Detection of Manufacturing Flaws in Ceramic Matrix Composites using Machining Force Signatures

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Metals and their alloys have become dominant materials used throughout the aerospace industry. In recent years, composite materials have made way and have brought promising results compared to their metal counterparts. A specific group of composite materials that have proven superior are ceramic matrix composites. These composites provide great physical-mechanical properties like high strength, hardness, thermal protection, and corrosion resistance. Due to its high hardness and abrasion resistance, the material makes it quite difficult to machine which has reduced large scale production of manufacturing. This paper will entail the research conducted on ceramic matrix composites and the experimental procedures applied to acquire a greater understanding of the quality of the composite through the machining processes.

I. Introduction

Composite materials have been incorporated in the aerospace industry for its amazing properties similar to metals but at a fraction of the weight along with many other advantages. A subgroup of composite materials are ceramic matrix composites (CMC). This composite material is made up of two ceramic parts; a reinforced fiber and the matrix material which holds everything together. Typical reinforcing fiber materials include carbon, silicon carbide, alumina and many more. They usually are made up of a polycrystalline structure in various forms like continuous fibers, nanofibers, and short fibers. Each of these forms will be utilized depending on the desired application of the material. CMC maxtrix material is also made up of similar materials to the reinforced fibers.The layers of the prepeg tape are stacked on each other and later the matrix material is converted into a ceramic.With regards to the field of machining composites, there has been extensive studies conducted to understand the nature and machinability of these composites. As for CMC materials, this field is fairly new and due its high demand, a greater understanding for is needed for future applications. Due to the high price of CMC, the bulk of drilling was applied to Hardie Board as this offered a similar process as it would on a CMC. Extensive literature surveys were conducted in order to acquire a good amount of knowledge on the subject of drilling through composite materials and how other experiments can be replicated to contribute to the studies needed to understand this process. Most previous studies worked towards understanding the specific drilling parameters to apply to the test piece and how this would effect the grinding forces, and the type of damage the material would endure. It is commonly found that the primary cause of crack in the material is due to the stress being greater than that of the fibers and matrix of the composite. It is important to be able to record the axial force applied to the material along with the torque to fully understand the integrity of the material.

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II. Literature Review

A. Manufacturing Ceramic Matrix Composites

Similar to the manufacturing of other ceramics, CMC has various different type of procedures in manufacturing depending on the desired results and properties you need from the material. Some of these processes include hot press sintering techniques, liquid phase infiltration, and polymer infiltration and pyrolysis (PIP). With the increase in research and development, these processes have been up-scaled for mass production. A common manufacturing process practiced by General Electric is the liquid phase infiltration process.

The process starts with the melting of a polysaline powder which allows for curing and heat treating into a silicone carbide fiber. This fiber is known to be 5 times smaller than that of a human hair. To enhance the fibers strength, it undergoes the application of proprietary coatings. Next, the fiber is passed through multiple baths of solvents, plastisizers, and binders. The treated fiber is spooled around a wet drum which allows it to become into a workable sheet of unidirectional fiber.

Now that the fibers are finished, the sheet is put through a computer operated cutting machine that accurately cuts the sheet into the desired measurements of the ply. The plys are then stacked onto each other with a desired thickness. The orientation of each ply is determined by the certain properties needed for its application. The stacked plys are then put into an autoclave where high pressure and low heat transitions the piece into a molded part. In order to convert the remaining organic material into carbon, the part is put through a burnout process. This results in open pores throughout the part in which silicone is melt infiltrated to add density to the part and complete the process of creating a ceramic matrix composite. From here, this is only the beginning as the part still must be test and machined to assure it is the right fit and quality before it is applied to the field.

B. Drilling Ceramic Matrix Composites

With the increased use of applications for CMC materials in the aerospace industry, manufacturing CMC has also increased, which has arisen its own complications and procedures. The unique nature of CMCs high hardness and abrasion makes it difficult to machine and ultimately hinders large scale manufacturing. The mechanical properties of the material is highly dependent on dimensional and positional accuracy which results in applying a secondary machining process to ensure an accurate surface shape through conventional and unconventional machining. Regarding conventional machining, the current secondary machining still requires extensive and thorough research. Due to drilling, the materials' surface integrity and expected performance is negatively impacted. Therefore, it is crucial to establish efficient drilling technologies for these composites.

There are various studies that analyze the drilling forces, quality of hole, and torque, on CMC materials. This analysis includes multiple parameters tested on the material that contribute to the quality and usability after machining. These various drilling parameter's include feed rate, cutting speed, type of tool, and tool diameter.

C. Acoustic Emissions Sensors

In determining if defects are present in CMC materials during manufacturing, we wanted to determine if using acoustic emission sensors would be beneficial to collect data and relate defects to acoustic emissions (AE). Through literature reviews on this matter, it was determined the use of acoustic emission sensors will be beneficial in determining if defects are present and also monitoring the damage which occurs on the material while drilling.

Breede et al.[6] used acoustic emission sensors with carbon/carbon-silicone carbide (C/C-SiC) composites under tension loading with different test specimens having different fiber orientations. Through this experiment, three acoustic emission sensors, model B1025 with sampling rate of 10 MHz, were situated along the length of the testing specimens in order to collect readings from different areas, as shown in Fig. 1, since the damage is not concentrated in a single region.

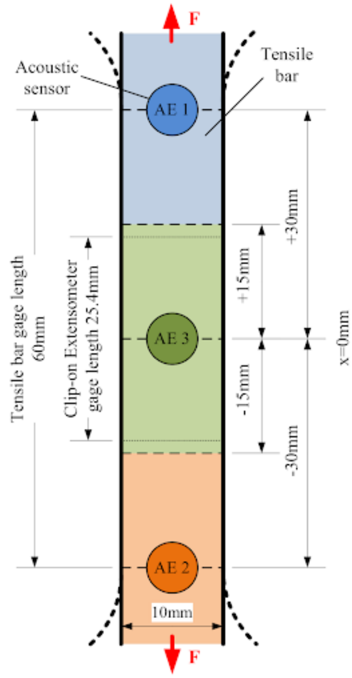

Fig. 1 Tensile testing setup with acoustic emission sensor layout

After filtering and analyzing the recorded data, it was determined the different energy levels could be related to different types of damage occurring during the test and the number of AE events varied due to the fiber orientation, as seen in Fig. 2.

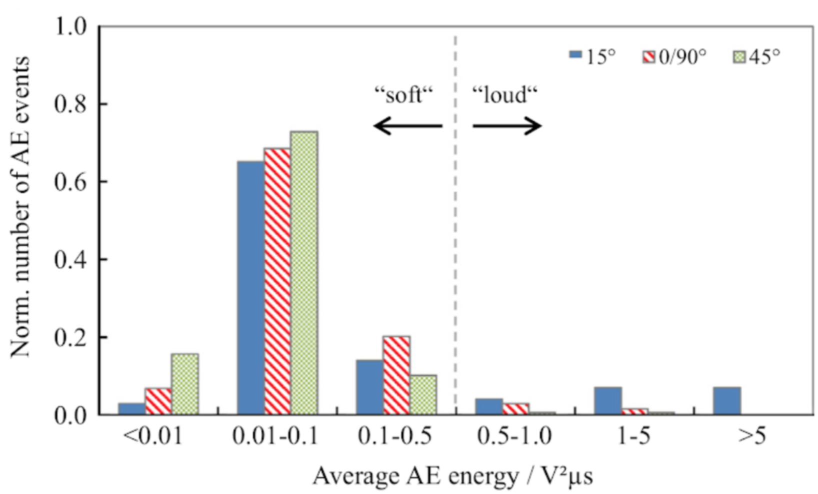

Fig. 2 Histogram of acoustic emission events for the different fiber orientations

In this study, the events collected were separated into two main groups based on the energy level from the sensors. The softer or events with lower energy were created by propagation and deflection of cracks in the matrix. However, the loud events were from damage which led to ultimate failure. These results were validated through microscopy analysis, depicted in Fig. 3, and there was very little difference between the data collected from the acoustic emission sensors and the tested microscopic images. From this validation, it was determined the loud AE events were created when multiple fibers and fiber breaks break, fiber pull-out fracture.

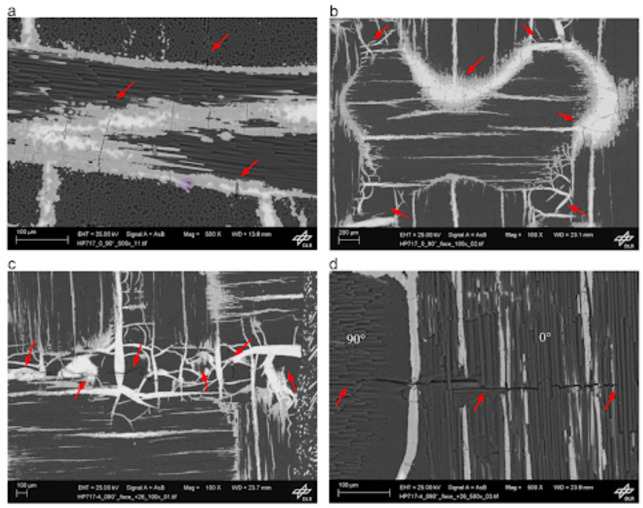

Fig. 3 Microscopy analysis of tested specimens

Therefore, from this, it was determined the use of acoustic emission sensors would be beneficial as it would allow for damage to be detected which is not easily audible and monitor the growth of defects, such as matrix cracks. However, for our specific project, the noise of the mill and vacuum would need to be filtered out and removed from the recorded information. Due to the limited time and availability, our current testing fixture does not use any acoustic emission sensors; however, it would be a great addition for future groups and research.

III. Project Proposal

A. Testing Fixture

In order to determine the porosity and detect imperfections in the test material during the machining processes, a testing fixture which can detect and record the changes in the magnitude of the forces applied by the machine to the test material is necessary. In a vertical mill, the forces applied during the machining process are the downward normal force of the drill bit pressing down onto the test material and the rotational force of the spinning motion of the drill bit. In order to measure these forces, load cells mounted on the test fixture were used.

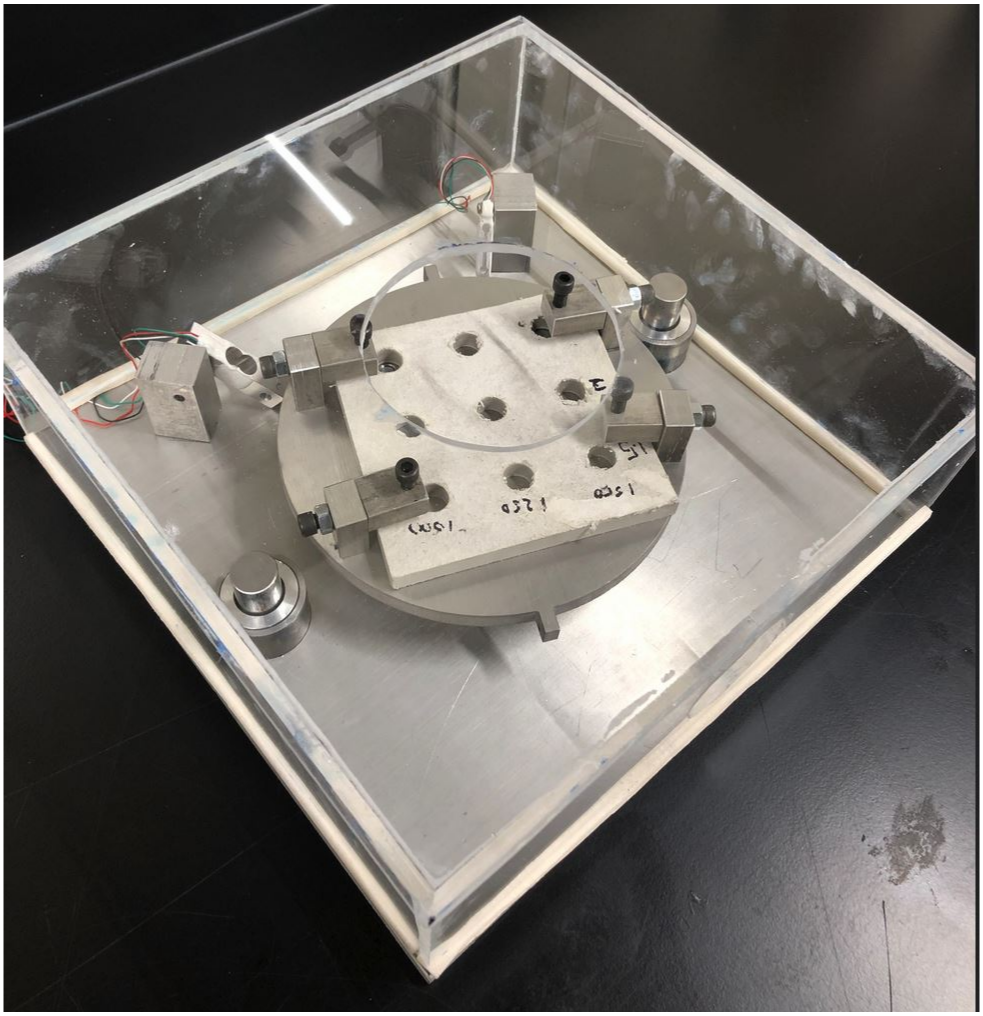

Fig. 4 Completed Rig

For the normal force, three cylindrical compression type load cells were used and were mounted underneath the test material in a triangular arrangement with the test material in the center, as seen in figure 5. This triangular configuration allows the normal force load to be flat in its distribution allowing for tolerances if the drilling operation is not directly in the center. If only one compression type load cell was used in the center of the testing fixture, any offset of the drilling procedure from directly above the compression type load cell can create a bending moment in the testing fixture and can lead to inaccurate measurements from the compression type load cell. Because the majority of the testing fixture is resting on the compression type load cells to yield a normal force reading during the machining process, locating pins fixed to the same plate as the compression type load cells were required. These locating pins serve to fix the loaded base plate in the X and Y plane while still allowing free Z axis movement. To prevent metal on metal contact friction from occurring and dampening the normal force from the machining process, roller bushings were fabricated and installed into the loaded base plate to reduce the friction of the moving loaded base plate against the fixed locating pins of the bottom base plate.

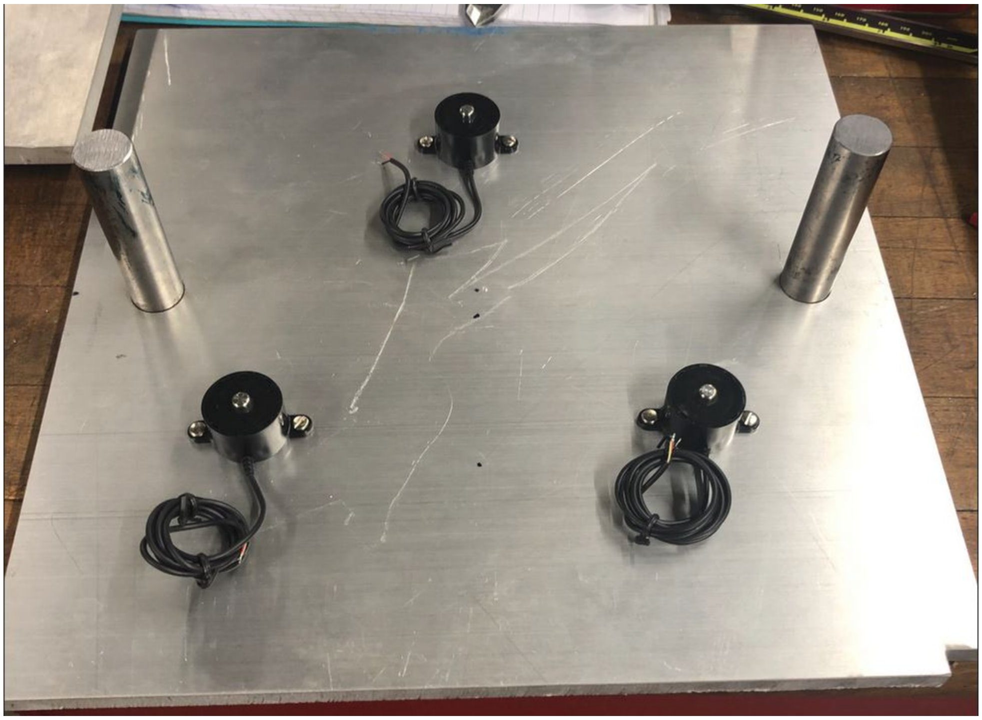

Fig. 5 Compression Load Cell Arrangement

For the rotational force, two bar type load cells were used. One of the bar type load cells is of a 500g load capacity and the other bar type load cell is of a 5kg load capacity. Two capacities were selected in case the rotational force exceeds 500g of load. For the bar type load cells, a lower capacity yields a more sensitive reading. This is important as the changes in rotational force of the machining process is not expected to be high. These bar type load cells are mounted to the testing fixture in a horizontal orientation where one end is fixed to the testing fixture and the other end is contacting the rotating base upon which the test material is mounted. The load cell is fixed at a known distance away from the drilling point. This known distance in combination with the force reading from the load cell yields a torque reading using equation 1. In order for the most accurate rotational force readings from these bar type load cells, the rotating base of the testing fixture needs to have as little inertia as possible. In order to minimize the inertia of the rotating base of the testing fixture, a turntable with a zirc fitting for grease is used as the bearing. The ability to reapply grease to the turntable helps minimize the inertia by allowing the turntable to be lubricated. Turntables without zirc fittings for the reapplication of grease can have the factory installed lubricant evaporate or clog with contaminants over time. Reapplying grease to the turntable lubricates the bearings as well as flushes out any dirt that may have accumulated.

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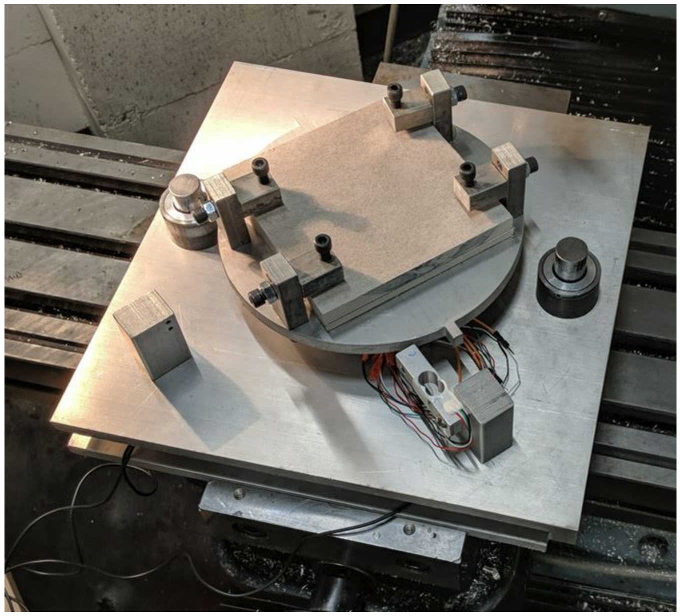

Fig. 6 Rig in mill

B. Ceramic Matrix Composite Alternative

Due to the high cost of ceramic matrix composites, an alternative material was needed for the testing phase of the testing fixture. This alternative material needed to have similar properties as the ceramic matrix composites but also needed to be affordable and accessible. The two characteristics of the ceramic matrix composite that needed to be replicated by the alternative material is the ceramic matrix composite's brittleness and its composite layered construction. The brittleness is required to replicate the behavior of the ceramic matrix composite during the machining process and the composite layered construction is required to test the sensitivity of the testing fixture's load cells to detect the changes in machining forces as the machining tool surpasses each layer of the composite structure.

The alternative material chosen for the preliminary testing and configuration of the testing fixture is cement board or Hardie Board. This material is a composite constructed from layers of mesh fused together with fiberboard and concrete. The concrete gives this material its brittleness and the layers of mesh create the layered composite structure.

C. Data Acquisition System and Sensor Information

1. NI 6003 USB

The National Instruments series 6003 USB data acquisition device was used for this project to collect data from each load cell and import it to the computer, where the data could undergo post processing. The NI 6003 has a high sample rate of 100 KS/s, which is important for this project, because a high resolution will be needed for testing.

Fig. 7   National Instruments 6003 USB

2. Load Cells

The two types of load cells that were used in the rig are compression type load cells and bar load cells. The compression type load cells that were used had a load capacity of 25 lb and are used to measure the normal force during drilling. Because three were used this gave the rig a total limit on the normal drilling force of 75 lb. The compression load cells also have a built in amplifier, which allows them to output a big enough voltage for the NI 6003 to be able to pick it up.

Fig. 8 TE Connectivity Compression Load Cells

A 500 g and a 5kg bar load cell were also used in the testing rig to measure the torque while drilling. The load cells would be interchanged according to the material that was being drilled. The bar load cells did not have a built in amplifier so a separate one was needed for the data acquisition to be able to read the data.

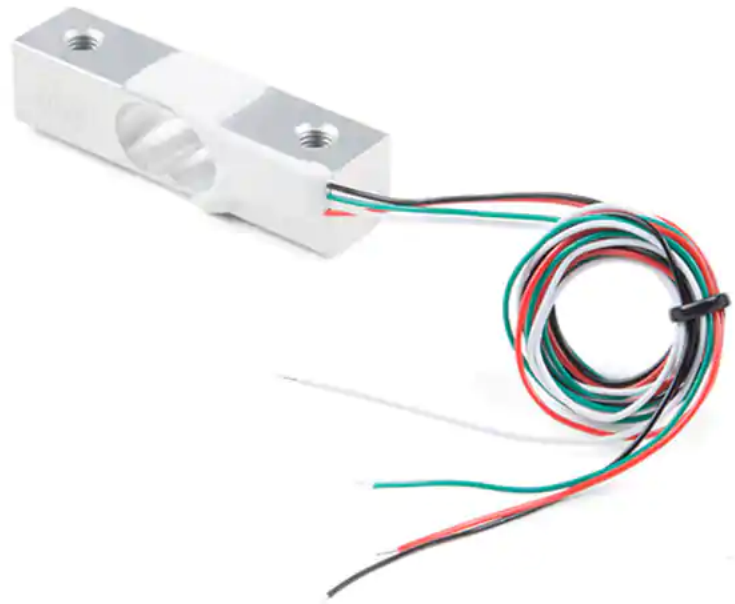

Fig. 9 Spark Fun Bar Load Cell

IV. Experimental Setup and Results

A. Milling on Hardie Board

As mentioned in previous sections, prior to testing on ceramic matrix composites, it was necessary to test on a separate but similar material. The purpose of testing this alternate material is to verify that the apparatus as well as the testing method for the experiment would work as expected. For the testing of the Hardie Board, testing parameters must be set to maintain a controlled experiment. Two of the most important parameters for testing would be the mill's spindle speed and feed rate. To find a spindle speed and feed rate that would be acceptable for the tests, a 1/2" thick specimen was set as a test piece. This test piece was then drilled into nine times, each drill with a different spindle speed and feed rate combination. Some of the tested combinations included:

Spindle Speed (RPM)	Feed rate (in/min)
750	9
750	6
750	3
1000	9
1000	6
1000	3
1250	9
1250	6
1250	3
1500	3
1500	2
1500	1.5
1500	1

Table 1 Various combinations of spindle speed and feed rate used in preliminary tests

In Table 1, the different combinations can be seen. For the preliminary tests, there was 1 hole drilled per combination. After each hole was drilled, each one was examined to inspect how the Hardie Board had been affected by the spindle speed and feed rate. It was quickly noted that a spindle speed of 750 rpm would not be sufficient as a testing parameter as each hole that had been drilled with this speed did not seem to cut as efficiently as the higher spindle speeds. The next increments tested utilized spindle speeds of 1000 rpm and 1250 rpm. These speeds were combined with the same feed rates as the 750 rpm tests. The last tests were run at a spindle speed of 1500 rpm. By the time all the previous tests had been run, it was decided that a feed rate higher than 3 in/min would be excessive. Therefore, for the runs set at 1500 RPM, tests were conducted with feed rates of 3 in/min or lower. After the testing for each section was completed and the quality of the drilled holes were checked, it was decided that the pairing of a spindle speed of 1000 RPM and a feed rate of 3 in/min would be the parameters used for the Hardie Board testing.This was chosen because it provided the best visual results of the combination. With these parameters, the inside of the drilled hole showed each layer of the Hardie Board, and cut without excessive force that would punch a hole and blow through the back of the test sample. One of the drilled holes can be seen below in Fig. 10.

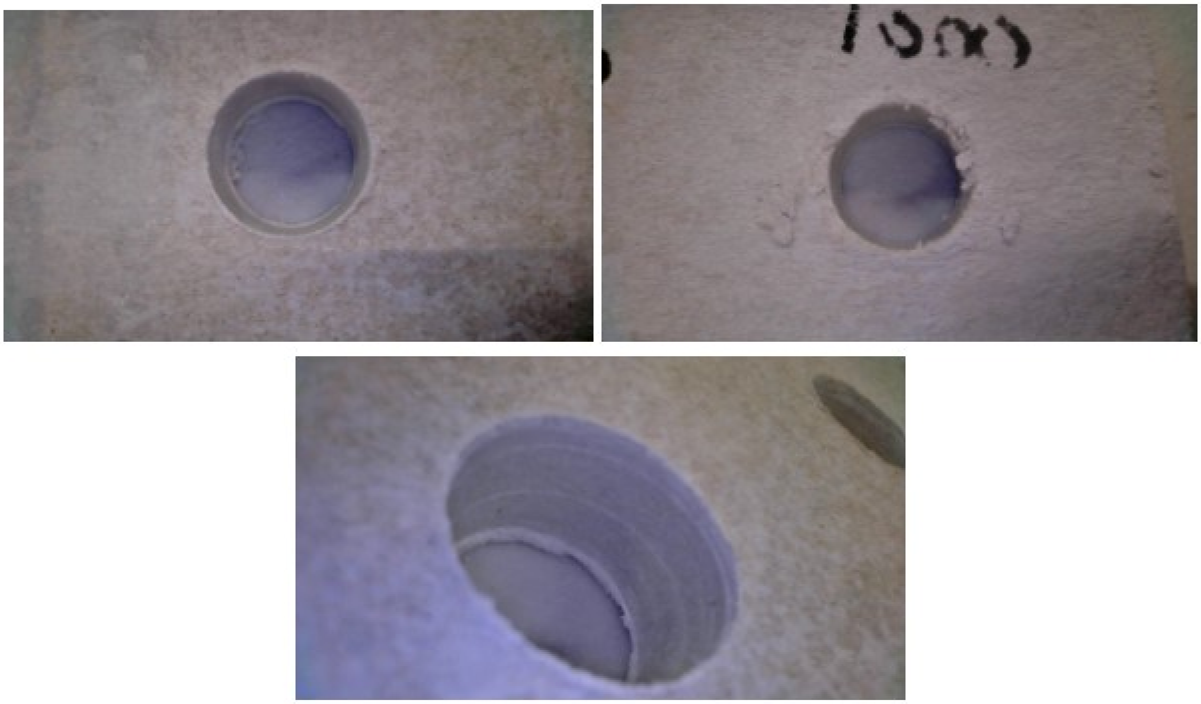

Fig. 10   Top View (Top Left), Bottom View (Top Right), Side View (Bottom) at 1000 RPM, 3 in/min

With the testing parameters determined, it was then possible to move onto getting readings for actual data. For the Hardie Board testing, there was a sacrificial piece of Hardie Board placed under the testing piece to protect the aluminum plate of the testing rig. One thing of note during testing is that the hole saw drill bit continuously needed to be cleaned, as the plugs from drilling the hole would block the hole saw. This would result in more of a pushing normal force than a cutting motion as the saw would not be able to move as intended. After cutting into the Hardie Board, it was possible to internally see the different layers of the Hardie Board.

B. Hardie Board Testing Results

The best results from the Hardie Board came from a test on a quarter inch piece of Hardie Board with testing parameters of 1000 rpm and 3 in/m spindle speed. The reason this test was so good was because it gave very distinct lines that can be seen in Fig. 11

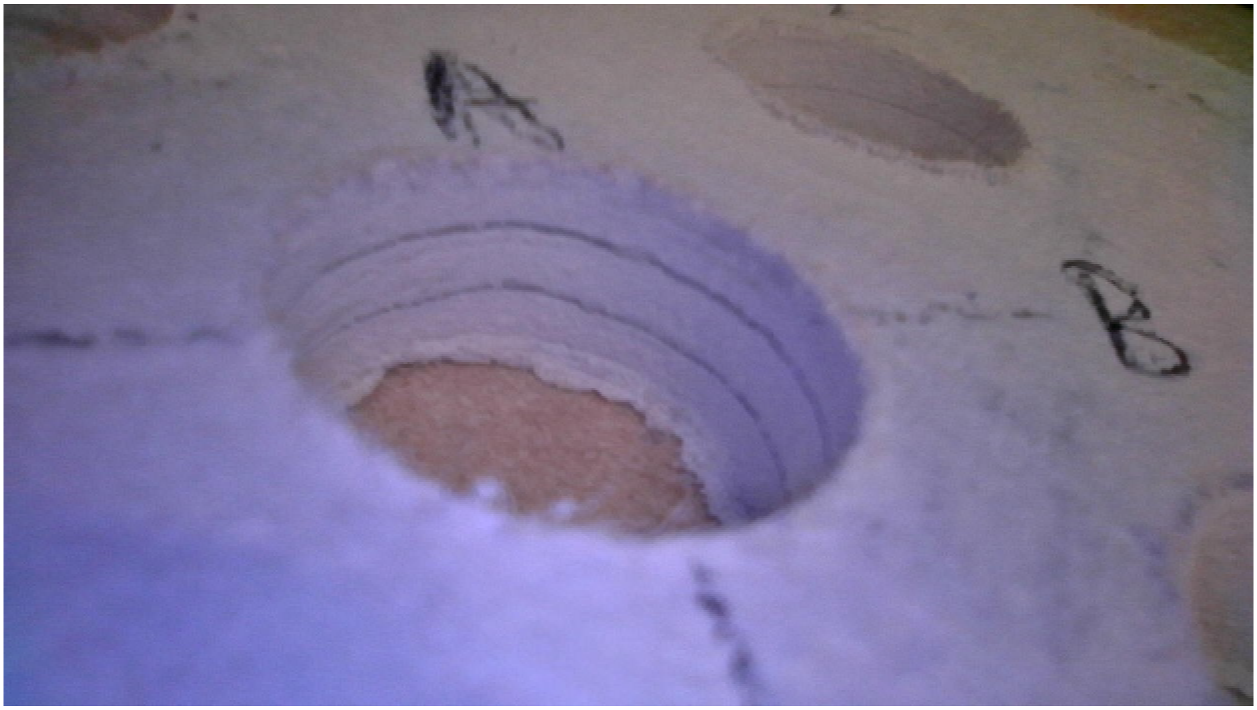

Fig. 11 Hardie Board Hole with layers lines

These distinct lines also show up in the compression load cell data as three distinct peaks throughout time. This correlation proved to us that our rig can measure the changes in drilling forces during drilling. At this point it was time to move onto the next step

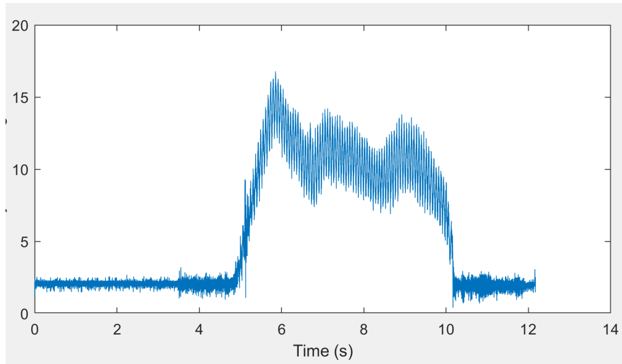

Fig. 12 Load Cell 1

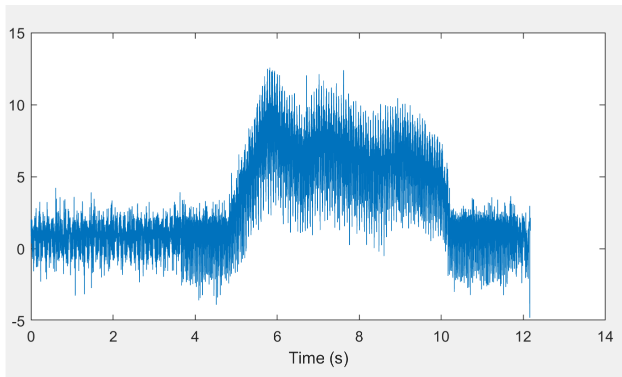

Fig. 13 Load Cell 2

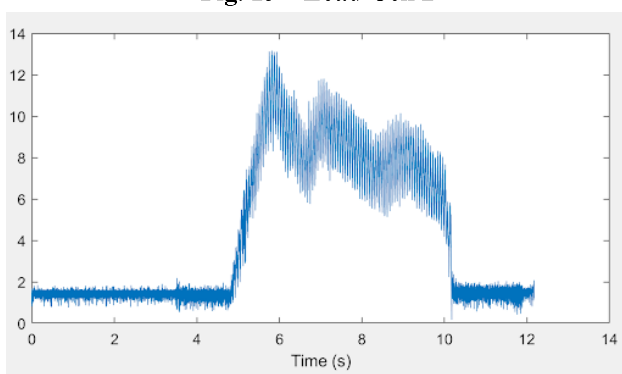

Fig. 14 Load Cell 3

Fig. 15 Hardie Board Compression Load Cell Data

C. Milling on Carbon/Carbon

Once the concept had been verified by testing on the Hardie Board, it was possible to begin running the experiment on the ceramic matrix composite: carbon/carbon. For the test, two specimens were used. The first was an unaltered 1/4" thick piece of carbon/carbon. The second was a specimen that consisted of two 1/4" thick carbon/carbon pieces that had been bonded together using a two part epoxy adhesive. To maintain the proper spacing between the two pieces, glass beads were also placed between the two pieces of carbon/carbon. There was a difficulty; however, as the bonded piece was not set correctly as the epoxy was hardening and as a result, the specimen became oddly shaped. Pictures of the carbon/carbon samples can be seen below in Figs. 16 and 17.

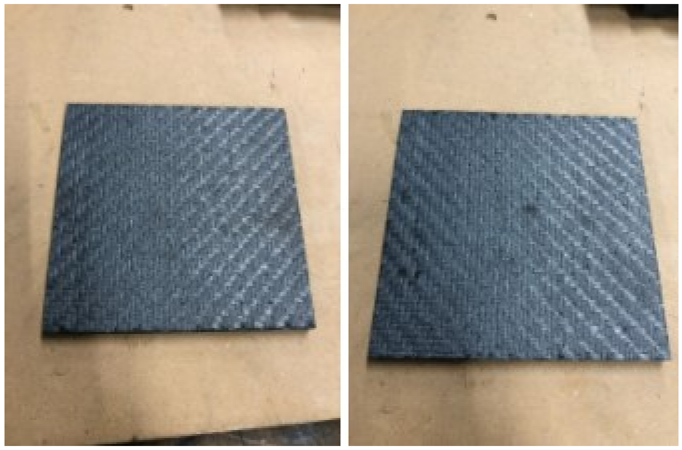

Fig. 16   Unbonded Carbon/Carbon sample

Fig. 17   Bonded Carbon/Carbon Sample

To begin the experiments, it was a similar process to the Hardie Board in which a spindle speed and feed rate needed to be found. Given the small amount of carbon/carbon available, the results needed to be found relatively quickly. After several runs, the spindle speed and feed rate combination that would be used for the tests were 1000 RPM at 1 in/min. The slower feed rate was due to the fact that the carbon/carbon was more brittle than the previously used Hardie Board. Just as a sacrificial piece had been used for the Hardie Board tests, one was also placed under the carbon/carbon samples. Similar to the problems with the Hardie Board, the plugs created by using a hole saw to cut these specimens would get stuck in the holes of the saw. The drills used for the carbon/carbon were also a finer grit hole saw, which meant that there was more frictional force during the cutting. This different hole saw drill bit would also pose a difficulty as it was much harder to remove the plugs created from drilling from the hole saw. As a result, the decision was made to change out the drill bit used every two holes. The first specimen used was the unbonded sample. This sample was able to be drilled five different times within the experimental rig. After this sample had been bonded the maximum number of times, it was time to move onto the bonded sample. In order to get the bonded sample to fit within the experimental rig, it was necessary to remove one of the stands that held the clamping system. This could potentially cause a problem as it resulted in one less secure point to hold down the test specimen. With the odd shape of the piece, it was only possible to drill three holes into this specimen. Some of the drilled specimens can be seen in Figs. (18) and (19).

Fig. 18   Holes drilled into unbonded Carbon/Carbon Sample

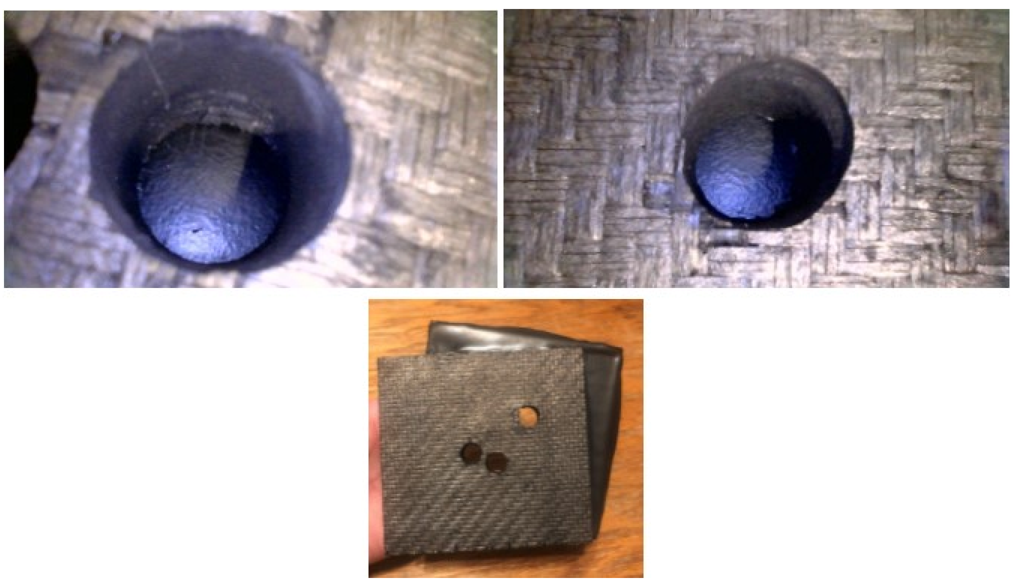

Fig. 19   Holes drilled into bonded Carbon/Carbon Sample

D. Carbon/Carbon Testing Results

After drilling and testing had been completed, the specimens could be analyzed. There were some immediate observations that could be seen after drilling into these specimens. The first is that the layers of the composite could be seen when looking into the drilled holes. Another one of these observations was that it was clearly visible that there was delamination around the top layers of the composite from the drilling. On the bottom of the drilled hole, it was also possible to see cracking around the edges of the holes. While drilling the bonded specimen, there was a clear change in the audio as the drill passed through the epoxy layer.

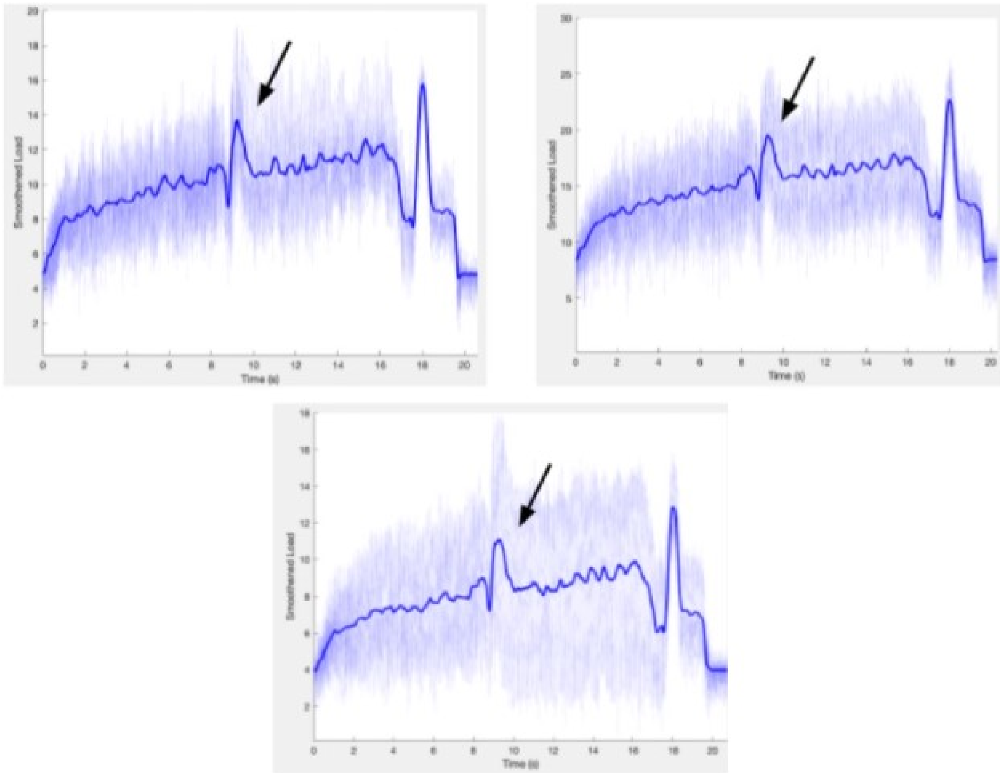

Fig. 20 Graphs of carbon/carbon drilling

The load vs. time graphs for the drilling can be seen above. These graphs correspond to the drilling of the carbon/carbon. From looking at the graphs, it is possible to see the increase in force as the drill travels through the specimen. As a result, this may be indicative that a higher spindle speed may be necessary to get better data.This is due to the mill most likely doing more pushing than it was cutting. The original data received from the load cells also included a large amount of noise, which can be seen in the background of the graphs. This noise was filtered out in post processing to get the more succinct graphs noted by the solid blue line. In the graphs, the large spike in the middle refers to the moment that the drill passed through the epoxy layer. This spike alone, confirms that our rig worked exactly as it was supposed as it clearly shows the change in force as the drill passes through different material. Also noted in this analysis, when compared to Hardie Board, is that a finer grit hole saw was used on this experiment. This would lead to more frictional force and an increase in normal force.

V. Conclusion

After conducting our tests on composite materials, we can confirm that the forces a machined part is experiencing is related to the layers and porosities within the part. It can be seen in the load cell data that the spikes in forces are consistently in the same position across multiple test runs. These spikes indicate the presence of a layer of different, stronger material. Conversely, the dips in force indicate the presence of either weaker material or gaps in the material. This concept of measuring forces during machining can be used to determine the quality of a material as it is being machined. For example, if one machining process is conducted on two identical parts, but one part experiences less force than the other, then the part that experiences a greater amount of force is the stronger part. Another application of force measurement during machining is that of failure detection. If a material is known to begin failing at certain force loads, then when a part being machined shows a similar force reading, it can be a sign of failure. The next steps for this project are to implement more noise reduction techniques as well as move the force measuring devices onto the machine itself, in this case, the mill, in order to test materials of any size that fits on the mill's working table as well as increase accuracy of measurement.

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