The use of advanced ceramics in the aerospace and defense industries continues to expand. Because the production of critical ceramic components requires a high degree of engineering expertise and manufacturing know-how, the collective abilities of engineers and manufacturers to define, specify, and produce the “correct” surface roughness for a particular application may determine whether the component will perform to specifications.

Advanced ceramic materials are unique because they are susceptible to subsurface damage during the machining process. The same component can be machined by two different companies, both meeting the same “generic” dimensional and surface finish specifications, yet one part fails in its application. There are many considerations related to surface roughness that aerospace and defense professionals should understand to ensure that a component will be manufactured at a reasonable cost, delivered on-time, and have the ability to perform as designed. Various machining methods, such as diamond wheel grinding, lapping, and polishing greatly affect surface roughness. Metrology is also critical for verifying and confirming the final results.
Typical uses of ceramics within the aerospace and defense industries include:

- Mirrors (Lasers, Telescopes)
- Radomes
- Gas Turbine Components (Shrouds, Vanes, Blades, Blisks)
- Transparent Windows and Domes
- Rocket Components
- Nuclear Components

**Application Considerations**

To understand how a component will be used in a given application, familiarity with strength and optical considerations is essential. Diamond wheel grinding is the primary way of machining advanced ceramic components to meet tight dimensional and surface roughness requirements. The diamond wheel grinding process itself creates subsurface damage that can directly affect component strength. Several parameters such as wheel grit, bond type, depth of cut, speed, and feed rate can influence the amount of subsurface damage created. Increased subsurface damage decreases the strength of the component, and directionality of the grind lines can also affect component strength in high stress areas. It is important to realize that components are often designed using material strength values derived from the results of very specific ASTM standards. Test specimens are machined to ASTM standards using strict guidelines that dictate the wheel grit, speeds, and feed rates. Often, these parameters are not translated to the detailed drawings of the final component, leaving a delta between tested and actual material strength based on how the material was machined.
Surface Roughness is critical for optical applications with the main consideration being minimal subsurface damage. Optical components typically have very tight surface roughness specifications, often in the sub-nanometer Ra range, which require lapping and polishing with increasingly finer abrasives to eliminate the subsurface damage. Frequently, the same vendor does not perform all operations on a component, so it is critical to specify the correct surface roughness at each step to mitigate subsurface damage, manage costs, and decrease lead times.

There is a wide range of advanced technical ceramics, and each has unique properties regarding surface roughness. There are monolithic, infiltrated materials, composites, and porous materials. It is important to be knowledgeable about the potential for pullout, reaction layers, porosity, and substitution of “lower grade” materials because one’s choice of material can have a tremendous impact on surface roughness.

Along with material selection, cost is always an important factor. Unnecessary or vague surface roughness requirements can increase the cost and lead times significantly. Ongoing communication between the customer and precision fabricator is critical from project start through delivery. Such close interaction is useful in determining inspection methods upfront to ensure that parts conform to specifications. Frequent communication also helps both parties establish reasonable lead times so that even components with the most unique requirements are delivered on-time and on-spec.
Manufacturing Considerations

Machining of advanced ceramics is typically accomplished with diamond wheel grinding, lapping, and polishing. Diamond wheel grinding consists of using a grinding wheel with industrial diamonds bonded to the periphery to remove ceramic material from the component thus achieving the desired dimensions and surface roughness. There are many types of grinding wheels such as resin-bonded, metal-bonded, vitrified, and electroplated. Grinding considerations, in addition to bond type, include abrasive size and concentration. Parameters of the grinding process such as depth of cut, orientation of grind lines, plunge vs. reciprocating, wheel truing/dressing, and spark outs can also greatly impact surface roughness. All of these considerations must be weighed when grinding to obtain the correct surface roughness while ensuring the part will function correctly in its application.

Lapping is the process of using a loose abrasive between two surfaces that are rubbed together, thus abrading the part. Lapping is typically used to achieve a surface roughness and flatness beyond the capabilities of standard grinding. The difference between a ground part and a lapped one is clear. (Figure 2 -- Comparison Pictures) The type of abrasive and lap material is based on the type of material being lapped and is critical because the choices will affect material removal rates, surface roughness, and how well the lap holds its form. A softer lap allows more of the abrasive to embed in it and produce a better finish with less material removal. If the lap is harder, the abrasive will be free to roll and produce more removal, but the finish will not be as good. Along with the changing of laps, abrasive size is decreased accordingly to yield better finishes.
Another way to increase removal rate is with machinery that can be automated, or that is
designed specifically for accelerating the process with pneumatics and faster spinning speeds.
Although the traditional method of hand lapping can produce highly accurate and repeatable
results, it is a time-consuming process. Clearly, having a component lapped to a specified finish
in a reasonable amount of time requires taking many variables into consideration.

Polishing is similar to lapping in concept, but the process of removing microscopic
surface roughness (asperities) is complicated. Polishing can involve the removal of molecule
clusters at an atomic level. Because polishing occurs at such a small scale, it is often difficult to
explain effective ways to remove asperities. There are differing opinions on how, and why,
polishing works with a majority of what we know coming from empirical data. Depending upon
the component material and kind of abrasive used, mechanical and chemical removal
mechanisms can work together or independently to achieve the desired result. Another polishing
consideration is the kind of material used as the lap. A lap can range in hardness from cast iron
or tin to wax or pitch.

Using zirconia toughened alumina (ZTA) substrates as examples, one ZTA piece is
polished with an aluminum oxide (Al₂O₃), and another with a diamond abrasive, giving both
surfaces a mirror finish. Nevertheless, a surface roughness profile shows that there are major
differences between the two surfaces. (Figure 3 Measurements)
The combination of a felt lap and a heterogeneous diamond slurry results in superior stock removal with a uniform finish as the abrasive affects the surface evenly and consistently. The felt lap and the $\text{Al}_2\text{O}_3$ will not remove the stock as rapidly, and will impact only the weaker parts of the surface, leaving behind traces of damage that can affect how the part will perform, especially in wear component applications.

Considering all of the variables involved in polishing, there are no simple rules about how and when to use it. The best way to meet a polishing requirement is relying on experienced hands who can prevent over-specifying and the resulting waste by calling for tolerances that are too tight or exceed limitations of the material being used.

**Metrology Considerations**

Metrology is critical for inspecting and quantifying a specific surface roughness when dealing with advanced technical ceramics. There are two basic ways of verifying a surface roughness: contact and non-contact. Both methods require technical expertise to understand when and how to use them.

The most basic method is a visual comparison to a known standard. While relatively crude, it can be useful when verifying a relatively coarse surface roughness in an area difficult to reach by other means. It does, however, open possibilities for error due to interpretation differences.
A Perthometer is a contact method of checking surface roughness for values greater than 2μ". It consists of a diamond-tipped stylus that measures surface variations based on vertical displacement of the stylus as a function of position. Various parameters that can affect measurements are the size of the radius on the stylus, traverse length, and what filters are set. Advantages of a Perthometer are that it is not sensitive to surface contamination, color of the material, or the reflectance of the material. They are often portable, allowing in-process inspection on the machine, a flexible and low-cost option. Precautions to keep in-mind are that the diamond-tipped stylus can wear quickly on ceramic materials and the stylus can scratch some parts. A stylus also has limitations on hard-to-reach geometries, and it does not work well on certain kinds of materials, such as porous ceramics. When using a stylus, the operator should ensure that measurements are taken “across the grain” to ensure the maximum roughness value is obtained. (Figure 4 Chart)

White Light Interferometry is a non-contact, optical method used when specifications require accuracy unachievable with a Perthometer. The optical profiler collects data over a field of view instead of a line, negating grinding orientation. Additionally, there is no risk of surface damage, and data gathered may be filtered or transported to software for interpretation. The optical profiler also allows for surface examination from different perspectives and can make measurements in the sub-nanometer range (<0.04μ” Ra). Drawbacks include the inability to measure work in-process on the machine and surfaces with low reflectivity. It also collects data over a relatively small area which may not be representative of the entire surface. Furthermore, ceramic microstructures can cause discontinuities that require filtering.
Regardless of which inspection method is used, the manufacturer and customer need to agree upfront about performing measurements identically on comparable instruments. Failure to do so can result in correlation issues that may affect part acceptance.

Conclusion

Typically, most detailed drawings lack the specifications required for producing and inspecting a successful ceramic component. Therefore, open communication is critical. Ongoing interaction among individuals who understand the application and those who produce the part is critical to the success of the final component. Additionally, effective lapping, polishing, grinding and metrology require a combination of experienced engineering and manufacturing professionals with outstanding judgment and state-of-the-art equipment. Working closely with a knowledgeable machining company that understands how machining can affect final component performance is key to the success of any given application.

###

PremaTech Advanced Ceramics (www.prematechac.com) grinds, laps, and polishes advanced technical ceramics such as Silicon Carbide, Silicon Nitride, Aluminum Oxide, Zirconia, and Composites for applications in aerospace & defense, and other industries. PremaTech employs “Application Adaptive Machining” to ensure that the component works successfully in its application. The company is headquartered in Worcester, MA, 40 miles west of Boston.

Word Count: 1,743
Figure 1: A lightweight silicon carbide (SiC) mirror has been optically polished to deliver superior field performance.

Figure 2: The ground finish has very evident grind lines with a distinct orientation. In contrast, the lapped finish has lines that are hard to resolve by visual inspection, and has no definite orientation.
**Figure 3:** Although the diamond abrasive is harder than aluminum oxide (Al₂O₃), the diamond produces a better surface roughness.

**Figure 4:** The roughness of a ground finish is measured with different orientations and methods.