedge) and (b) a closer view of the diagonally placed reinforcement rods (reference dashed lines) to carry the bending load when the matched top half closes into it

progresses. Figure 3 is an image of the first use of this concept at Boeing in an SPF press.

The advantages of stand-alone ceramic dies over conventional steel or CRES dies are:

- Cost: Ceramic dies are much less expensive, typically 5 to 10% the cost of a comparable CRES die.
- Lead time: Ceramic dies require only 3 to 5 weeks to build versus 8 to 14 months, which makes them an outstanding application for rapid prototyping of hardware.
- Inventory reduction: Ceramic dies are not stored, they are simply recast when needed.
- Net shape: No machining or hand blending is needed after casting.
- Die surface: RA 16 or better surface finish can be achieved.
- Unlike metal, the ceramic surface does not scale at elevated temperatures.

There are some limitations with having only a planar seal surface between the lid and cavity of SPF dies. Producing parts of greater complexity often requires that the material be preformed as the die closes together onto the sheet to reduce thinning when forming begins. For SPF/DB, it is necessary to take the multipack stack thickness into account. To answer this problem, a variation of the stand-alone ceramic die method was developed to cast the die halves as matched sets so that a nonplanar seal surface methodology can be used. Figures 4 and 5 show sample matched ceramic dies. Virtually any shape of SPF/DB or SPF part that can be fabricated with CRES dies can now also be built with ceramic tooling.

2.2 Reinforced Ceramic Dies

In the past, premature die cracking was the biggest limitation for using ceramic tools. This problem has been eliminated by adding an appropriate number of high-strength (70 MPa, or 10 ksi) reinforcement rods, made of monolithic fused oxides of silicon or aluminum, which are embedded directly into the ceramic aggregate during the casting process (Ref 7). Figure 6 shows a standard test brick that has two rows of the reinforcing rods. Boeing tested 37 different types of ceramic reinforcement rod materials before the simple quartz rods with approximately 70 MPa strength were adapted for use with ceramic dies. Although high-temperature refractory and ceramic rods with strengths of 225 MPa are available, they were found to be unacceptable for this application during testing due to the mismatch in the coefficient of thermal expansion with the fused silica ceramic base material.

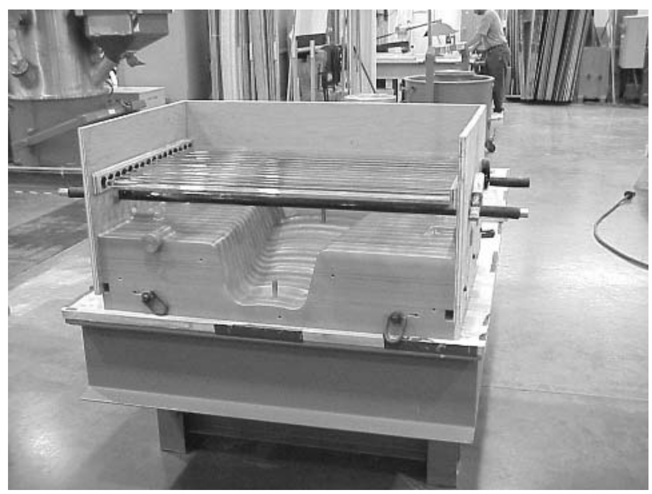


Fig. 8 A ceramic die casting model boxed and ready to cast the raw material into a plywood encased mold.

The quartz rods are placed along the bending or expected flexural joints, such that the twisting and deflection loads across the die are diminished. Figure 7 shows images of a reinforced die that has been used to hot form titanium sheet metal parts for commercial jetliners. Die life has been increased roughly ten-fold by using the rods.

2.3 Fabrication of Ceramic Dies

A fused-silica aggregate, combined with a calcium aluminate binder, is combined with water before it is poured into a mold, as shown in Fig. 8 and 9. Once kiln dried and fired, these dies can be used to superplastically form between 10 and 350 parts. The survival of the ceramic die depends strongly upon the pressure load that is applied and the geometry of the part that is being molded. In general, it is the bending load to which the die is subjected that causes hairline cracks to first appear and then grow. Dies can be thickened in the areas that are subjected to large bending loads.

Fig. 9 Pouring of the raw ceramic into a casting mold

2.4 SPF Hot Press Technology Adapts for Ceramic Tools

If ceramic dies are to be used in a hot press, there are additional considerations that must be taken into account for the press platen, bolster plate, and insulation design. Ceramic dies are very brittle and crack when subjected to excessive bending loads. As an example, analysis has shown that a ceramic die $1.2 \times 2.4 \times 0.5$ m thick can only sustain about 0.5 mm overall bending deflection before it cracks. If ceramic tools are to be used for SPF, the press platen assembly must be reinforced to approximately three times the rigidity of a standard press to reduce die deflection under maximum loads. For safety reasons, it is essential that the heat shields of an SPF press be designed to contain brittle catastrophic failures of the ceramic die during pressurization. After 14 years of ceramic die use at Boeing, two such episodes have occurred, whereby the ceramic die was destroyed, but neither caused damage to the presses or injury to the employees because the heat shields of the presses are designed to resist explosion.

2.5 Glaze Coating for Ceramic Dies

The majority of aerospace components that are superplastic formed at Boeing are made from titanium alloys, such as Ti-6Al-4V, which must be heated to 900 to 950 °C. At this temperature, the CRES dies suffer from high-temperature oxida-

(a) (b)

Fig. 10 (a) Severe high-temperature oxide scale on the surface of an SPF CRES die. (b) Surface degraded die cavity due to scaling. Mark-off (unwanted surface bemishes) is common on SPF titanium parts made with damaged CRES dies.

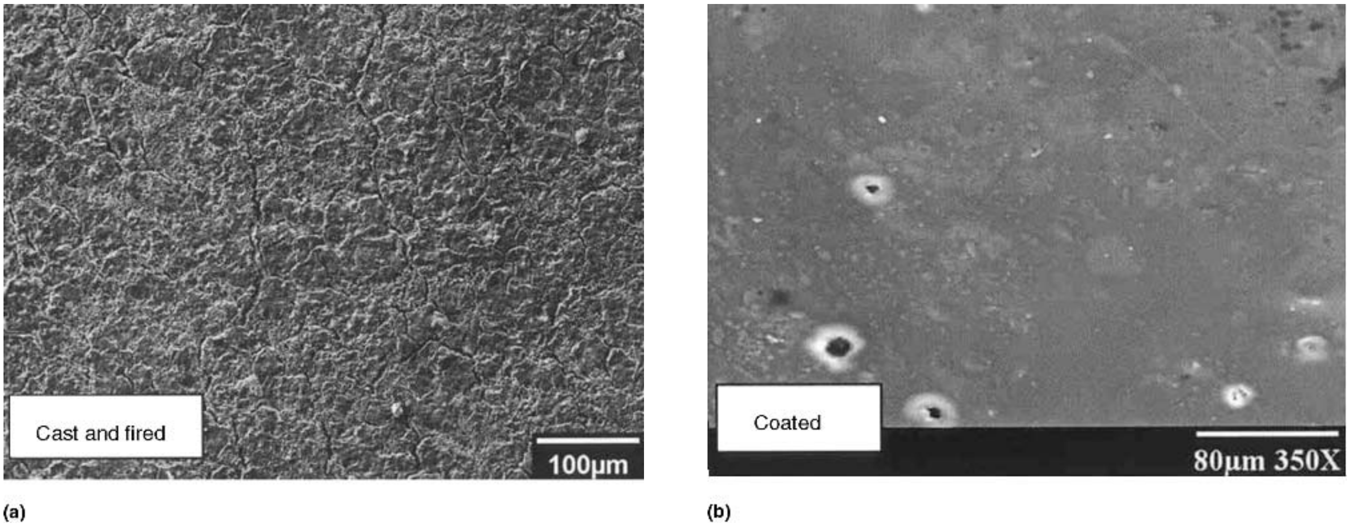


Fig. 11 (a) Untreated ceramic die surface, as-cast and kiln fired and (b) cordierite glaze coated die. Note how the surface of the glaze coated die is much smoother and uniform than the as-cast die. Micrographs courtesy of Dr. David Van Aken, University of Missouri at Rolla.

tion, which causes scaling of the die surface. When forming titanium SPF parts, even small size imperfections on the surface of the die are transmitted onto the parts that are made with it. Figure 10 shows the surface of two SPF dies that have deteriorated to the point where they can no longer be used to make production parts.

The last remaining technical hurdle for ceramic tools to overcome is surface degradation due to microcracks, abrasion, and the reaction of TiO_2 with the SiO_2 at temperatures above 800 °C. Boeing, teaming with the University of Missouri at Rolla, has recently completed the development of a cordierite-based ceramic glaze coating (Ref 8) that can be plasma sprayed onto the surface of ceramic die to create a very hard (Moh's hardness above 7) protective coating. Figure 11 shows the improvement in surface texture that has been achieved by glaze coating ceramic dies.

3. Summary

Aluminum and titanium alloys are increasingly being used for the design of many transportation products such as aircraft, helicopters, missiles, rockets, military hardware, trains, bicycles, motorcycles, freight trucks, and even high-volume production passenger cars (Ref 9). As these industries move toward eliminating steel and phasing in aluminum alloys for their designs, SPF is becoming a highly attractive option when compared with matched metal die forming or hydropress forming. For many applications, the nonrecurring cost and lead time for metal SPF tooling is the most significant factor in the economic trade studies. The experience developed by the aerospace industry in the casting of ceramic dies has resulted in a viable lower-cost alternative tooling method for SPF, which can be exploited for many other industries.

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