Conventional Machining of Green Aluminum/Aluminum Nitride Ceramics[1]

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ABSTRACT. **Current methods for producing ceramic parts rely on finish machining using diamond creep feed grinding or some other non-traditional machining method. As a result, machining may represent as much as 90% of the cost of some ceramic parts. This research project focused on creating dimensionally accurate parts made from "green" engineering ceramic bodies. These bodies were designed to be reaction sintered. Reaction sintering is a method which drastically reduces shrinkage, from about 20% to about 1%. This project investigated the use of conventional milling to machine ceramic green bodies. The green bodies, consisting of 80% aluminum and 20% aluminum nitride, were machined under feed, speed, and depth of cut conditions designed as a 2^3 factorial experiment. Also, green bodies of 20% aluminum and 80% aluminum nitride were prepared, presintered, and machined. The key measurements taken were the number of chips on the machined geometries of the green body caused by the mill. In the 2^3 factorial experiment all green bodies exhibited chipping when subjected to drilling and milling. Feed, speed, and depth of cut were found not to be significant in chipping. The machined presintered bodies did not exhibit any chipping when machined.**

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INTRODUCTION

Engineering ceramic materials are finding increasing use in a broad spectrum of applications. The market for monolithic structural ceramics materials is expected to grow 14% by 1997 (SME 1994). Engineering ceramics are advantageous materials because of their hardness, resistance to wear, light weight, and ability to withstand difficult environmental conditions (e.g., high temperature or corrosive atmospheres). Designers seeking to incorporate engineering ceramic components are faced with many choices of materials, and often have little training in their use. Manufacturing engineers are presented with difficult problems in fabrication, ranging from methods for creating complex geometries to ensuring densification while maintaining net-shape.

Engineering ceramics of particular interest are ceramic nitrides, oxides, carbides, and silicides (DeGarmo et al. 1988). Several materials have come to the forefront as engineering ceramics. One of these materials is aluminum nitride. In current ceramic production methods (Fig. 1) powders are ground and mixed, then "binders" and/or "sintering aids" may be added to improve forming and sintering. The powders are pressed into shape to form green bodies, which are then sintered to achieve final hardness and density. Sintering aids remain in the final, dense mixture forming the part, thus affecting the final products' density and mechanical properties.

"Machining" in current ceramic practice and research includes the use of diamond creep-feed grinding, ultrasonic machining, and other non-traditional machining methods on sintered bodies (American Machinist 1991). The need for machining ceramics has been recognized by the National Institutes of Standards and Technology (NIST). The NIST Ceramics Machining Consortium (SME 1992) is focused on the use of grinding and non-traditional machining methods for finishing sintered ceramic pieces. Norton Corporation, in cooperation with customers and the NIST consortium, is investing heavily in research leading to new grinding methods, machines, and abrasives for processing engineering ceramics (SME 1994). Machining of green ceramics has been used mostly in the preparation of whiteware items such as spark plug insulators and slicing of fins for heat sinks (SME 1992).The literature contains few formal investigations of the machining of green engineering ceramic materials.

Sintered ceramics are very hard and brittle. Ceramics are also costly to machine using existing practices. Machining a sintered ceramic part may represent as much as 90% of the total cost of the part (König and Wagemann 1993). There has seemingly been little alternative to the machining of sintered parts, as the sintering process usually involves significant shrinkage (often as

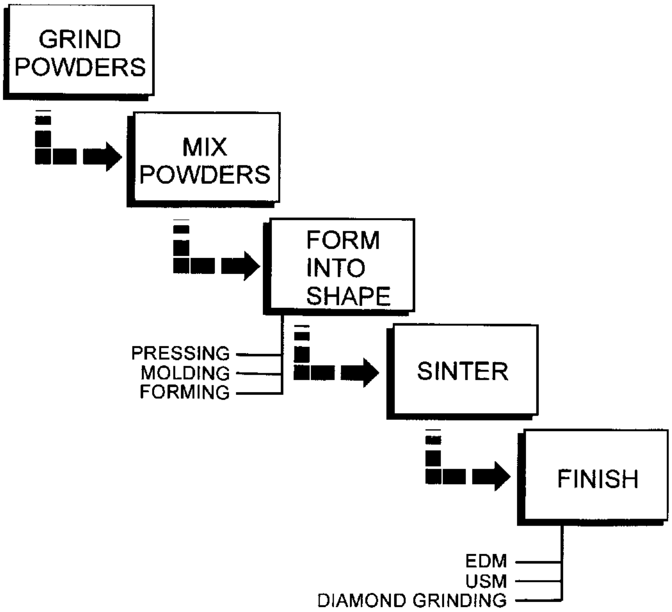

FIGURE 1. Current ceramic part production process.

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much as 20%) and warping of the parts. Materials scientists have investigated techniques for sintering which drastically reduce the amount of shrinkage and warping. It has been shown that compacted silicon powders can be reacted with nitrogen to form reaction bonded silicon nitride (RBSN). RBSN components can be formed to near net-shape with a high degree of dimensional control, because little shrinkage occurs (Mangels and Tennenhouse 1980). The principle of reaction sintering can be extended to other materials, in particular aluminum oxide ceramics (Claussen et al. 1989) and aluminum nitride.

At this time, "Research shows, however, that there is little, if any, systematic understanding of the process design necessary for green machining." (König and Wagemann 1993). The focus of the present research was to prepare brittle ceramic green bodies for reaction sintering using conventional machining methods, i.e., drilling and milling. It is necessary to ensure that the bodies do not chip when machined. Chipping may lead to several problems with the green body, including crack propagation and loss of dimensional integrity, requiring additional post sintering processing. In order to produce machined green bodies which will be economically viable alternatives (after reaction sintering) to metallic parts, chipping must not be a significant problem.

MATERIALS AND METHODS

The present research investigated the machining performance of systems of aluminum (Al) and aluminum nitride (AlN). Cylindrical blanks were created for machining. The part (Fig. 2) was produced through drilling and milling. The initial 50 blanks were composed of 80% Al/20% AlN by weight and weighed 15 g each. This particular composition was chosen, because of the machinability provided by the quantity of Al powder in the mixture, and the belief that a body with a high proportion of aluminum would be less brittle than one with a high proportion of AlN.

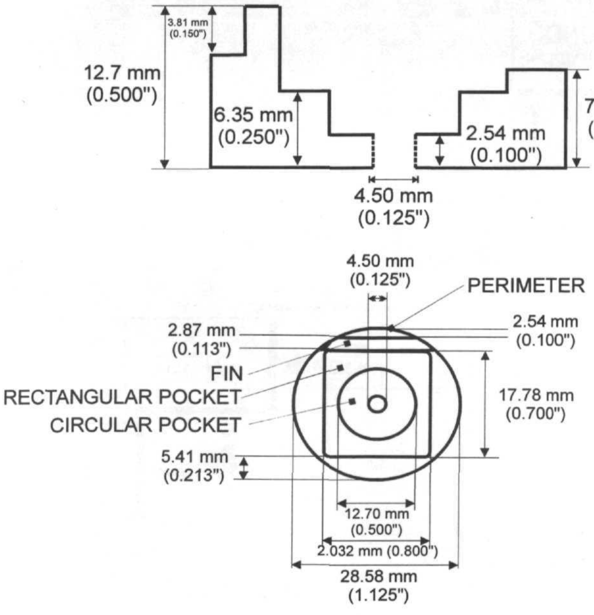

FIGURE 2. Design of part to be machined.

Average density was 5.786 g/cm^3. The blanks were formed in a die 28.6 mm (0.125 in) in diameter under 68.5 MPa (10,000 psi) in a uniaxial press. These blanks were machined directly as pure powder compacts. In addition to these blanks, four blanks composed of 20% Al/80% AlN were fabricated and machined. The second group of blanks were presintered at 550° C under 0.1013 MPa (1 atm) of pure N_2 for four hours, to reduce brittleness. All of the blanks were weighted to the nearest 0.01 g and measured to the nearest 0.0254 mm (0.001 in) using a coordinate measuring machine (CMM). A special fixture (Fig. 3) to hold the blanks during machining was designed and fabricated. This allowed the clamping forces to be spread evenly around the part, as opposed to concentrating the forces at opposing points using a vise. The bodies were fragile.

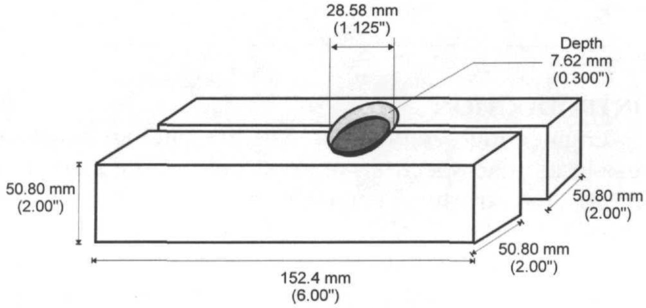

FIGURE 3. Special holding fixture.

A milling and drilling program was written and executed on a computer numerically controlled (CNC) milling machine. Specific operations to cut the part (Fig. 2) included: drilling (central hole), upmilling (along the outer edge), pocket milling (removal of surface material and creation of pockets), and conventional surface milling (creation of the "fin"). The feeds, speeds and depths of cut used for the 80% AL/20% AlN pieces were part of the 2^3 factorial experimental design (Table 1). The experiment was replicated four times, requiring a total of 32 sample parts cut under eight conditions. Cutting was performed using a 4.50 mm (0.177 in) diameter high speed steel (HSS) drill and a 6.35 mm (0.250 in) diameter titanium nitride (TiN) coated high speed steel end mill. [Note: The coated milling tool was chosen after preliminary trials showed that a HSS tool would wear out before completing a single part. TiN coated end mills were good for eight parts.] The 20% Al/80% AlN presintered blanks were machined separately at the high levels of speed and feed (Table 1). The low depth of cut (Table 1) was used for the presintered pieces.

Following machining, each part was reweighed and remeasured using the CMM. The number of chips present was recorded on each of the following features: perimeter, rectangular pocket, circular pocket, fin, and total on the part. For the 80% Al/20% AlN parts the analysis of variance (ANOVA) for a 2^3 factoral experiment was performed on the number of chips present on each feature and in total ($a = 0.10$). Descriptive statistics were developed for chipping of the presintered parts.

Table 1

Factor levels for 2^3 factorial experiment.

Factors	Factor Levels Low	 High
Feed	0.00127 m/sec (3 in/min)	0.00254 m/sec (6 in/min)
Speed	0.665 m/sec (1570 in/min) (2000 rpm)	0.831 m/sec (1963 in/min) (2500 rpm)
Depth of Cut	0.635 mm (0.025 in)	1.27 mm (0.050 in)

RESULTS

In the ANOVAs of the 2^3 factorial experiments (Table 2) both the main effects and interaction effects were tested. In each test performed, the settings of feed, speed, and depth of cut made no significant difference in the mean number of chips per part. All of the 80% Al/20% AlN parts cut on the CNC mill exhibited chipping. The distribution of the number of chips per part (Fig. 4) showed that 62.5% of the parts had five or fewer chips. An additional problem for these parts was that material would break off around the exit point of the drill. As the parts were cut, powder was produced by the tool, as opposed to the ductile chips associated with the machining of metals.

In sharp contrast to the behavior of the 80% AL/20% AlN samples, the four bodies of presintered 20% Al/80% AlN had no observed chipping. Machining these bodies produced powder, just as the pure powder compacts did. These bodies were noticeably less fragile, even though they contained a much higher percentage of AlN (a brittle substance).

An underlying assumption was made that the distribution of the number of chips on a single body is Poisson (Fig. 4), an improvement on the normality assumption required for ANOVA. A comparison was then made between the presintered and nonpresintered bodies. The four nonpresintered blanks machined at high speed, high feed, and low depth of cut had accumulative average of 17 chips. The probability of machining four blanks all having zero chips, given a Poisson distribution with a mean of 17, is 4.14 x10^{-8}. Therefore it is highly unlikely that these presintered and nonpresintered blanks are from the same Poisson distribution. Hence a conclusion is made that there is a significant differences in the number of chips between the two groups of bodies.

TABLE 2

Summary of ANOVA results for 2^3 experiment on feed, speed and depth of cut.

Feature	Mean Chips/Piece	ANOVA Results (α = 0.10)
Perimeter	1.6	No Significant Differences
Fin	2.5	No Significant Differences
Rectangular Pocket	0.9	No Significant Differences
Circular Pocket	0.6	No Significant Differences
Total	5.6	No Significant Differences

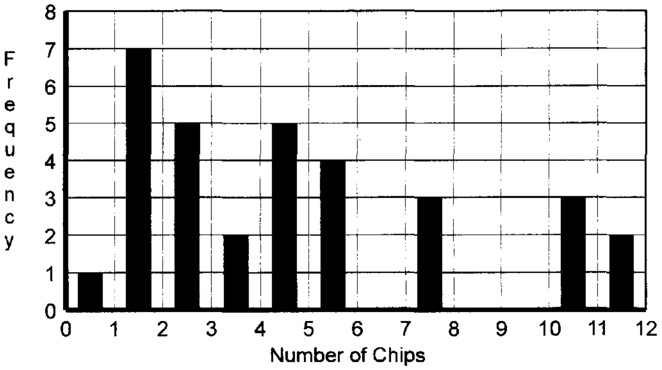

FIGURE 4. Distribution of total number of chips per part.

DISCUSSION

The fundamental result of this research was that none of the parts which were pressed and not presintered avoided chipping. The chips formed on the various geometries within the pieces were such that extensive grinding would be needed to remove them. Indeed even with the grinding, net-shape would not be achieved. The grinding would most likely be performed after sintering. Grinding before sintering would put enough compressive force on the parts that fracture would be a significant concern.

Chipping was neither diminished nor avoided by changing the feeds, speeds and depths of cut used in producing the non-presintered parts. While care must be taken not to over generalize on ceramic materials, this result has strong negative implications for the manufacture of cut green bodies, which are not presintered. Chipping of a workpiece is generally considered a significant defect and may lead to scrapping of the workpiece. In the case of the parts produced in this study it must be concluded that the chipping was unacceptable. There appeared to be no discernible pattern in the chipping, i.e., it was a random occurrence. This means that in process planning it would be impossible to anticipate chipping and revise the process accordingly. Hence any post-sintering grinding would require the labor of a skilled machinist, greatly increasing the cost of the part. Since the sizes of chips varied considerably there is no guarantee that any one part would be salvageable. While chipping in and of itself is a concern, another concern is the number of chips. Fully half of the samples contained three to six chips each.

The six presintered parts were another matter, however. Despite the fact that they contained a much higher proportion of the more brittle AlN, these parts exhibited no chipping when machined. The bonds formed between the particles of Al during the presintering strengthened the parts, consistent with reports in the literature (Sonnenreich et al. 1988). The parts appear to be strong enough to prevent chipping as the parts are machined.

Both the presintered and non-presintered bodies appeared to machine in a brittle regime. Unlike the machining of a metal, which machines in a ductile mode where chips are formed during cutting, the green ceramic bodies produced a powder while being cut. The powder was blown clear of the work area using compressed air. It quickly became evident that protecting the machinery from the abrasive particles was important. A result consistent with published experience (König and Wagemann 1993).

In summary, it seems very clear that for the Al/AlN system, machining in the green state requires presintering. Attempting to machine pure powder compacts, particularly low density compacts, will lead to chipping and thereby an undesirable product. Several aspects are still to be investigated, however. These include the effects of higher compaction pressures, use of a cold isostatic press, and the effects of presintering time. Probably the richest opportunities lie in extending this research to other material systems.

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