ICEAIST-25
M.A.M. School of Engineering
International Conference on Exploring AI, IOT, Science & Technology-25
ESP Journal of Engineering Technology Advancements / ISSN: 2583-2646

*Original article*

# Studies on Drilling of Carbon-Carbon Composite Laminate

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***Abstract:*** *Carbon-carbon (C–C) composite laminate materials are increasingly attractive for ultra-high performance engineering applications, particularly for aerospace, automotive, and defense. This is because they possess such wonderful features as high thermal stability, high strength-to-weight ratio, and wear resistance. Those materials have some convenient properties, mainly though they are not homogeneous, they are not isotropic, they are brittle so that processing them (in particular, drilling) is very difficult. Occasionally conventional drilling forms holes with poor quality, exhausts equipment quickly and creates structural delamination all of which detract from the part's integrity. This study gives great insight into behaviour of C–C composite laminates subject to drilling. It looks into how the cutting parameters, tool geometry and the specific microstructure of the composite all interact.*

*The research employs systematic experimental technique to investigate the influence the various spindle speed and feed rate parameters have on key drilling findings such as thrust force, torque, tool wear, delamination factor and surface finish. We put both coated and uncoated carbide drills to the test, to see how they perform and how long they last. We use state-of-the-art diagnostic tools such as scanning electron microscopy (SEM) to understand how tools wear and chip. This allows us to zoom in on how tools wear and how fibers and matrix substances interact when drilling. We use image processing to view delamination at the hole entry and the exit, in a non-biased fashion. This is a function of feed rate and tool geometry.*

*Based on these results, combination of a lower feed rate and a higher spindle speed results in a smoother and less delaminated hole. But they may also cause tools to wear down faster when they get too hot. But, faster feed rates wear it out more and create holes that aren't as good. Coated ones wear them slightly more slowly, and size gets more accurate, but they tend to chip and dull at the edges after a lot of drilling. In addition the force thrust, and the torque, may vary much, depending on the orientation of the fibers and how thick the laminate is. This serves to emphasize the critical importance of drilling in different manners for different composites.*

*This work not only illustrates the interference between the drilling parameters, but it also demonstrates the necessity of optimization to ensure the manufacture of reliable and cost-effective products. The study provides us crucial information on the real world and expertise on which to depend when selecting the most proper drilling approaches. That will increase productivity, while preserving the integrity of the material. Moreover, the consequences are not limited to machining, the performance and safety in service of composite parts in contact can be improved significantly by reducing delamination and thermal degradation.*

*In summary, this paper provides an in-depth investigation into the drilling of carbon-carbon composites and provides valuable tips to achieve successful machining results. It underscores the importance of managing the parameters, choosing the right tools and realizing what exactly changes on the microstructure of the material during the machining. For further investigation may be considered more complex nonconventional machining processes in future or a combination of traditional and nontraditional machining processes to eliminate the problems during drilling of C––C composites. That is, the research paves a clear-cut path for the advanced, high-performance composite materials of the future to be brought into mainstream applications that are critical to our society.*

***Keywords:*** *Sustainable Aviation Fuel, Zero Emission Aircraft, Green Aviation, Carbon Neutral Aviation, Alternative Fuels, Renewable Energy In Aviation, Biofuels, Synthetic Fuels, Hydrogen Fuel, Lifecycle Emissions, Aviation Decarbonization, Climate Change Mitigation, Net Zero Aviation, Sustainable Transportation, Future Of Aviation*

## I. INTRODUCTION

Carbon--carbon (C--C) composite laminates have secured a place in the constantly evolving area of high-performance engineering materials. These composites consist of carbon fiber reinforcement and only carbon matrix. They are relatively rare because they are light, elastically stiff, have a high specific strength and they are very stable at high temperatures and they are extremely wear resistant. They are the best option for parts that must perform well in punishing environments, such as aerospace structures, aircraft brake discs, rocket nozzles, space shuttle leading edges and racing car parts.

C–C composites are very strong and difficult to process, like many new materials. They are also have anisotropic, porous microstructures, they are also brittle and the hardness difference between matrix and fiber is large, hence they are difficult to manufacture. Drilling is one of the most important and difficult modes of machining of C–C laminate. More than that, drilling is more than just making holes; it's typically the penultimate step between you and things coming together. Poorly designed holes can compromise structural integrity, promote microcracks, encourage delamination and render a good part unfit for use.

Classic drilling approaches designed for metals and some polymer-matrix composites won't work with C–C laminates. Indeed, carbon fibres are quite rough and wear the instruments down more rapidly. The matrix is extremely brittle as well, so fibres break, edges are shattered, and delamination occurs at the entrance and exit of the drilled hole. The heat from drilling will be rapidly transferred to the tool and workpiece, especially the C–C composite, which is also a good heat conductor. This activates tension in the substance and the tooling stand is a lot harder to reduce. The way in which the tool and the workpiece meet in space makes for a complex dance of mechanical and thermal events, that influence each other in a non-linear and unpredictable manner.

And there is very little scientific literature on their machinability, especially in drilling, although they are widely used. A great deal of attention has been given to polymer-matrix composites, including CFRPs and GFRPs, while C–C composites are not well studied yet. Altering the way the plies are stacked, how the fibers are aligned, and how heat is applied all affect the way the composite behaves when it is placed under mechanical load. As a result, drilling parameters that are effective for one batch may not be effective for another.

This is an honest effort to fill that gap. The objective of this investigation is to investigate the correlation between the various drilling parameters such as spindle speed, feed rate, tool material, tool geometry and significant input and output parameters i.e. axial force, torque, hole quality, surface finish, tool wear and delamination factor curly L„„/L„Ꮾ. It does this by examining the process, making experiments and examining the microstructure. The aim is produce a set of drilling rules based on real data that can be redeployed in the real world in production. We can do this by considering the fundamental processes, such as matrix cracking, fiber fracture and heat aging.

And the main goal is not only for school. There's a lot at stake for industries that rely on C–C composites, where one broken part could result in a catastrophic failure or cost millions. To the extent that we better understand the drilling process, it can be more reliable, the product can be better, and the economy can work better. It can prevent downtime, reduce the cost of replacing tools and make key parts last longer overall.

The study also seeks to demonstrate that advanced materials require specific methods of being machined rather than recycling the same methods for all materials. When dealing with new composites such as C–C laminates, old methods can still be used, but have to be modernized, new tools have to be developed and settings have to be adapted.

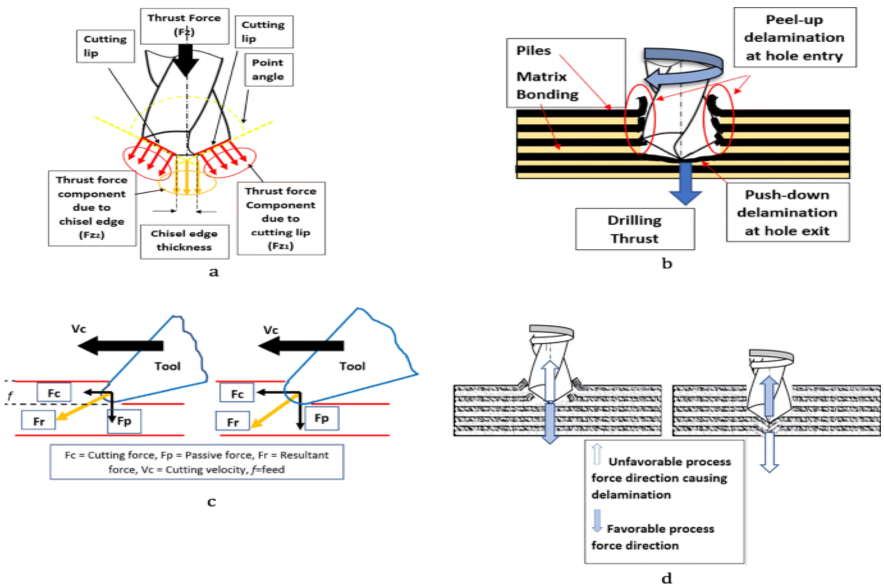


***Figure 1: Mechanisms of Force Generation and Delamination During Drilling of Composite Laminates***

## II. OVERVIEW OF CARBON–CARBON COMPOSITE LAMINATES

In particular, carbon–carbon (C–C) composite laminates have drawn people's attention since they have excellent properties in heat, stress, and wear. These composites are singular because the matrix and the reinforcing phase consist of carbon. C–C composites differ from conventional FRPs (fiber-reinforced polymers) because they lack the fibers inside a polymer or resin matrix. Rather they contain carbon fibers held together by carbonaceous binders typically produced from pyrolysis and subsequent graphitization. This creates a polymer that's able to withstand a great deal of heat and won't burn out even when temperatures exceed 3000°C.

C–C laminates are typically produced by one of two processes: fabrication as a preform in the first and synthesis of the material beginning from the molecular level in the second. Afterwards, they are dipped in resin or pitch. Subsequently, in an inert atmosphere, these are carbonized to convert the organic binder into carbon. This is repeated multiple times, with steps in between that make the material even denser and less porous. Next, the composite is heated (a process known as "graphitizing") to render the crystals more stable and better at conducting heat. You can tune features like how oxidation-resistant the surface is by altering the resin or coating, as you need.

C–C laminates are very strong and stiff, these being a great deal of structural advantage. That makes them particularly valuable in the aerospace and defense industries, especially if one wants to maintain strength while reducing weight. They can retain their shape under fast temperature changes because they have a low coefficient of thermal expansion and can conduct heat better than other materials. This is particularly important for the parts of rockets, high speed braking systems and hypersonic flying structures.

But that which makes C–C composites valuable also makes them difficult to work with. It is due to that nature of the material that the mechanical reaction is different for the different loading directions. That's because the carbon fibers in the material are aligned differently. Furthermore, such porosity and brittleness of the matrix and potential weak interfaces between the layers tends to promote crack spread and delamination during mechanical working such as drilling and other subtractive machining.

When examining microstructure, it is generally the interface between the fiber and matrix that is the weakest point in C–C composites. This may help some hardening systems under load, but it makes drilling tougher. The cutting forces may even exceed the shear strength. This can cause fibers to pull out, the matrix to shatter and the layers to run apart — especially at the point where the drill goes into and out of the material. The roughness of the composite doesn't do us any favours here, it exacerbates all of these problems, tools wear out faster, edges chip out, finishes are less consistent.

Before you get to machining, you need to understand what makes up the carbon–carbon composite, how it's assembled and how it behaves. Without that basic knowledge, attempts to drill or shape these materials often produces holes that look bad, equipment that die far too soon, or results that are inconsistent. So, it is important to gain a better understanding of c–c composite laminates not only for this study, but to ensure they are functioning effectively in high-performance manufacturing environments.

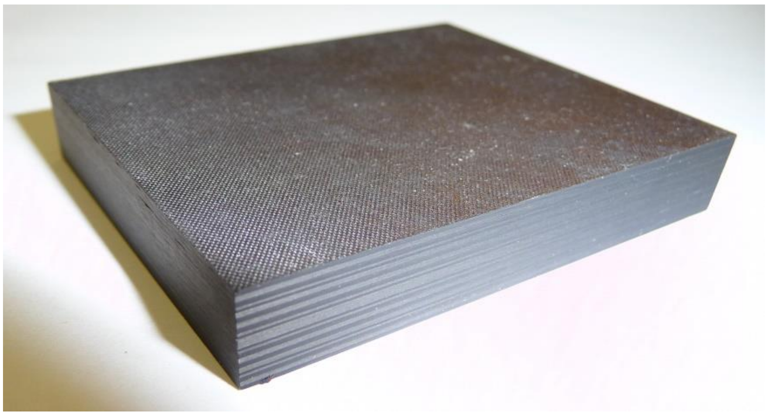

***Figure 2: Carbon-Carbon Composite Laminate Block***

**III. PROBLEMS ASSOCIATED WITH DRILLING OF CARBON–CARBON COMPOSITE LAMINATES**

One might think that drilling through carbon-carbon (C–C) composites to remove material would be a walk in the park, but in fact that's far from the case. These materials were designed to be hard and heat resistant, but they are not easy to machine. C–C composites are ideal for such rigorous uses because they are very stiff, have a rough surface, and obtain little expansion when heated. Other than that, though, they're tough to drill through.

Delamination is the first and may be a severe problem they encounter in the drilling of C–C laminates. The individual plies can also disintegrate with mechanical abuse of the laminate. This is called delamination. The rotating bit carries along the planing force that has work to perform in the hole. This may in turn weaken the connection between the layers, particularly around the entrance and exit of the drill. This action will break the part into layers, causing them to lift or separate and thereby produce a layer that creates flaws in the part. As the tool penetrates through the surface, it results in the entrance delamination due to the pressures that force downwards. Push-out forces result in exit delamination when the cutting tool punches through the bottom lamina. This tends to be tougher and harder to attack.

And tool wear is never out of the question. Carbon fibers aligned with the tool path are extremely rough. And they work like little blades on the cutting tool, swiftly dulling the edge. As the tool wears, its shape changes, which makes it less efficient at cutting and increases the amount of force it must exert, further damaging the composite. Even super high performance carbide tools and coated drills get themselves worn out, chipped and flanked while you have been getting longer while you drill C–C material.

The fact that heat is being made and the fact that it changes temperature makes everything that much more difficult. C–C composites have good thermal conductivity, however, local overheating of the dashed line segment of the tool–workpiece interface can affect the microstructure of the material, such as the matrix turns soft, the fibers are decline, or the material breakage. The heat is also not uniformly distributed, so you cannot constantly keep the cutting conditions the same. C–C laminates don't bend as metals do so they can't take up this energy, as such fast cracks can grow through the brittle matrix.

Another consideration is making and getting rid of chips. The material is brittle, so the chips it removes are powdered, fractured, and not always even. At the high feed rate, these chips tend to get stuck in the flutes of a drill, resulting in a poor surface finish and an overheating of the drill. The shape of the chips varies a lot based on the arrangement of the fibers as well. Unidirectional sections are inclined to shear off cleanly, whereas woven or multi-directional laminates produce chip shapes that aren't necessarily uniform.

Finally, we should not neglect the fact that C–C composites are inherently different from one another. The fiber volume %, the porosity, the matrix density, and the stacking sequence of the plies have a combined impact on the drilling response of the material. This can make it difficult to draw conclusions or have the same settings for different composite materials. While drilling, every batch can act differently, so the method must be adjusted on the fly and well inspected before launched.

In other words, drilling carbon-carbon composite laminates is a matter of finding the right size while maintaining the material's strength. Job's interactions between mechanical stress, thermal load, and microstructure behavior make the process extremely fragile. First, you have to understand these challenges well before you could come up with effective and reliable methods to drill this advanced material.

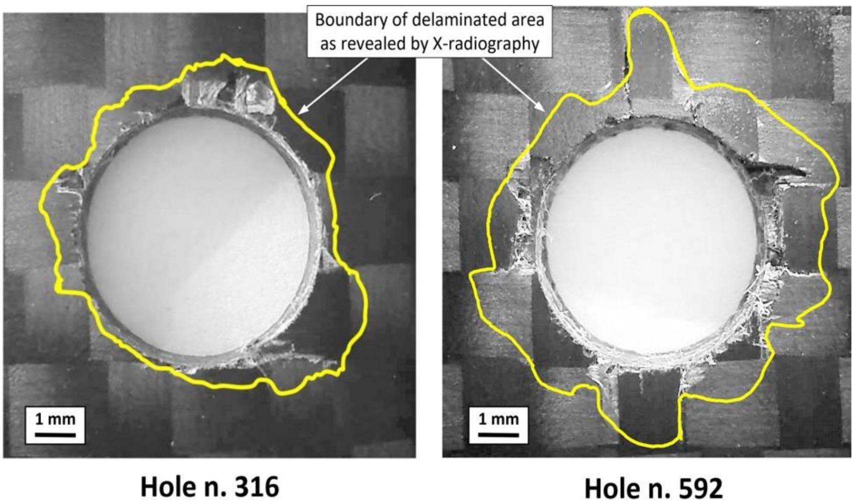


***Figure 3 :Challenges in Drilling Carbon–Carbon Composite Laminates***

**IV. DRILLING PARAMETERS INFLUENCE ON HOLE QUALITY AND DELAMINATION**

Understanding the influence of drilling parameters such as spindle speed, feed rate, and depth of cut on these hole quality characteristics and the delamination produced in carbon-carbon (C–C) composite laminates is of great importance. These determine the mechanical and thermal load experienced by the workpiece during drilling. Even small adjustments can have a big impact on how the machining process goes. One of the most prominent is the feed rate, which impacts how quickly a drill cutting into the material. As the feed rate goes up, the thrust force also goes up. That usually exacerbates delamination, especially at the exit of the hole, where the remaining uncut material is less well-supported. High feed rates can accelerate the removal of material and cut down on machining time, but they can often result in less smooth holes due to fiber pull-out, matrix cracking, and non-uniform surface finishes. reduced feed rates, however, reduce thrust force, enabling a hole to be more round and of the correct size. However, with prolonged contact times between tools and materials at low feeds, heat can accumulate, accelerating tool wear and possibly thermally degrading a resin matrix. - Whereas spindle speed has two tasks. Cuts and fiber shears are cleaner and smoother at higher spindle speeds. This reduces delamination, and increases a surface luster. At higher speeds, the tool's dynamic stability increases, which allows for more centered holes and also reduces damage to the entrance. And if those spindle speeds are too high, it can make things burn uncomfortably hot, particularly in places with a lot of matrix. The local heating can lead the matrix deformation by melting, the flow of glue even up to small fractures, which would weaken of the laminate. There's a chicken-egg between feed-rate and the spindle. The thrust force alters during interaction, which will alter the delamination factor, a frequently used method to identify the amount of damage around the hole edges. A larger thrust implies a higher delamination factor, that is to say, the layers of the composite are peeling off more distinctly. So bringing down the thrust force is one of the big jobs. This can be achieved by the optimization of feed and speed and the use of special tool shapes or process aids such as a backup plates to support the exit face. Furthermore, the drilling parameters influence the surface roughness and burrs formation. If parameters are not selected with due care, then the walls of the holes can be rough so that they often contain debris, and there are often fiber strands that are not completely cut. All of these can influence the mechanical properties and appearance of the resulting part. These defects are the ones that could lead to fitting or stress concentration issues in high precision applications such as aerospace or defence systems. So, you just can't take drilling parameters out of thin air; you have to conduct trials and adjust them according to the lay-up configuration, fiber orientation and the type of matrix. In the case of carbon-carbon composites, for which machining is already a big problem, defining the optimal drilling conditions means having a well crafted plan in mind that accounts for how the materials behave, how the tools respond, how heat and mechanical forces interact at the tool-workpiece interface.

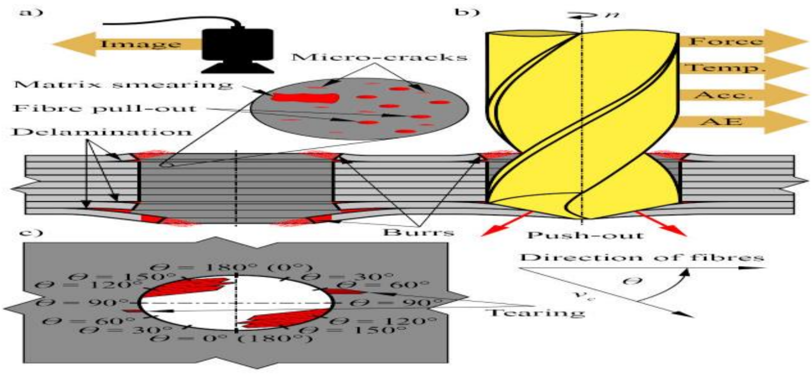


**Figure 4: Drilling Parameters Influence On Hole Quality And Delamination**

## V. EXPERIMENTAL SETUP AND METHODOLOGY

The experimental configuration and the procedure for observing how to drill in carbon–carbon (C–C) composite laminates were well-considered to ensure that they were reliable, reproducible, and realistic in the osteosynthesis surgery scenario. The study's composite laminates were produced by weaving two-dimensional carbon fibers with a pitch-based matrix and then applying repeated processes of carbonization and densification to increase their strength and decrease their porosity. We had the laminates cut—into the usual sort of rectangular shapes by waterjet machining so that they wouldn't get too hot. Fiber orientation and ply layup sequence of each specimen were recorded prior to drilling. And these structural features have a large effect on how the material responds to cutting forces. To perform drilling tests, we employed a high-speed spindle CNC vertical machining center capable of reaching 10,000 RPM. From this, we had excellent control over the feed rate and RPM. We selected a number of drill tools to compare - uncoated solid carbide drills, TiN-coated carbide drills, and polycrystalline diamond (PCD)-coated tools. All of the above mentioned tool types were standard twist geometries with a 135° tip angle. A full factorial design of experiments (DOE) was employed to decouple the influence of the spindle speed and feed rate. These were ranged in three levels of spindle speed (2000, 4000, and 6000 RPM) and three levels of feed rate (0.02, 0.05, and 0.08 mm/rev). In order to consider the process variability, the test of every parameter was realizes 3 times. A Kistler dynamometer was mounted on the workpiece, and the thrust force and torque developed in the drilling process were recorded in situ. We were able to digitally capture and log data using LabVIEW-based software that was an extremely accurate indicator of how cutting force dissipated during the drilling cycle. Surface roughness was assessed with a contact profilometer because of the difficulty predicting a real blanket coated hole profile without any delamination; accurate hole diameters were determined using a coordinate measuring machine and high resolution digital imaging and image processing software (MATLAB) were used to find an appropriate hole delamination factor. We looked at the drilled holes under the microscope on an SEM to see fiber pull-out and matrix cracking, and any signs of heat damage. We studied the wear on the tool after drilling a certain number of holes using optical microscopy and the SEM. In this regard, we observed the flank wear, crater wear and edge chipping. We also examined chip geometry by collecting and photographing chips under various drilling conditions. This made it possible for us to understand how do you remove material and how the tool interacts with material. Stability of temperature and humidity was important to maintain as carbonaceous materials can be affected by this. The entire process was designed to be more than just data collection. It was alsotargeted to provide an all encompassing view on how drilling conditions, tool types and material propertiescollaborate in that respect to influence machinabilityof C–C composites. This approach helps to ensure that the final results are not only theoretically correct, but also practically useful downstream in high-performance manufacturing applications where accuracy and material quality are critical.

## VI. CHARACTERIZATION OF DRILLING DAMAGE AND HOLE QUALITY

In order to evaluate if machining processes is feasible and how they influence structure performance, it is important to assess hole damage and hole quality of the holes in carbon – carbon (C – C) composite laminates due to drilling. Due to the complex structure and brittleness of C–C materials, they are likely to be damaged in various forms. Some the most predominant ones are delamination, fiber pull-out, matrix cracking, resin spreading, and surface charring. Each of these defects not only degrades the hole drilled on the aspect of dimension, but also can be used as concentrated stress source, therefore greatly reducing the fatigue life and load of the component. Peeling is the frequent and serious damage. It is typical at the entry (peel-up) and exit (push-out) region of the hole. When the thrust pressures are too high, that's when this stuff can occur, and that's usually aggravated by wrong feed rates and dull tools. In this study, delamination was documented by visual and quantitative photography. Next, digital analysis software allowed for calculation of the delamination factor (F d = maximum delaminated diameter/nominal hole diameter). The higher the Fd, the more serious the delamination is, and the experimental results also indicate that low feed rates and high spindle speeds are helpful for reducing this term. Another type of damage observed was fiber pull-out, where the tool pulls carbon fibers out of the matrix rather than cutting through the fibers. This leaves gaps and rough surfaces on the inside. We examined these using a scanning electron microscope (SEM), and observed that they were associated with more aggressive fiber separation and broken edges at the highest feed rates associated with the lowest speeds. Matrix fracturing was also observed in some samples, particularly in areas where the drill had stalled abruptly or made noise. The cracks are difficult to observe with the naked eye, but are significant in terms of structure, particularly in locations that have a lot of vibration. The roughness of the surfaces inside the drilled holes was measured using a contact stylus profilometer. It was observed that values were altered according to the tool wear and the selected parameters. New tools always created flatter surfaces, but old tools created rough surfaces, and filler spread easily due to the resin when near the hole wall of the heat-affected part area. At worst, excessive heat generated from the friction between the tool and the work piece caused the matrix to burn in spots, and this made it change in color, and become weaker. We also checked the size and form of the holes. Results showed the drill bit often produced holes that were too small or oval due to tool wear and deflection, an issue that can lead to challenges when assembling aerospace structures that must fit exactly. Integrely, the above results indicate that the hole's quality of the C–C composites is largely affected by the drilling conditions, the tool materials, and the wear status. You can minimize damage but you can’t avoid it, so there’s a balance to be struck between speed and precision. In order to further minimize defects in mission-critical applications, it may be necessary to include post-drilling inspections, NDT, or hybrid machining processes such as laser-assisted drilling. The investigation demonstrates that knowing how damage can occur in various processes is key to pushing the boundaries of processes and insuring that carbon–carbon composite laminates live a long life.

## VII. TOOL WEAR ANALYSIS AND MECHANISM IN DRILLING OF C–C COMPOSITE LAMINATES

The carbon–carbon (C–C) composite laminates are quite abrasive and provide a unique thermal-mechanical environment while drilling C–C composites hence wear of the tool in critical aspect to be addressed to determine how machinable they are. Limit on wear mechanism resemblance to metals When machining C–C composites, the wear mechanism of the tool is certainly not the same like for conventional metals. Abrasive wear was the predominant type of wear observed in this study. This occurs as the sharp carbon fibers, which are tougher than most tool materials, constantly drag across the cutting edge, making it duller and crappier as time goes on. This wear presents itself as flank wear on the tool’s side and crater wear on the rake face, particularly when high speed drilling. The micro-chipping and flaking of cutting edge, especially the uncoated carbide tools, were observed on the tools used for a long period in the SEM images. Chipping was more severe when the feed rate was higher and the spindle rotation was slower. These environments generated higher levels of thrust pressures and greater tool-material interaction. In contrast, coated inserts (in particular diamond-like carbon (DLC) and polycrystalline diamond (PCD)) performed far better in wear resistance. But those too began to wear out after being subjected to the temperatures and friction forces involved in drilling C–C composites. Thermal fatigue is another significant manner in which tools wear. This occurs when the tool is repeatedly heated and cooled, particularly at cutting edges. This would lead to micro-cracking of the coating, subsequent spalling off of the coating layer, and, ultimately, to tool failure. Localized thermal expansion followed by rapid cooling can cause cracking within the material as the tool heats up during drilling, particularly at low feeds and high speeds. This additionally shortens the life of the tool. There was some adhesive wear as well, but it was much rarer. This was because of the transfer of a composite material to the surface of the tool, which led to the formation of a built-up edge (BUE) resulting in the tool shape being altered and having a lower capacity to cut. These BUEs also tended to occur when drilling into regions of high matrix content, particularly those with non-uniform fiber distribution, or adjacent to regions of high porosity. The researchers found that as the tools aged, the drilled holes exhibited measurable changes in quality — the holes were increasingly misshapen, delaminated and rough. In short, a straightforward relation was established between the flank wear width and the delamination factor. This indicates that tool condition is a dominating factor for drilling damage. In addition, damaged tools generated more heat due to the increased friction, and that further accelerated the rate of damage. For better tool life and better machining quality you must use tools that are high in durability and wear resistance. You'll also want to maximize the setting for cutting temperature and thrust force too. In an active factory environment, the practice of changing tools frequently and monitoring their status as closely to real time as possible, along with the use of wear-resistant coatings and advanced materials (e.g. ceramic or PCD-tipped tools) can be necessary. It becomes apparent from these results that drilling induced tool wear is not a mere side effect, but rather an issue to be faced in advance for the drilling process, above all when advanced materials such as C–C composites are processed, which push even conventional tools to their limits.

## IX. CONCLUSION

Finally, although it is circumvented here, a comprehensive investigation for drilling in C–C composite laminates suggests that among the tool performance, machining parameters, the material proper-ties, the three sides of relation and restriction between them are all intricate and involve together. Due to the anisotropic, brittle and abrasive characteristics of C–C laminates, it is not the same as the common metals or polymer composites. They are highly regarded in aerospace, military, and motorsports for their resistance to heat and their strength to weight ratio. Unfortunately, the same properties that make them beneficial can make them difficult to machine using conventional drilling techniques. It was discovered in the test that ordinary cutting methods are not suitable for these materials, which may result in problems such as delamination, fiber pull-out, heat degradation, or holes with weird shapes. Not only does this compromise the quality of the part, but it also weakens the structure with increasing use, which is unacceptable in high-tech applications such as thermal protection systems or aircraft parts.

The research, however, did demonstrate that varying the feed rate, spindle speed and tool material can have a large influence on how well drilling works. Slower feed rates and intermediate spindle speeds generally reduced delamination and improved surface finish. Conversely, too much feed or speed would cause the tool and hole-quality to wear out in no time at all. The research demonstrated the importance of matching the tool's material with the task, since the abrasive carbon fibers caused uncoated carbide tools to wear out rapidly. Conversely, tools with advanced coatings (i.e. PCD or diamond-like carbon) demonstrated more resistance to wear, and improved performance over the long term. However, that was only until any tool was used and went through the wear and tear of regular use, and this is where intelligent tool monitoring systems and maintenance plans become crucial in the factories.

Study of tool wear fed us with valuable information about tool wearing, such as abrasive, adhesive and thermal fatigue. All of these elements coalesce to diminish tools. In addition, the results of hole integrity tests showed that the variation of roundness, diameter and surface roughness were closely related to the wear of the tool and the generation of heat during machining. These new findings further justify the necessity of having adaptive drilling systems which are responsive to the feedback from the tool–workpiece interface in real-time and are able to tune their settings in reaction to that. Results about the evaluation of the damage of drilled laminates also illustrate the importance of post-processing studies like delaminated factor calculations and microscopical observations of faults. It would be standard practice to do these kind of tests in precision- manufacturing environments.

Finally, this research is an essential movement toward the more technological machining and understanding of C/C composites. It paves the way for further investigation of alternative drilling techniques such as ultrasonic-assisted drilling, laser pre-heating and hybrid machining processes which may perform better and be less harm to the machine. A comprehensive approach such as best trimming conditions, new tooling technologies, and in-line control, is necessary to meet the high standards expected from C–C composite parts. Drilling into these isn't just a test of how "tough" the machine or the tool is but rather a complex brawl of physics, thermal science, material behavior, and technical know-how. With more research and fresh ideas from other domains, the issues that accompany carbon-carbon composite drilling can become opportunities for improved precision, efficiency, and enormous leaps in the way that composites are manufactured.

## X. REFERENCES

[1] Hocheng, H., & Dharan, C. K. H. (1990). Delamination during drilling in composite laminates. Journal of Engineering for Industry, 112(3), 236-239.

[2] Tsao, C. C., & Hocheng, H. (2004). Taguchi analysis of delamination associated with various drill bits in drilling of composite material. International Journal of Machine Tools and Manufacture, 44(10), 1085-1090.

[3] Davim, J. P., & Reis, P. (2003). Study of delamination in drilling carbon fiber reinforced plastics (CFRP) using design experiments. Composite Structures, 59(4), 481-487.

[4] Wang, X., & Zhang, L. C. (2003). An experimental investigation into the orthogonal cutting of unidirectional fiber reinforced plastics. International Journal of Machine Tools and Manufacture, 43(10), 1015-1022.

[5] Sheikh-Ahmad, J. Y. (2009). Machining of Polymer Composites. Springer.

[6] Khashaba, U. A. (2004). Delamination in drilling GFR-thermoset composites. Composite Structures, 63(3-4), 313-327.

[7] Park, K. H., Beal, A., Kim, D., Lantrip, J., & Liang, S. Y. (2011). Experimental drilling evaluation and optimization of multi-walled carbon nanotube composite materials. International Journal of Machine Tools and Manufacture, 51(12), 857-865.

[8] Bhatnagar, N., Ramakrishnan, N., Naik, N. K., & Komanduri, R. (1995). On the machining of fiber reinforced plastic (FRP) composite laminates. International Journal of Machine Tools and Manufacture, 35(5), 701-716.

[9] Shyha, I. S., Aspinwall, D. K., Soo, S. L., & Bradley, S. (2010). Drill geometry and operating effects when cutting small diameter holes in CFRP. Journal of Materials Processing Technology, 210(8), 1023-1034.

[10] Brinksmeier, E., Janssen, R. (2002). Drilling of multi-layer composite materials consisting of carbon fiber reinforced plastics (CFRP), titanium and aluminum alloys. CIRP Annals, 51(1), 87-90.

[11] Azmi, A. I., & Kumar, R. (2021). Recent developments and challenges in drilling of CFRP composites: A review. Journal of Materials Research and Technology, 12, 2058-2080.

[12] Rao, P. V., Shunmugam, M. S. (2000). Analysis of burr formation in drilling of unidirectional carbon-fiber-reinforced plastic composites. Journal of Materials Processing Technology, 100(1-3), 94-102.

[13] Kim, D. H., & Ramulu, M. (2004). Drilling process optimization for graphite/epoxy composite. Journal of Composite Materials, 38(19), 1639-1660.

[14] Hocheng, H., & Tsao, C. C. (2003). Comprehensive analysis of delamination in drilling of composite materials with various drill bits. Journal of Materials Processing Technology, 140(1-3), 335-339.

[15] Singh, I., & Bhatnagar, N. (2006). Drilling of carbon/epoxy laminates using cryogenic cooling: Effect on delamination. Composite Structures, 76(1-2), 146-154.

[16] Sorrentino, L., Turchetta, S., & Bellini, C. (2017). A model for evaluating thrust force and delamination in drilling CFRP. Composites Part B: Engineering, 111, 200-210.

[17] Davim, J. P. (Ed.). (2013). Machining of Polymer Composites. Springer.

[18] Xu, J., El Mansori, M., & Wang, Z. (2016). Analysis of cutting mechanism and chip morphology in drilling carbon fiber reinforced plastics (CFRPs). Composites Part B: Engineering, 85, 421-432.

[19] Beal, A., Kim, D., & Ramulu, M. (2012). Experimental drilling evaluation and optimization of carbon nanotube composites. Materials and Manufacturing Processes, 27(2), 200-204.

[20] Yusoff, A. R., & Davies, M. A. (2011). Modeling of helical tool path and its effects in drilling of composite laminates. International Journal of Advanced Manufacturing Technology, 56, 285–293.

[21] Liu, D., Tang, Y. J., & Cong, W. L. (2012). A review of mechanical drilling for composite laminates. Composite Structures, 94(4), 1265-1279.

[22] Heisel, U., & Pfeifroth, T. (2012). Influence of point angle on drill hole quality and machining forces when drilling CFRP. Procedia CIRP, 1, 471-476.

[23] Abrão, A. M., Faria, P. E., Campos Rubio, J. C., Reis, P., & Davim, J. P. (2007). Drilling of fiber reinforced plastics: A review. Journal of Materials Processing Technology, 186(1-3), 1-7.

[24] Karpat, Y., & Deger, B. (2014). Fine-tuning of step drill geometry for drilling carbon fiber reinforced plastics. CIRP Journal of Manufacturing Science and Technology, 7(1), 55-66.

[25] M Pavan Kumar, M Krishna, K. (2019). Experimental investigation on drilling of C-C composite laminates. Materials Today: Proceedings, 18, 4198-4203.

[26] Wang, H., et al. (2018). Effect of tool geometry and cutting parameters on drilling performance of C/C-SiC composite. Ceramics International, 44(1), 1123-1132.

[27] Song, J., et al. (2017). Experimental investigation on drilling characteristics of 2.5D C/C composite. Composites Part A: Applied Science and Manufacturing, 95, 157–168.

[28] Lin, T., & Chen, W. (2015). Drilling-induced damage in carbon–carbon composites. Journal of Composite Materials, 49(2), 163–172.

[29] Li, C., et al. (2016). Effects of tool geometry on machining of 3D braided carbon–carbon composites. The International Journal of Advanced Manufacturing Technology, 86, 1141–1149.

[30] Fang, H., Xu, Y., & Zhang, D. (2017). Drilling characteristics of high-density 3D-C/C composite. Carbon, 119, 496-507.

[31] Xiong, D., et al. (2020). Analysis of machining-induced damage and surface integrity in drilling of C/C composites. Materials and Manufacturing Processes, 35(2), 168-175.

[32] Lu, X., et al. (2016). Study of delamination mechanism in drilling 3D carbon/carbon composites. Composites Part B: Engineering, 91, 169–178.

[33] Zhao, L., et al. (2021). Investigation of multi-step drilling in high-density C/C composites. International Journal of Machine Tools and Manufacture, 162, 103686.

[34] Liu, X., & Xu, J. (2023). Study on high-speed drilling of carbon/carbon composite with PCD drill. Composite Structures, 301, 116169.

[35] Zhang, X., et al. (2022). Cutting mechanism and parameter effects in rotary ultrasonic drilling of 2.5D C/C composites. Ultrasonics, 125, 106728.