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Experimental studies on improvement of "Material Removal Rate" and "Cutting tool life" while machining Gel-cast fused silica ceramics

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Abstract

There are requirements to develop Ceramic radome made of fused silica for critical defence applications. Green ceramics are sintered as soon as processes related to green ceramic are completed. This sintered ceramics are further processed to obtain final geometry. Processing sintered ceramics at various machining stages pose great difficulty owing to their mechanical and thermal properties, due to which the machinability is very poor for these ceramics. In this paper, an attempt has been made to improve the *material removal rate* and *cutting tool life* while machining fused silica ceramics. For this purpose, a change in processing sequence has been attempted. With the modification in the sequence, an improvement in MRR by 332% is observed. Also it is observed that tool life has been improved by 43%. This paper elaborates machinability study of green and sintered fused silica samples in respect of material removal rate and consumption of diamond cutting insert.

Keywords: Green Ceramic Machining (GCM), Gel-cast ceramic, Material Removal Rate(MRR), Cutting tool life

1. INTRODUCTION

The usage of ceramics in aerospace and missile applications are significantly increasing day by day. Ceramics is one of the preferred materials for missile radome due to its superior electro-magnetic and di-electric constant properties. Radome, an acronym coined from radar dome is a light weight structural, weather proof enclosure that protects a microwave or radar antenna.

Radome is made of some material that minimally attenuates the electromagnetic signal transmitted or received by the antenna. In other words, the radome is transparent to radar or radio waves. Radomes can be manufactured into desired shape and are widely used in marines, naval shipboard, aircraft, and missiles, stationary antennas, and radar dishes to protect radar antenna from wind, blowing sand, snow, ice, rain, ultraviolet sun light, temperature, fungus, and corrosion. Radomes are widely made of ceramics as they were light in weight and have good mechanical and electronic properties [1].

High speed cruising vehicles at high altitude are subjected to severe aero-thermal and mechanical loading. The surfaces of such vehicles are subjected to aerodynamic heating, mechanical stresses and erosion. Radome must have sufficient structural strength and fracture resistance to withstand the aerodynamic forces and foreign object impingement and also it should offer minimal aerodynamic resistance. The Radome should have minimal attenuation and distortion of the outgoing and incoming radar energy [2].

The materials used for construction of radomes for high-speed missile applications should possess high flexural strength, low dielectric constant, low loss tangent, high thermal shock resistance, high rain erosion resistance, etc. Selection of ceramics as radome material is primarily driven by these reasons [3].

It is well known that the powder processed and densified ceramic materials are very hard and brittle in nature. More particularly, in the structural ceramics family, fused ceramics is familiar for its lowest mechanical strength and high brittleness characteristics. Both of these characteristics are undesirable in terms of ease of machining. Low machinability of ceramics is the primary reason behind the limited use of ceramics. This prohibits the replacement of metal parts with ceramic parts in nearly all industries.

In practice, green ceramics are sintered as soon as processes related to green ceramic are completed. This sintered ceramics are further processed to obtain final geometry. Processing sintered ceramics at various machining stages pose great difficulty owing to their mechanical and thermal properties, due to which the machinability is very poor for these ceramics.

In this paper, an attempt has been made to improve the *material removal rate* and *cutting tool life* while machining fused silica ceramics. There were no previous studies found in literature related to MRR and tool life while machining of ceramics. For this purpose, a change in processing sequence has been attempted. This paper elaborates machinability study of green and sintered fused silica samples in respect of material removal rate and consumption of Diamond cutting Insert.

2. FUSED SILICA FOR RADOME

Fused silica is a non-crystalline form of Silicon Di-oxide. Highly cross linked three dimensional structures of this material result into high temperature resistance and low coefficient of thermal expansion. The two most important parameters to evaluate the dielectric properties of a material are its dielectric constant e and loss tangent d (also called as dissipation factor). To obtain excellent wave-transparent properties for high-speed

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radome materials (e) and tan d should be less than 4.0 and 0.01, respectively.

Near-net shape ceramics are commonly produced through forming techniques such as tape casting, slip casting, pressure casting, freeze casting, cold iso-static pressing, direct coagulation casting, electrophoretic casting, hydrolysis-assisted solidification, injection molding and gel-casting[7]. In each of these techniques, the ceramic powder is suspended in liquid-binder system for shaping and all these forming methods start with a suspension where the ceramic particles are mixed with solvent, proper dispersant and possibly further additives such as binders, plasticizers, and antifoaming agents so as to produce well-dispersed, non-agglomerated ceramic slurry. Upon forming, the component is solidified by gelling, drying, or cooling and finally any remaining liquid present is removed, organic binders are burned out, component is sintered, and further may be machined if necessary.

In the present study, the radomes are manufactured by *gel-casting* process using MAM as monomer and MBAM as a cross linker with 70% (Volume) solid loading. As cast silica is referred as *Green-Ceramic* and this is dried at different stages from room temperature to 110°C. Completely dried samples are subjected to subsequent operations such as binder removal at 600°C for two hours and sintering at 1200°C for two hours. It is referred as S*intered-ceramic*.

Before sintering, density of Green-Ceramic is of the order of 1.54 g/cc and after sintering, density of Sintered-Ceramic is of the order of 2.02 g/cc. After complete densification, *bending strength* of sintered-ceramic will be of the order of 40 MPa and *hardness* will be of the order of 600 Mohs.

Table 1. Properties of Fused Silica

Density	2.02 g/cc
Elastic modulus	73 GPa
Shear Modulus	31 GPa
Hardness	600 mohs
Maximum use temperature	1100 deg
Co-efficient of thermal expansion	0.55
Dielectric strength	30
Dielectric constant (e)	3.82

There has been requirement to manufacture following radome for one of our missile applications as shown in figure 1 and figure 2. In this work, near net shaping has been carried out using Gel casting process and further machining has been carried out to obtain final geometry. In the present study, the sequence in which final machining is carried out after sintering has been modified in order to improve Material Removal Rate (MRR) .

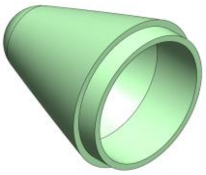

Figure 1. CAD Model of Radome

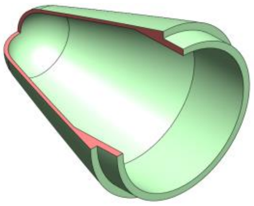

Figure 2. Cross Section view of Radome

3. PRESENT METHODOLOGY

Due to certain process limitation in gel casting process for forming near net shape of this particular radome, the thickness of the radome is 35.45mm after sintering as shown in figure 3. In the present methodology as given in the flow chart, the radome is machined to final geometry after sintering. Nearly 31 mm has to be machined out from the sintered ceramic. The total time involved in machining is around 20-24 hours and the total consumption of PCD inserts for complete machining is around 18-20 inserts. This posed severe economic issues when the radome needs to be manufactured in numbers.

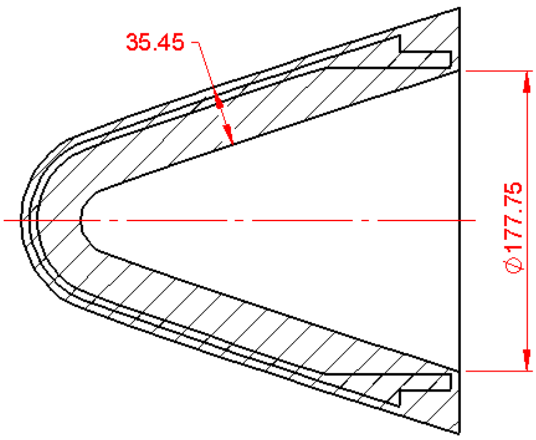

Figure 3. Geometry of gel-casted ceramic raw material

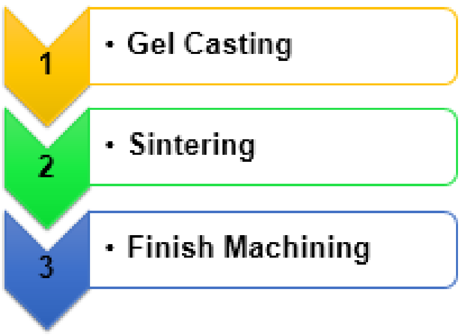

Figure 4. Flow chart of present methodology

4. PROPOSED METHODOLOGY

For machining of gel cast radomes, various machining techniques can be used such as green ceramic machining (before sintering) [4], direct laser machining, and laser-assisted machining (after sintering) [5]. Advanced ceramic materials such as silicon nitride are hard, tough, wear-resistant, and chemically stable, even at high temperature. These properties which are desirable make it very difficult in machining of these ceramic materials.

Since the present methodology is not suitable for mass production, Green Ceramic Machining (GCM) has been utilized for improving production in future. Green ceramic machining (GCM) has been investigated as an alternative method for manufacturing of complex-shaped ceramics. Machining of ceramics in the un-sintered state is called green ceramic machining. Recent advancement of CNC machining technology makes GCM a potential alternative for the rapid fabrication of ceramics.

The flow chart of the proposed methodology is depicted in figure 5. In this approach, green ceramics are subjected to machining after el casting process before sintering process, keeping just only the sufficient allowance for final machining. After green ceramic machining, semi-finished green ceramics are subjected to sintering process and then finish machining has been carried out.

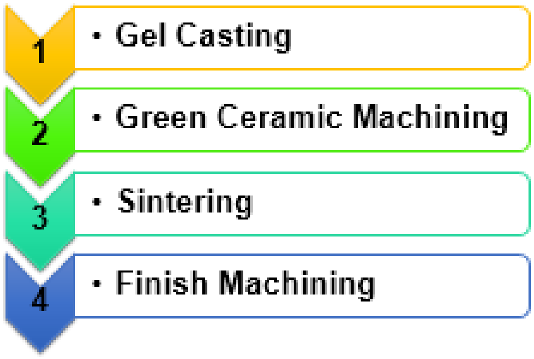

Figure 5. Layout of proposed methodology

Gel casting process leaves lot of excess material which has to be machined in further finishing operations. In green ceramic machining stage, majority of the excess material is removed and only 2 mm allowance is kept before sintering, as shown in figure 6. This allowance material will be removed to obtain final geometry during finish machining stage.

Thus green machining of ceramic allows fast, customized shaping. This approach is applicable to all ceramic materials, as this does not require any special tooling. Green machining does not damage the material and does not induce defects that cannot be corrected during sintering / finish machining. Green ceramic machining is performed whenever possible as the machining of ceramics after firing is very costly. GCM offers several distinct advantages compared with other technologies currently used for the fabrication of net shape ceramics in terms of the cost-effectiveness and surface finishing.

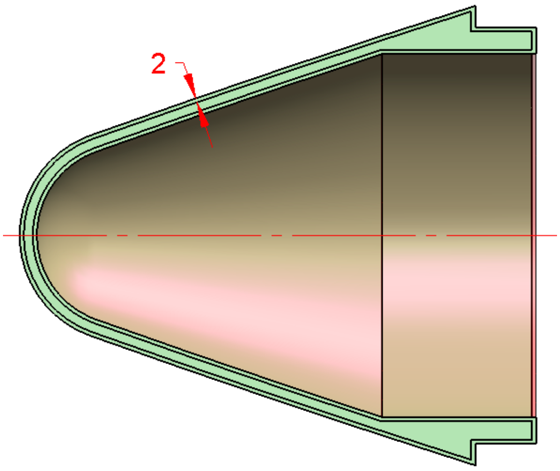

Figure 6. Geometry of ceramic after green machining

In any machining process, a wear-resistant cutting edge separates material from the work piece because of the velocity of the cutting tool edge relative to the work piece. When cutting metals, intense heat causes plastic deformation, producing chips or a curl of material. Green ceramic is different; it is machined by a process of fracturing the material rather than a plastic deformation. The cutting edge crushes the ceramic just ahead of the tool edge as it moves through the material. This forms small particles, resulting in ceramic powder as an end product rather than chips or a curl, as when cutting metal.

The ceramic cutting process does not generate high temperatures. Attention must be paid to the avoidance of chipping at the edge of a work piece and development of internal cracking caused by compressive stresses. Coolants or compressed air is needed to wash away the swarf. When cutting green ceramic, most tool wear is caused by the abrasive nature of the ceramic particles rather than by material temperature or cutting speed. This places emphasis on selecting the most abrasion resistant tool surface material, specifically, diamond. Shrinkage and warping of the ceramic part occurring during its sintering does not allow achieving tight dimensional tolerances and high quality surface finish in the pre-sintered state.

5. EXPERIMENTATION

Researches in green machining of ceramics are rare and know-how is mainly empirical. For studying the advantages that green ceramic machining can provide, two types of samples have been prepared for carrying out experimental studies; one sample is subjected to sintering followed by machining; other sample is subjected to gel casting followed by green machining followed by sintering followed by finish machining operation.

Both the samples are of the size of 50 mm diameter and 100 mm length as shown in figure 7. Turning operation has been carried out to reduce diameter 50 mm to 40 mm using diamond insert. MRR and cutting tool life has been estimated. The first sample has been prepared by following present methodology and second sample has been prepared by followed the proposed methodology.

Figure 7. Sample for Green ceramic machining trials

The cutting parameters, established in the previous study, have been used for this study also [6]. The parameters used for both the methodologies are listed table-1. All the experiments have been conducted on 7.5 kW CNC lathe machine. Demineralized Water as a coolant has been used while machining of sintered samples.

Table 2. Cutting Parameters

Parameter	For machining Green Ceramic	For machining sintered ceramic
Cutting Speed (m/min)	75	30
Feed (mm/rev)	0.5	0.1
Depth of cut (mm)	0.8	0.2
No of samples	09	09

6. RESULTS AND DISCUSSION

For the first sample (all sintered ceramics), MRR has been found to be 141 mm^3/min and the same has been found to be 608 mm^3/min for second sample. Hence an improvement in MRR by 332% is observed by changing the sequence of processing operations as depicted in Table 2. It can be noticed that the total time required to remove the material is also reduced from 301 minutes to 181 minutes, thereby giving 66% time saving.

Tool life improvement study was carried out to measure flank wear. Time taken to attain 0.3mm flank wear consider the tool life of PCD insert. Flank wear has been measured using optical microscope for both the methodology. In the present methodology, 0.3 mm flank wear is observed in 36 minutes, whereas in proposed methodology, it was found to be 51.6 minutes, thereby improving the tool life by 43%.

Having conducted this study, it is confirmed that proposed methodology with green ceramic machining will be economical by multi fold. Hence the radome for our application has been machined using the proposed methodology.

Table 3. MRR Calculation

Parameter	**Present Methodology**	**Proposed Methodology**	
		Green Ceramic	**Sintered Ceramic**
Original Diameter (mm) Do	50	50	42
Final Diameter (mm) Df	40	42	40
Length of cut (mm) L	60	60	60
Total Material removal (mm^3) M	42390	34666	7724
Total time consumed (min) T	301	64	117
Material Removal Rate MRR (mm^3/min)	141	542	66
		608	

7. CONCLUSION

In this work, machinability study of green and sintered fused silica samples in respect of material removal rate and consumption of Diamond cutting insert has been studied. By following the proposed sequence of machining of ceramic samples more than 3 times improvement observed in material removal rate and 43% in tool life.

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