

## Advances in Drilling with PCD (Polycrystalline Diamond)

### Abstract

PCD properties were optimized to drill stacks of CFRP/Ti using an accelerated wear test milling gray cast iron. The optimized PCD was then used to prepare PCD drills. Tests were made to determine the best drilling conditions for the optimized PCD. The results yielded a significant improvement in cycle times as compared to earlier studies using PCD drills. Notched PCD cutting edges were found to eliminate oversizing of the CFRP near the interface of the two materials.

### Introduction

In 1906, Frederic W. Taylor in addressing the opening annual meeting of the American Society of Mechanical Engineers highlighted the questions that must be answered "...by every machinist..." that is, "what tool shall be used, what cutting speed shall be used, and what feed shall be used." [1] While we have witnessed vast improvements in technology since Taylor's presentation, these same questions continue to be at the heart of machine optimization and the macro-economics that govern part production.

While today's CNC machines are capable of remarkable fetes of productivity, it remains for the cutting tool to perform the critical work of cutting, drilling, reaming or milling the part to provide the full utilization of the machine.

Polycrystalline diamond (PCD) cutting tools represent an important part of the cutting tools available to optimize modern CNC machines. First introduced in 1970 [2], with the addition of various grades and shapes, PCD has become an essential contributor to the advances made in machine productivity.

Scott, T. [2], in a review of literature published in 2018 relating to the mechanical properties of PCD expressed a wish that his work would "...allow continued development in the field...of the same or greater magnitude as when PCD first entered the market." Motivated by similar thoughts, the authors undertook a series of experiments specially aimed at improving the performance of PCD drills for drilling stacks of CFRP/Ti.

The unique properties of CFRP, light weight combined with high strength, have accelerated its use in airframe structures for both commercial and military aircraft. Airframe designs requires a way of joining CFRP to other materials most commonly aluminum or titanium or some combination of these three materials.

The most widely used method of joining these materials is by drilling precision holes through a stack of the materials and then joining them with fasteners. This approach has been widely used in the industry in joining aluminum parts without significant difficulty. However, joining CFRP to aluminum or especially titanium creates unique problems.

The term CFRP (carbon fiber reinforced plastic) is a generic term to describe many variations of carbon fibers and plastic binders, each with unique properties and challenges. But what is generally common to all CFRP is the highly abrasive nature of the carbon fiber. Standard HSS drills widely used with aluminum airframes generally wear so rapidly and cause so much damage to the CFRP as to not provide a realistic tool material for drilling CFRP. Tungsten carbide (WC) drills fare much better but suffer from short tool life. PCD and CVD coated drills on the other hand, both demonstrate excellent tool life in drilling CFRP but have challenges in drilling titanium.

There are a number of good academic studies that have been designed to address the challenge of drilling CFRP combined with either or both aluminum and titanium. The difficulty facing most of these researchers, however, is the confidential nature of drilling practices being used in the aircraft industry.

As a result, while valuable, these studies often are not in line with current practices and therefore fail to provide meaningful guidance for the use of either WC drills, CVD coated carbide drills, or PCD drills. Shyha [3] and Park [4] are examples of well-meaning research that suffers from a lack of understanding of current practices or constraints in drilling CFRP.

Shyha studied drilling a stack of aluminum, CFRP, and titanium with both carbide and CVD coated carbide drills. Finding that the titanium swarf caused "severe damage" to the surfaces of both the aluminum and the CFRP, chose to reverse the arrangements of the stack and drill the titanium first. Further, the study found their best results with flood coolant and recommend the use of through the drill coolant at 70 bar. No hole quality data was provided to validate their recommendations.

One is rarely free to choose the way the materials are stacked or allowed to use coolant with CFRP, the practical value and the conclusions lack utility in addressing the current issues faced by industry. Additionally, it fails to address the importance of finding drill designs and conditions that allow the titanium swarf to exit without damaging the CFRP.

Park similarly studied drilling stacks of CFRP and titanium. Both carbide and PCD drills were evaluated. While the drilling conditions and approach were nearly aligned with current practices, essential elements were missing leading to the failure of the PCD drills in this study. Park chose to use exterior mist coolant in drilling the stack of CFRP and titanium without a peck cycle. This essentially meant that the PCD drill was drilling dry in the titanium, a condition that would account for the failure of the PCD drill.

Garrick [5] on the other hand, had the benefit of working directly with both airframe manufacturers and their machine supplier in studying the use of PCD drills for stacks of CFRP and titanium. This work showed that PCD drills could successfully be used in drilling CFRP/Ti stacks and as a result have found wide commercial use.

The purpose of this paper is to optimize PCD for the drilling of stacks of CFRP/Ti and explore PCD drill designs and drilling parameters to improve PCD drill productivity beyond parameters found by Garrick in 2007.

## Difficulties in Drilling CFRP/Titanium

Lightweight titanium alloys are widely used in modern aircraft structures due to their combination of high strength low weight ratio, low density, excellent corrosion resistance and low modulus of elasticity [6]. Machinability however is very challenging because of low thermal conductivity, abrasiveness, and high strength. A CFRP/Ti stack greatly increases the level of difficulty in achieving close tolerance holes in the combined materials.

The first problem encountered is the damaging nature of the titanium swarf as it exits through the composite layer. A second problem arises from the highly abrasive nature of the CFRP which dulls the cutting edges of the drill and contributes to exit burrs on the titanium layer. An additional problem is low thermal conductivity of the titanium that can result in high drill rake face temperatures even at moderate cutting speeds and can cause thermal damage to the CFRP layer.

Using embedded thermocouples in the work piece, Zeilmann [7] studied temperatures during drilling titanium alloys at three different cutting speeds. With internal MQL, temperatures of 200° C were found in the work piece at 15 m/min, 270° C at 30 m/min, and 320° C at 40 m/min.

A number of approaches are used to mitigate these issues. Through the spindle MQL is commonly applied to reduce the cutting temperature of the drill rake face, significantly reducing the heat being generated in the titanium. Peck drilling combined with low feed rates and modest cutting speeds helps in managing the nature of the titanium swarf reducing damage to the CFRP as

well as vibration-assisted drilling. Unfortunately, the low feed rates used affects productivity adversely.

## PCD Grade Optimization

The most direct way to improve the productivity of PCD drills is to use higher feed rates. Historically PCD drills have been restricted to a depth of cut of .020  $\mu$  or less per cutting edge in drill CFRP/titanium stacks due to the limiting tensile strength of the PCD layer. Higher depths of cut are more likely to cause the cutting edge to chip or fracture, hence the first area focused on in this investigation was to see if it was possible to increase the strength of the PCD layer to improve PCD drill productivity.

Significant improvements in PCD grades have been made in the application of PCD to oil and gas drilling according to Scott, D. [8]. PCD used in that field is commonly referred to as a Polycrystalline Diamond Cutter (PDC) to be distinguish from PCD used in cutting tools. The underlying science, however, is the same. Those improvements have allowed the application of PDC in the field of oil and gas drilling to grow from 2% of bits in the late 1980's to currently over 50%.

A study of improvements in PDC showed that sintering pressures along with grain size have contributed to these improvements [9]. In this study, both pressure and grain size distribution were studied as a way of improving wear resistance and strength of the PCD layer of the drill.

An accelerated wear test that both addressed impact and wear was developed milling gray cast iron (ASTM A247) with a PCD milling insert. Milling was done at 250 m/min., feed of 0.1 mm/rev, with a 0.25 mm depth of cut. The test parameters were found to be repeatable and amplified small variations in the PCD formulation.

The milling cutter and PCD insert used in the study are shown in Figure 1.



Figure 1. Milling Cutter with PCD insert.

Diamond powders layered on 16 mm discs of tungsten carbide were sintered at different pressures with different distributions of diamond grain size using infiltration of cobalt from the carbide substrate to form the PCD test samples. Pressure was varied from 5.5 GPa to 8.0 GPa with temperature between 1450 and 1550 C.

The finished PCD was polished, EDM wired and brazed on to steel bodies and then ground to a common configuration used for PCD milling inserts. The finished PCD inserts were then used in milling the cast iron.

Typical wear scars (the white areas on the PCD) for the inserts used in the milling test are shown in Figure 2.

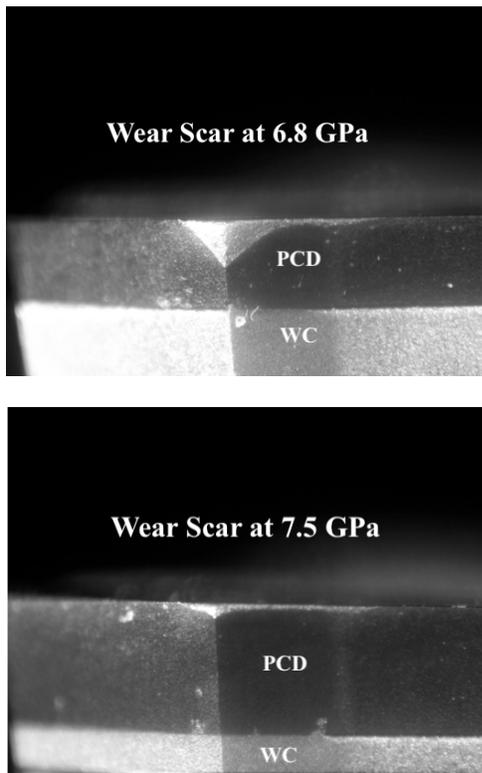


Figure 2. Wear scars on PCD inserts sintered at 7.5 GPa and 6.8 GPa showing the effects of sintering pressure on wear properties of PCD.

The study led to an optimized PCD grade we refer to as MD-5. This grade showed the best overall performance in the gray cast iron milling test and was used in all of the PCD drill studies.

## Drilling Tests with Optimized PCD

The next step was to use this optimized PCD grade in drilling stacks of CFRP/Ti. PCD drills were fabricated and tested using various parameters to determine the effect of this optimized PCD grade on improving drill productivity. Table 1 shows the cutting conditions that provided the best performance and decrease in cycle times in drilling the CFRP/Ti stack. Feed per revolution

was increased over those used by Garrick from .042 mm to .075 mm, an improvement of 78%.

The stack used in the tests consisted of a top layer 5.3 mm of M21E CFRP and a second layer of 4.9 mm Ti-6Al-4V. Mist MQL sprayed at a rate of 12 ml/hr was applied to the drill. A Promicon Spike® wireless tool analyzer was used to capture cutting forces during the drill tests. The drilling was done on a Makino F5-5XR vertical mill as shown in Figure 3.

Table 1. Drill Parameters providing the best conditions for improving cycle time with optimized PCD.

|                  | Drilling Parameters |            |
|------------------|---------------------|------------|
|                  | Garrick[5]          | This Paper |
| Drill Diameter   | 6.350.              | 4.830      |
| Speed (M/min).   | 13.96               | 15.17      |
| Feed (mm/rev).   | 0.042               | 0.075      |
| Peck Cycle (mm). | 1.0                 | 0.5        |
| Stack.           | CFRP/Ti             | CFRP/Ti    |

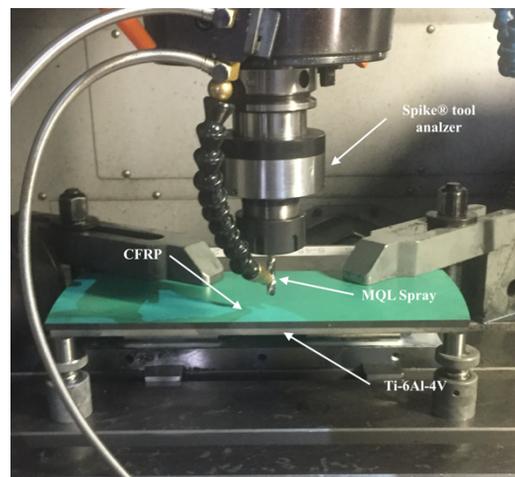


Figure 3. Setup for drilling CFRP/Ti with MQL spray using Spike® tool analyzer on Makino F5-5XR vertical mill.

Figure 4 shows a comparison of cutting forces between a WC drill and a PCD drill of diameter of 4.830. Both drills ground to the same geometry with a 160° split point. The difference in thrust force over the sixty holes drill demonstrate the difference in wear rate between PCD and WC drills drilling CFRP/Ti stacks. Drilling parameters were as listed in table 1.

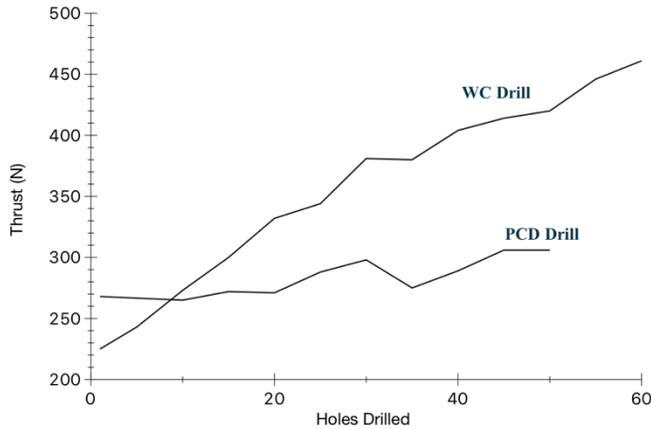


Figure 4. Drill thrust (N) comparing PCD drill to WC drill.

Hole sized was measured for the optimized PCD drill as compared with a WC drill with the same drill geometry. Figures 5 and 6 provide the results of that comparison.

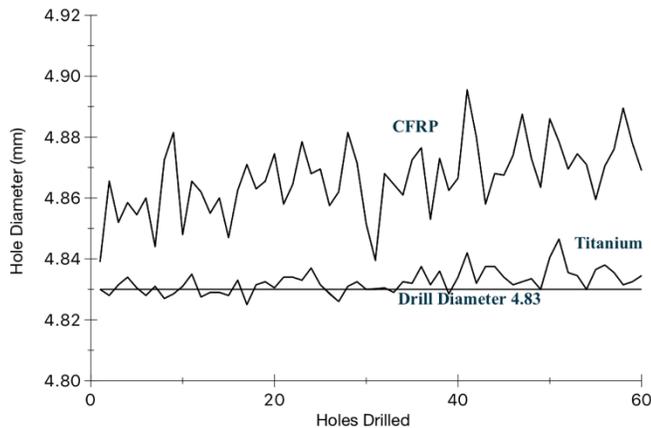


Figure 5. Hole diameters when drilling with WC drill in stack of CFRP/Ti.

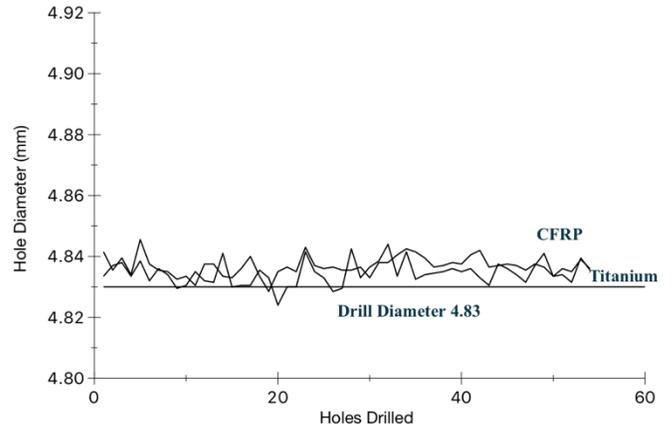


Figure 6. Hole diameters when drilling with PCD drill in stack of CFRP/Ti.

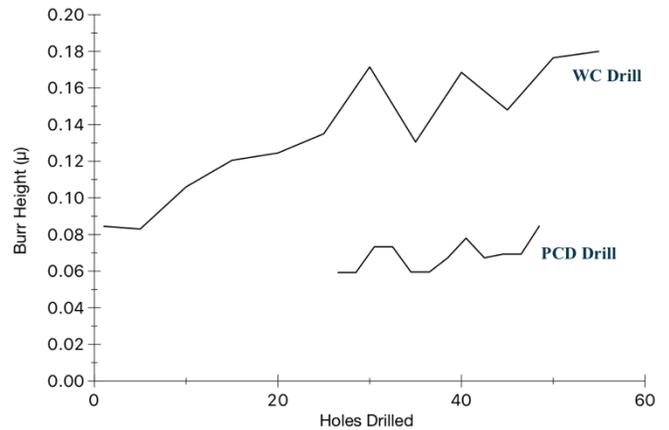


Figure 7. Exit burr on the Titanium generated by WC drill compared with a notched PCD drill.

### Improving CFRP Hole Quality.

In addition to investigating the effects on productivity of the optimized PCD, improvements in CFRP hole quality when drilling stacks of CFRP/Ti were studied.

CFRP hole size is typically measured in the mid-point of the hole. A more detailed examination of the CFRP hole can show an oversize condition just above the titanium/CFRP interface of as much as 150 μ. This condition is a result of the titanium swarf degrading the composite layer as it exits through the CFRP.

The impact of the titanium swarf on CFRP at the interface with the titanium layer is clearly shown from the results shown in Figure 8. A series of holes were drilled with one PCD drill. The first and second set of 25 holes varied the amount of MQL used to drill the holes. The holes between 26-50 used a lower rate of MQL. The holes between 51-75 were drilled with a Mitis unit

(vibration-assisted drilling) creating very small titanium swarf that was able to exit the CFRP without enlarging the hole.

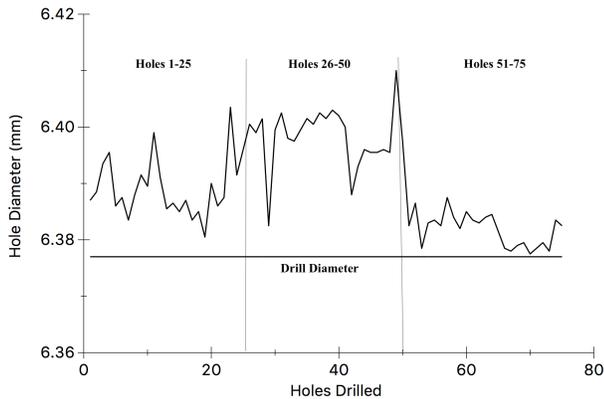


Figure 8. Three series of holes drilled with a PCD drill diameter 6.377, 140° point with through the tool MQL. The last 25 holes were drilled with a Mitis unit providing vibration-assisted drilling.

Figure 9 is a photo of a PCD drill with a notched cutting edge which was investigated as a way of minimizing the damage from the titanium swarf. Figure 10 shows a comparison of the hole size at the titanium/CFRP interface of a notched and un-notched PCD drill.

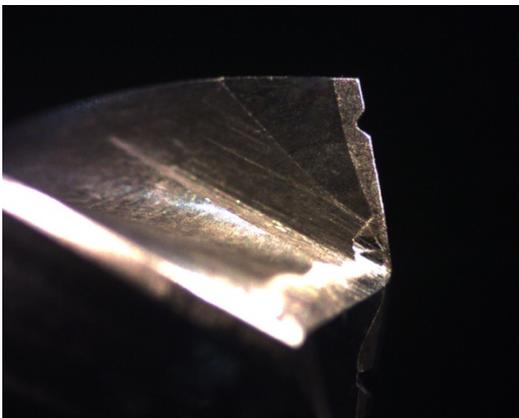


Figure 9. PCD Drill with notched primary cutting edge after drilling 100 holes. The wear on the cutting edges was typical for drilling CFRP/Ti.

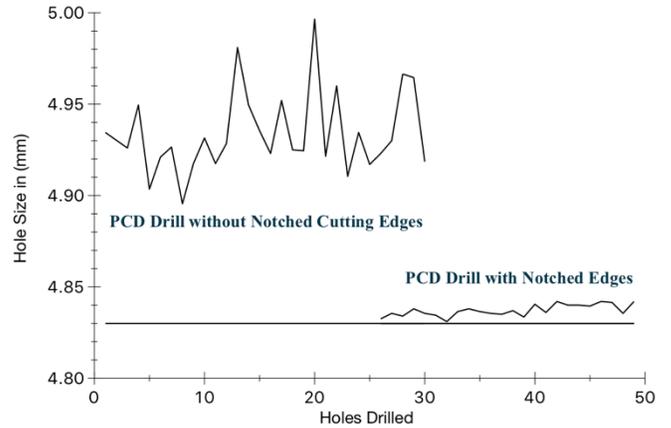


Figure 10. Hole diameters when drilling with un-notched PCD drill as compared with notched PCD drill in a stack of CFRP/Ti.

The notches changed the characteristic of the exiting titanium swarf by breaking it into several smaller chips. This allowed the chips to exit through the CFRP layer without resulting in an oversized condition within the CFRP at the titanium/CFRP interface.

## Summary/Conclusions

The study has shown that cycle times can be improved in drilling stacks of CFRP/Ti using PCD that has been optimized for the application. The strengthened PCD was able to be used with an increase in depth of cut. This significantly improving the productivity of PCD drills.

The addition of notches to the primary cutting edges was shown to eliminate an oversize condition in the CFRP just above the interface between the two materials. Both hole quality and burr height were improved when using PCD drills as compared with WC drills.

## Acknowledgments

Facet Precision Tool GmbH provided the optimized PCD drills and WC drill used in this study.

## References

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