Industry Viable Strategic Tooling Enablers for MRB (Material Review Board) Elimination
Abstract for 67th Technical Conference and Expo

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1.0 Introduction

Investment casting tooling is extremely expensive and time consuming to manufacture as well as to repair. This is especially true for high pressure ceramic core dies where the question often comes up as to where, within the allowable tolerance band, should the die be targeted. If the focus is on maximizing tooling life, then the smallest tolerances are used (since die wear will only increase these dimensions over time). Unfortunately, this can result in a significant increase in MRB activity at both the casting house and OEM due to the increased likelihood of having many castings fall out of specification. Another other option is to target closer to nominal tolerances, but this is at the expense of tooling life. On top of these concerns, quite often the MRB cores are sent off to the wax room for repairs by hand in an attempt to save them, which often results in further downstream MRB activity for both companies. What if a core/wax die had more or less no surface roughness to create friction, resulting in lower ceramic slurry injection pressures and making the die easier to fill, even for the smallest feature? With 10x lower friction than Teflon, the STS coating system will result in fewer green core MRB related issues. A DLC coated commercial core die was Beta tested and preliminary results showed a *dramatic reduction, if not the elimination of core die wear*. Core dies can now be targeted at the nominal tolerances, since tooling wear is no longer the primary concern. The Surface Treatment System (STS) is the one and only three step coating system that can be used to improve the durability of nearly a limitless number of products. From increasing the hardness and life of casting core dies, cutting and drilling tooling, shafts, gears, gas turbines for the airline and power industries, medical instruments and lenses to name just a few of the nearly endless list of application possibilities. Another parallel initiative that is in development to support further (and possibly even more significant) reductions in investment casting core related MRB activity, is the co-development of a new core system that has significant improvements to green strength, shrinkage, firing temperature and duration that also requires no setters!

2.0 The Cost of Quality

The cost of quality can have a significant impact on a company's Return On Investment (ROI) as reported by David Garvin[1] , "Quality on the line" stated that a 1983 survey of U.S. companies in ten manufacturing sectors found that total quality costs averaged 5.8% of sales. This means that if a $1 Billion corporation reduced quality costs by one tenth of one percentage point, it would save $1 million annually. Other studies show the direct cost of good quality to a company's ROI can be significant. In the same article, David states that for businesses with less than 12% market share, those companies with inferior product quality averaged a ROI of 4.5%, while an average quality product had a 10.4% ROI, and a superior quality product producing a staggering 17.4%

ROI. What this means, is that there is a significant opportunity for increased profit margins, improved product reliability, and reduced warranty costs for the OEM.

3.0 No Single Surface Measurement Technique Captures all Surface Profile Information

Surface roughness is typically not even thought about when we purchase a product. It is also not typically known is that there are many different ways to look, measure and calculate surface roughness. Figure 1 below show two of the more well-known and two of the lesser known surface roughness measurement methods. R_a is the primary surface roughness measurement method used in the U.S., while R_z is the primary method used in Germany. The two lesser known surface roughness measurement techniques R_{pk} and R_{vk} have become more and more recognized as manufacturers are coming to have a better understanding that paying attention to surface roughness can lead to cost reductions. Rp and Rpk are of special interest for the thin DLC coating since it is important for coating integrity that no sharp peaks protrude through the coating, since the uncoated material can lead to early base material degradation. A closer look at the figure 1 below shows that the Ra measurement method doesn't capture either the surface roughness peaks or valleys. The Ra method eliminates the fewer high and low points, and generates an average surface roughness profile based on the remaining information. That's is why we have typically neglected surface roughness in the U.S., because the method used to calculate Ra ignores them.

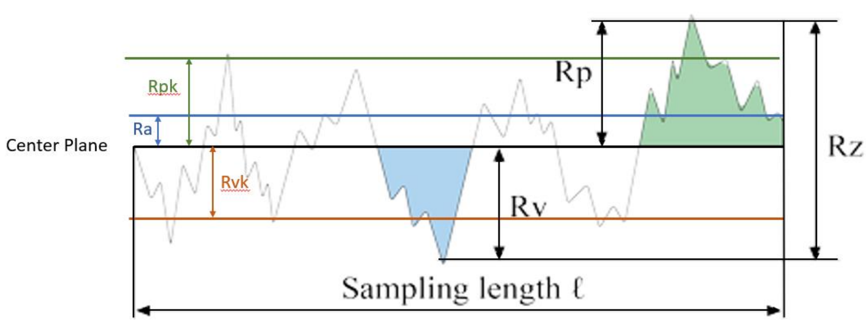

Figure 1: Example of Several Surface Roughness Measurement Methods

However, depending on the thin film application technique used in the manufacturing process, these peaks can easily penetrate the coating, leaving an opportunity for external attack. The coating attack can be started by chipping off that high feature leading to early erosion of the exposed base material, coating loss and eventually early tool repair or replacement. It is also easy to see how the deeper valleys can harbor foreign material, such as chlorides and oxides that if left on the material surface, will begin to attack the substrate and coating from within.

4.0 STS Process Overview

The Surface Treatment System (STS) three step process solves many of the limitations of current coating systems.

The first step of the three step STS process is the rapid and simultaneous removal of surface contaminants, including metal-oxides and corrosion products with a laser ablation system that does not affect the underlying material. This surface preparation process has been demonstrated on both ferrous and non-ferrous metals, as well as composite materials and is used in production today.

The second step is a surface treatment system that will significantly reduce the surface roughness while not re-contaminating the surface in the process, as most surface finishing processes do.

The third and final step is the application of a thin film vapor deposited carbon coating, called Diamond-Like Carbon (DLC). Even if one of the three steps can't be completed, the application of any of the three steps will still improve the product. The complete three step STS process results in an omniphobic (meaning that nothing will stick to it), extremely durable surface finish with 10x lower friction than Teflon which oils, machining chips, ceramic mixtures, etc. will not stick to, resulting in a nearly self-cleaning surface that provides significantly reduced friction, improved wear resistance and life of numerous consumer products.

4.1 Laser Ablation System Process

A typical laser ablation system pulses on and off between 10,000-25,000 times per second resulting in a vaporization of any surface contaminants that have accumulated during the manufacturing and post manufacturing processes. The remaining chlorides, oxides, oils and cleaning solvent residue lie within the valleys left over from the manufacturing process are completely eliminated. Depending on the specific material being used for the tooling, the material surface can be left in what is called a "passivated" condition. Tests conducted by the U.S. Navy have concluded that the "laser process is effective in removing chloride contamination from grit-blasted surfaces and that this results in substantial improvements in the corrosion resistance of the coatings that were applied to laser-prepared surfaces" as compared to non-laser ablated steel and aluminum used for surface war ship construction.

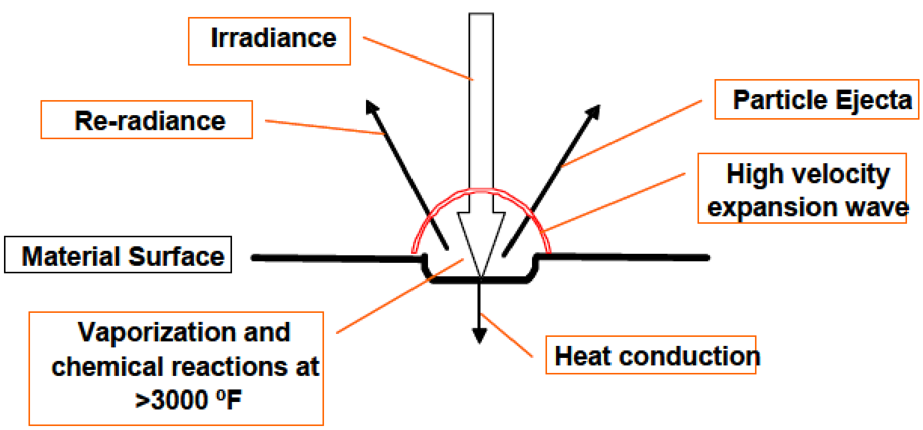

Figure 2: Example of Typical By-products of Laser contacting Substrate Material Surface

Figure 3 below shows how significantly different the surface of these scrap commercial jet engine CFM-56 fan and compressor blades look after the laser cleaning process has been completed.

Figure 3: Laser Ablation cleaned CFM-56 Fan and 1st Stage Compressor Blades

The yellow circled areas in Figure 3 are the locations where the laser ablation cleaning was not conducted. The larger fan blades took approximately 2 minutes to clean completely, so the process is simple and fast.

4.2 Surface Micro Finishing Process

The micro surface finishing system has several primary roles in the three step STS application process. Firstly, to significantly reduce the highest surface features which if left as is, will result in those peaks protruding outside of the thin Diamond Like Carbon (DLC) coating, which is ~2 µm or 0.000078 inches thick. Secondly, there can't be any loss of base material and thirdly, to not re-contaminant the surface after the laser ablation process. Figure 4 shows an example of one of several scrapped CFM-56 commercial aircraft engine test airfoils that are currently being processed using a variety of micro finishing process to support process optimization. The key is reduced variation.

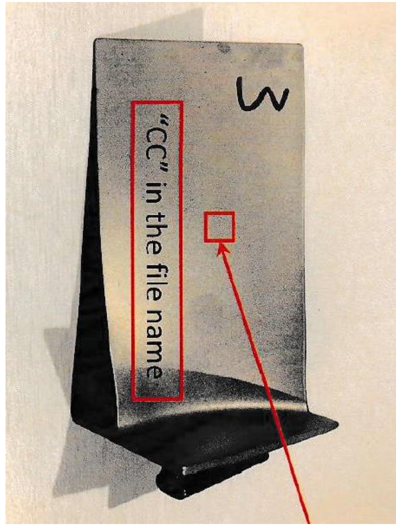

Figure 4: CFM-56 1st Stage Compressor Blade High Resolution Scan Location

Figure 5 is a high-resolution scan of a section of the airfoil prior to micro finishing. Note that there are two sets of results, the top figure is a surface scan over the entire target area (as noted in figure 4), while the bottom figure is a 2D line scan along a section in the target area. What is of most interest in figures 5 and 6 for the STS process are the high, sharp machining peaks, (which is best represented in the lower figure) and the Rpk value found in those tables on the right.

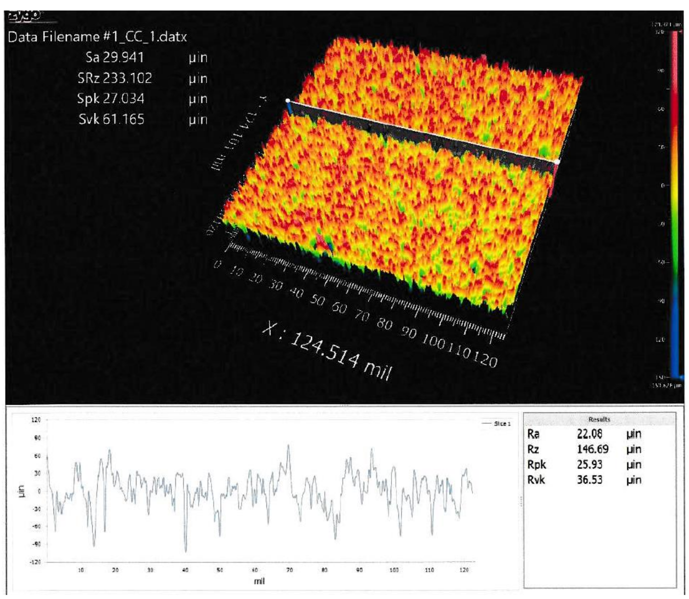

Figure 5: High-Resolution Scan prior to Micro Finishing

Figure 6 is a high-resolution scan of a section of the airfoil after micro finishing. It should be noted that the scales are different between figure 4 and 5, so an absolute comparison is difficult. However, Rpk was reduced by roughly 5x (from 25.93 to 5.67 micro-inches) as compared to the pre-micro finishing scan, and possibly just as important is that the sharp peaks have been eliminated. Depending on the final review of the ~20 CFM-56 fan and compressor airfoils that will have gone through the STS DOE process, further optimization is likely and may also need to be optimized for each specific STS application?

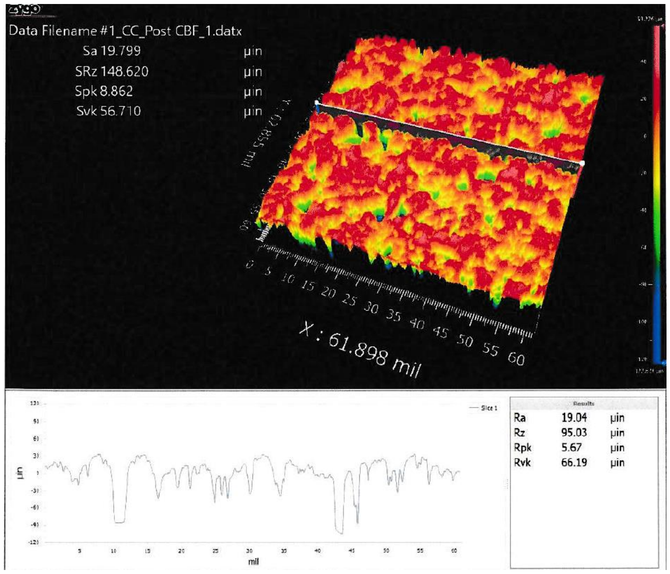

Figure 6: High-Resolution Scan after Micro Finishing

Figure 7 is a comparison of several endurance tested compressor airfoils that were only cleaned (shown on the left) and several other airfoils on the right that went through both the cleaning as well as micro finishing process. The progression of the quality of the airfoil surface finish going from left to right is amazing in the photo and even more so when one is in your hand! Several micro finishing studies were conducted early on and it was found that if a component is left in the micro finishing machine for too long, the surface finish becomes so smooth that the adhesion strength of the original coating system was reduced so much that the hardware needed to be roughened up.

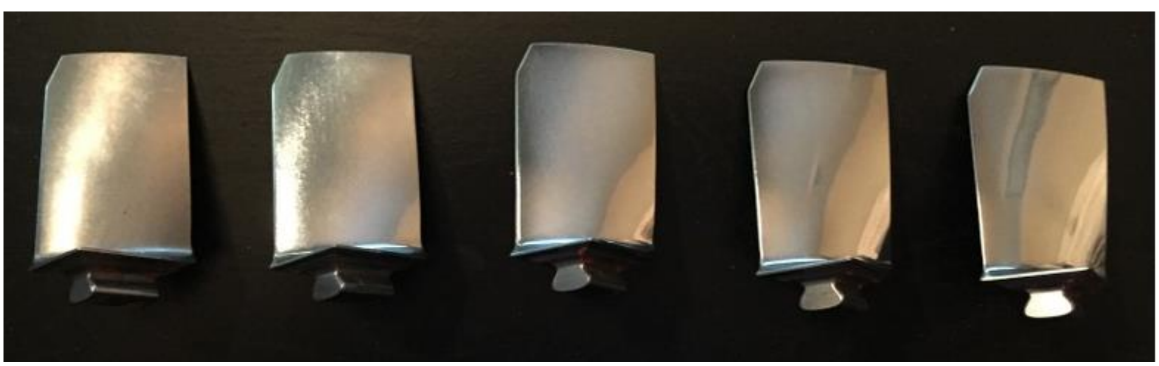

Figure 7: Comparison of Cleaned and Cleaned / Micro Finished Compressor Airfoils

4.3 Dimond Like Coating (DLC) Application Process

The Diamond Like Carbon (DLC) coating uses a “Plasma Enhanced Chemical Vapor Deposition” (PECVD) process that was originally developed as an inexpensive thin film coating application process. Many of our everyday high-volume commodity products use the PECVD process to apply the coatings. The DLC coating was originally developed to support the need for a protective coating to be applied to the various Infra-Red (IR) lenses of U.S. military fighter jets operating in the Middle East. DLC coating has been applied to the IR targeting pod on the Navy's F18 fighter jets. In addition, the DLC coating has been applied to every one of the +20 lenses on the Air Force F-22 air superiority fighter (Figure 8), with over 10,000 lenses coated to date. It is also interesting to note that there hasn't been a single lens returned for DLC coating re-application.

Figure 8: F-22 Fighter with both P&W F119's in full afterburner

The version of the DLC coating that is used for our STS coating has been specifically modified for use on metallic products with the addition of an adhesive layer that is applied prior to the DLC application resulting in a 0.000078-inch total coating thickness (as a comparison an average human hair is around 0.003 inches in diameter). For improved durability it is important to keep the DLC coating as thin as possible to make sure that it remains sufficiently flexible to allow for hardware thermal expansion as well as any micro deformation that may occur under operating conditions.

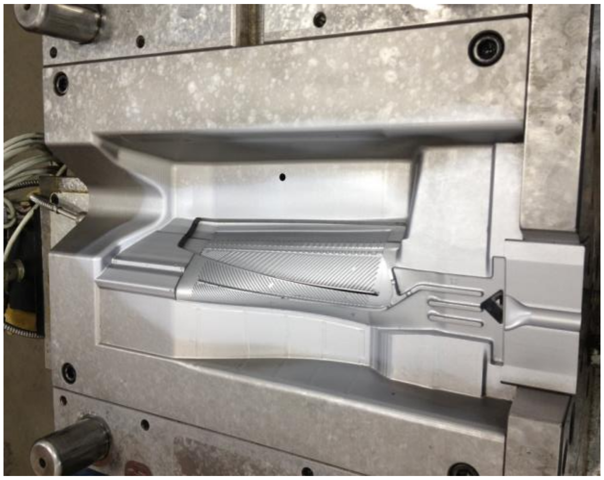

Figure 9: Photo of the core die used in Beta testing without DLC coating applied

The version of the DLC coating that is used for our STS coating has been specifically modified for use on metallic products with the addition of an adhesive layer that is applied during the DLC application. For improved durability it is important to keep the DLC coating as thin as possible to make sure that it remains sufficiently flexible to allow for hardware thermal expansion as well as any micro deformation that may occur under operating conditions. As mentioned previously, the DLC coating has been Beta tested at an investment casting OEM on core die tooling as shown in Figure 9. These initial results showed a dramatic reduction in core die insert wear, and with the complete three step STS process, the improvements are expected to be even more impressive.

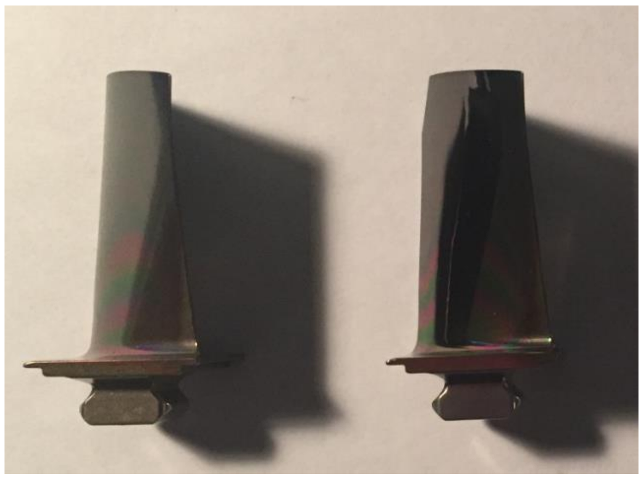

Figure 10: Example of DLC Coated Compressor Airfoils for NASA Glenn

Figure 10 shows several early DLC coated compressor airfoils that NASA Glenn requested to be coated for their review. However, these airfoils did not go through either the laser ablation or micro finishing processes prior to the application of the DLC coating. As indicated earlier in this paper, the current group of ~20 fan and compressor airfoils are going through the entire three step process and are now at the DLC coating vendor.

5.0 Conclusion

The Surface Treatment System is the only three step process that focuses on surface contamination and roughness, coupled with a nearly impervious Diamond Like Carbon (DLC) coating system. In order to get the full benefit from the STS coating, all three steps are needed to adequately address the primary issues associated with tooling wear, and the costly MRB activity that typically results from worn tooling and dies. However, by eliminating any of the remaining surface contaminants, any existing coating will likely benefit with increased durability and longer life, as was concluded in a report issued by the Navy which stated the following, the "laser process is effective in removing chloride contamination from grit-blasted surfaces and that this results in substantial improvements in the corrosion resistance of the coatings that were applied to laser-prepared surfaces”. Secondly, by reducing the surface features that remain after the manufacturing process, the significant reduction in friction related forces that are encountered every day in the investment casting and manufacturing processes will occur. By reducing surface roughness, tooling wear will also be reduced, resulting in a reduction in MRB related activity due to worn dies and tooling. As stated previously after the application of the DLC coating, the surface has 10x lower friction than Teflon and becomes omniphobic (meaning that nothing will stick to it). It is not hard to imagine how much less energy it will take, and therefore, how much less of a concern tooling and die wear related issues will be by such a significant reduction in surface roughness. Separating multi-pull plane core dies will be significantly easier due to the lower surface roughness, and especially important for the newer cores containing multiple fine features that often require rework and repair activity. This extremely durable DLC coating was developed specifically to address a serious issue with sand related damage to the lenses on high speed military fighter jets targeting hardware operating in the Middle East. The application of DLC coating eliminated 100% of the dirt and foreign object wear on these lenses, with not a single lens being returned for damage or loss of coating to date. The STS application process has combined several proven and existing technologies together to form a truly remarkable system that has yet to find all of the applications where this product can be utilized.

As mentioned earlier, there is also the co-development of a new ceramic system that has several unique properties that when coupled with the STS coating system, could provide even more of a significant reduction in quality related issues in the investment casting industry, thereby resulting in an overall improvement in OEM product performance and reliability.

5.1 Next Steps

- Need to review surface roughness **test** results to determine how each variable impact’s surface roughness reduction.
- Need to verify that the DLC coating conforms to the more rounded peaks and if further micro finishing is needed.
- Conduct STS durability testing on existing STS coated CFM-56 compressor airfoils.
- Conduct STS Beta testing on a commercial tooling.
- Conduct STS Beta testing on selected cutting tools for durability evaluation?

6.0 Definition of Terms:

- **Beta test** Typically the first limited duration test of a new product to see how well it performs
- **DLC** "Diamond Like Coating"
- **MRB** **"**Material Review Board" is an industry term for a manufacturing deviation that needs to be reviewed in more detail
- **OEM** "Original Equipment Manufacturer"
- **Omniphobic** A surface that nothing will stick to
- **Passivation** The final cleaning process used to reduce the chemical reactivity of the surface, typically resulting in improved corrosion resistance
- **PECVD** " Plasma Enhanced Chemical Vapor Deposition"
- **STS** "Surface Treatment System" the three-step patented coating system
- **R_a** Most common surface roughness method used in the U.S.
- **ROI** "Return On Investment"
- **R_{pk}** "Reduced Peak Roughness"
- **R_{vk}** "Reduced Valley Roughness"
- **R_z** Most common surface roughness method used in Germany.

References:

1) David A. Garvin, Quality on the line, September 1983 Harvard Business Review