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Precision Machining of Polymer Matrix Composites

By
Victor Martinez Polanco

A Thesis Submitted in Partial Fulfillment of the
Requirements for the Degree of
Masters of Science
in
Manufacturing Engineering Technology

Minnesota State University, Mankato
Mankato, Minnesota
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This thesis has been examined and approved by the following members of the student's committee.

Advisor

Committee Member

Committee Member

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Abstract

This experiment was started to figure how the precision machining of polymer matrix composites differ from metals such as aluminum and steel. Polymer matrix composites are highly used in powered vehicles for their strength and light weight properties, but they are typically not machined to their final product how metals are. Polymer matrix composites are typically manufactured near their final shape, with some trimming involved to complete its shape. This research machined carbon fiber manufactured through a wet layup and through resin infusion, as well as aluminum and steel to compare their machineability and their surface finish. These materials were machined using a CNC mill, while comparing the properties of machineability and surface finish when using three different endmills: a AlTiN, a DLC, and a Diamond coated endmill. The three endmills demonstrated different positives and negatives of machining with the different materials. First, the best endmill to machine polymer matrix composites is a diamond coated endmill because it provides the best surface finish on composite materials, and it takes the least amount of effort to machine the material. Second, it is best to machine polymer matrix composite materials that have been manufactured through wet layups over materials made through resin infusion since there is less delamination through these layups. Third, while machining polymer matrix composites the best direction to machine the material with the least amount of delamination is in the same direction that the fiber is placed. Lastly, the research determined that there is not a significant difference between machining aluminum and polymer matrix composites, except that the composites experience delamination from machining with some endmills.

Introduction

Polymer matrix composites have been around since the 1930s and have been used in a variety of projects from marine to automotive to aerospace. Fiber reinforced polymers (FRPs) are commonly used because of their high strength to weight ratio; very high strength with very low weight. The high strength to weight ratio provides a great product with multiple areas of applications. Such applications can be found in race vehicles and airplanes, light weight is necessary to achieve high speeds and acceleration. Some applications require the precision of the material, which may only be achieved if the material is machined. However, it has been an issue to precisely machine fiber reinforced polymers how metals are machined. This is due to the chip formation being so different between metals and FRPs; a plastic deformation occurs while machining metals, while a compression shearing occurs while machining fiber reinforced polymers. Another issue of machining fiber reinforced polymers are the cutting tools, the tool must have hardness and toughness to overcome the fibers' cutting forces. The most common cutting tool in industries to cut polymer matrix composites are diamond coated tools. Diamond coated tools are one of the top-rated cutting tools available today because they provide the best surface finish on every material, including metals and polymer matrix composites. For this reason, diamond coated tools are also expensive, which reduces their availability to many consumers.

Polymer matrix composites are typically close to their finished shape when made using a mold, but they do require some final operations such as trimming and drilling to complete the desired product. Depending on the product being made, some fiber reinforced polymers require more finishing operations than others; these extra operations can create machining mistakes and ruin the product. Such machining mistakes and failures can happen just by using an inappropriate cutting tool for the job. Delamination is a type of failure that fractures a material into layers and it’s very crucial because it reduces the strength of the composite laminate and can occur while machining without being noticed right away. Other machining failures that can occur while machining FRPs are uncut fibers, pulled fibers and burnt resin. Some machining failures could be visible, while others may not be such as delamination and fibers being pulled. The visible machining errors such as uncut fibers and burnt resin can demonstrate whether the correct cutting tool is being used. In the end, all these machining failures can reduce the final product’s surface finish and strength which are necessary to be as best as possible when the product is finished. To overcome all these difficulties this research compared the machinability and surface finish of metals and polymer matrix composites. This research also compared different cutting tools to find which cutting tool is the best for cutting polymer matrix composites and provided the best surface finish. This research lastly compared the machineability of different fiber orientations while machining.

Methodology

Material information

To get precision machining on polymer matrix composites, a good cutting tool will be required. On a 3 axis CNC mill, surface roughness and dimensional precision was tested by using three different endmills. The three endmills used are ¼” square endmills of three different coatings, Aluminum Titanium Nitride (AlTiN) coated, Diamondlike Carbon (DLC) coated, and Diamond coated. These three coatings were chosen because they are commonly used to machine metals and polymer matrix composites. The AlTiN coated endmill provides a smooth finish, it’s excellent for shearing and chip removal in stainless steel and titanium [1]. The DLC and diamond coated endmills are both for machining abrasive material, such as carbon fiber, fiberglass, and graphite [2]. However, DLC coated endmills are cheaper than diamond coated endmills and are used for short operations. Diamond coated endmills are used for long production operations, they can run twice as fast as other carbide endmills and last up to 30 times longer [3]. The three endmills were used to machine the same operation and compare each of their finishes based on surface roughness and dimensional precision.

Figure 1. Image of the three endmills.

Each tool did the same operation on different materials, which included carbon fiber (CFRP), aluminum, and steel. Carbon fiber was selected for this research because carbon fiber has high strength and is highly used in all industries. As for aluminum and steel, they were both chosen to compare the carbon fiber machineability and precision to two widely use materials in many industries. Comparing aluminum and steel to carbon fiber lets manufacturers and researchers understand the material of carbon fiber since there is so much information about metals already known. To completely compare these materials, the CNC tested the resistance load that each polymer matrix composite and metal is providing while being machined. See the table below for materials and endmills matrix.

Table 1. The combinations of all the test pieces with their endmills combination.

Test Piece	Material	Endmill Used
1	Wet Layup	AlTiN
2	Wet Layup	DLC
3	Wet Layup	Diamond
4	Infusion	AlTiN
5	Infusion	DLC
6	Infusion	Diamond
7	Aluminum	AlTiN
8	Aluminum	DLC
9	Aluminum	Diamond
10	Steel	AlTiN
11	Steel	DLC
12	Steel	Diamond

The carbon fiber test pieces were all hand made at Minnesota State University, Mankato. The carbon fiber used for this experiment was 6k carbon fiber fabric because it's the material that was available at the school's lab, and it's also the carbon fiber grade that is typically used for constructive components on aircrafts. 6k stands for the number of filaments or single strand of carbon fiber in each tow, in other words there are 6000 filaments in each untwisted bundle of filaments. There are other carbon fiber tow sizes such as 1k, 3k, 12k, they all weight different and will have different strength properties [4]. The resin used for this experiment was Orca 555 vinyl ester from Express Composites, Inc. This resin was used because it’s one of the most common resin used for resin infusion, and it combines the chemical properties of poly ester and epoxy resin. This resin has high static and dynamic load that is great for use in marine applications, flooring, tanks, and more [5, 6].

Test Piece Manufacturing

Six test pieces were made, three were made by a wet vacuum layup and three were made by resin infusion. A wet vacuum layup lets us to individually wet out each layer of carbon fiber with resin, so that every layer can have resin placed on both sides of the fiber. A wet layup can be done without being sucked and flatten by vacuum, but by doing so the layup can end up with air gaps between the layers and can be extra thick. By vacuuming the wet layup after it has been wet out with resin the layup removes excessive resin, flattens the part layup as much as possible, and it removes any air gaps in between the layers of carbon. As for resin infusion, it’s a process that is slightly more complicated if done incorrectly, a bad layup will be achieved. Resin infusion is done to fill the carbon fiber with resin after it’s already under vacuum, this way only the necessary amount of resin is mixed with the carbon. The vacuum bag over the carbon fiber has 2 tubes: an inlet tube and an outlet tube for the resin. The resin enters through the inlet tube, passes through the carbon, and then exits through the outlet tube. This process does require to have a perfect vacuum in order to prevent any air to be in the layup; this is a process that when done correctly there are 0 air gaps or air bubbles in any placement of the carbon.

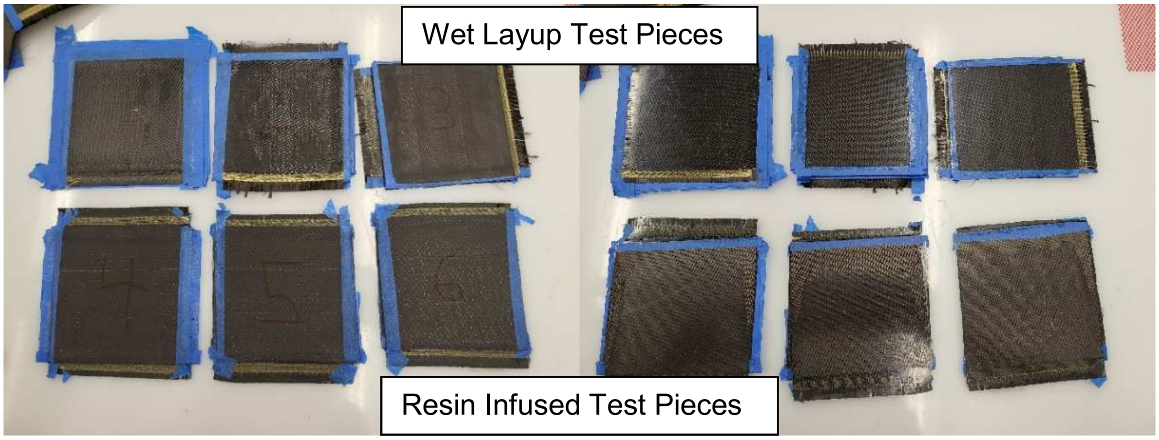


Figure 2. Front (left) and back (right) of the carbon fiber layups.

Each test piece consists of 10 plies of 6k carbon fiber fabric facing the twill the same direction, with vinyl ester resin using 2% of Methyl ethyl ketone peroxide (MEKP). Each ply of dry carbon fiber was first cut to make a square of 6” x 6”, every dry ply of carbon fiber weighed 0.016lbs. A good mix of carbon to resin ratio is 60% carbon to 40% resin by weight or by volume, this was the mixture ratio that was kept on all 6 test pieces. 0.016 x 10 = 0.160lbs for 10 layers of carbon fiber, then 0.16 / 0.6 = 0.266lbs is the total weigh with the resin. The weight of the resin would then be: 0.266 x 0.4 = 0.106lbs of vinyl ester. Since, these are small amounts of resin being measured, the resin was placed in a volumetric measuring cup while on a scale. Once 0.106lbs of resin was in the cup, the volumetric measuring system was used, which demonstrated that 0.106lbs of vinyl ester is 125mL. The measuring system was primarily changed, because the 2% of MEKP required to mix with the resin is 0.00213lbs, which the scale could not measure. Syringes were used to measure the volumetric ratio; the syringes could read up to 5mL which was all that was necessary because 2% of 125mL is 2.5mL.

The vinyl ester resin after it has been mixed with MEKP, took 20-30 minutes to start gelling up. This is the point where the resin cannot flow for resin infusion and for a wet layup it cannot mix with the carbon very well. After the layups are completed, each layup takes 8-24 hours to dry and become completely solid. A finished layup will be unbendable by hand, versus a layup that is not entirely dry will still be flexible and bendable by hand. The finished layups have a nice glossy finish on one side because of the mold's surface, while the other is smooth, but not glossy because of the peel ply that prevents any material from gluing onto the carbon fiber.

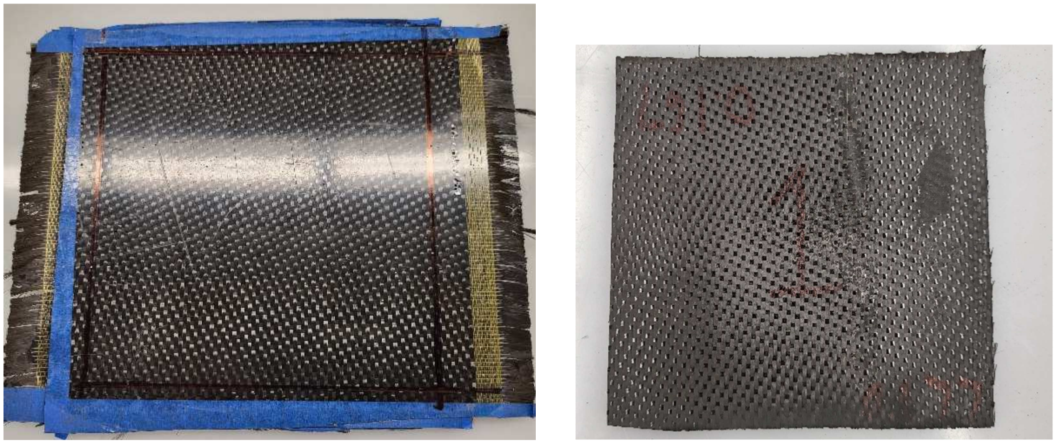


Figure 3. Glossy side versus nonglossy side of carbon fiber.

The wet layups turned out to be better done than the infused layups because the wet layups were completely wet out with resin on the top and bottom side. The infused layups were wet on the peel ply side, but the mold side had dry spots near the outlet tube because the resin flowed through the top layers and then went to the outlet tube before reaching the bottom layers. This issue is hard to avoid with many layers of fiber, but it can be avoided if the resin was flowed through the vacuum bag slower or if no meshing material was placed over the carbon fiber layers to let the resin flow through the carbon fiber more thorough.

Figure 4. Resin infused test pieces before and after being infused with resin.

To fix the dry spots on the resin infused layups, the three test pieces were given a finishing resin wet layup without vacuum bagging. The resin was squeegeed into the carbon wherever it was dry to force some resin to the center layers where it's unknown whether they are dry or hardened with resin. The fixed pieces were left to dry in room temperature with the resin side facing up, which undoes the nice flat finish from the mold that it had. As soon as the test pieces were dry, they were ready to prepare for machining. To prepare the test pieces for machining they had to be trimmed because the 6"x6" pieces had thin sharp edges that could not be clamped on a vise on the CNC. To trim the edges of the test pieces, each piece was measured and marked to be cut as a square sized 5"x5" on the center of the piece to not have any tape on our test pieces. Each piece was also measured for thickness before cutting, the table below demonstrates the thicknesses of all

6 carbon fiber pieces. Test pieces 1,2,3 are the wet layup and test pieces 4,5,6 are the resin infusion layups.

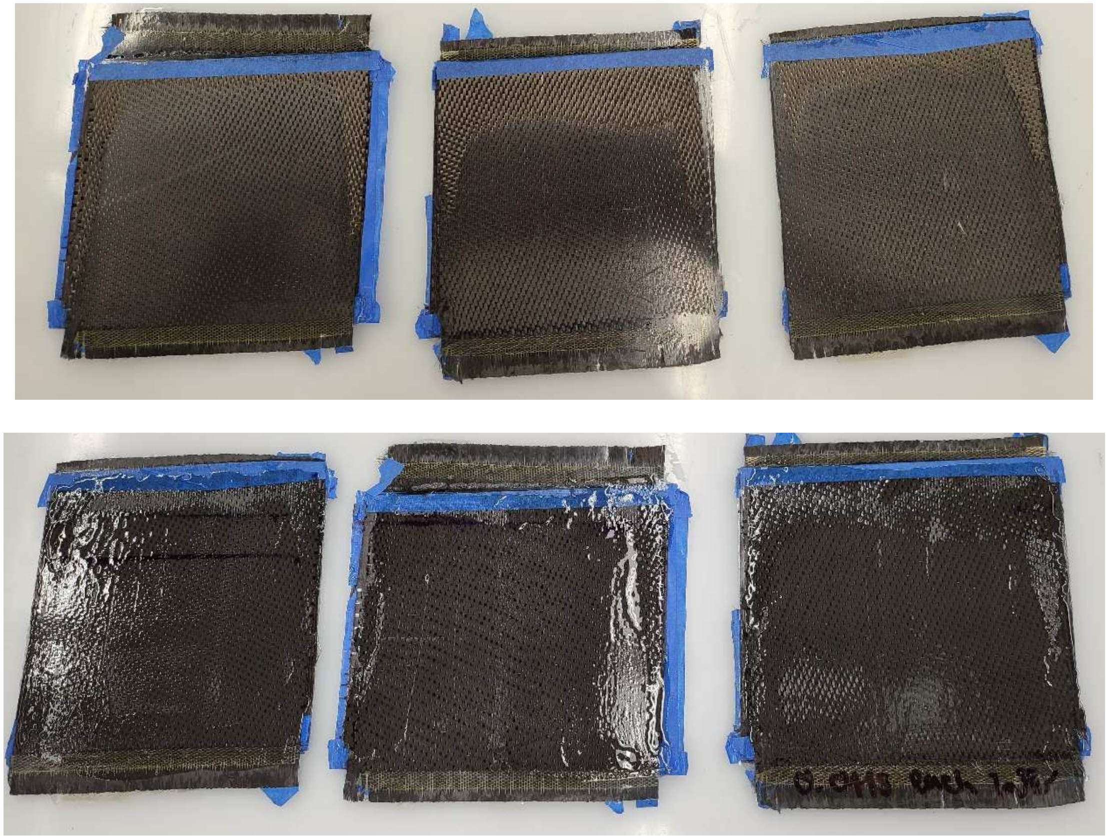


Figure 5. Before and after of the resin infused test pieces fix up.

Table 2. Thickness of all the carbon fiber test pieces.

Test Piece	1	2	3	4	5	6	Average
Thickness	0.172	0.159	0.1575	0.116	0.1175	0.1145	0.139

The pieces were trimmed using a rotary cutting tool with a diamond cutting disc to easily cut the material [7]. These discs had a maximum rated RPM (revolutions per minute) of 22,000, the rotary cutting tool had an RPM range from 8,000 - 35,000 RPM; it was ensured that 22,000 RPM was not exceeded to not damage the cutting disc. A metal cutting disc would be sufficient to cut the carbon fiber, but the diamond cutting disc were more available when purchased. Each diamond disc was sufficient to stay sharp to completely cut 3 test pieces; 1 disc could cut twelve 6” edges that are approximately 0.139” thick.

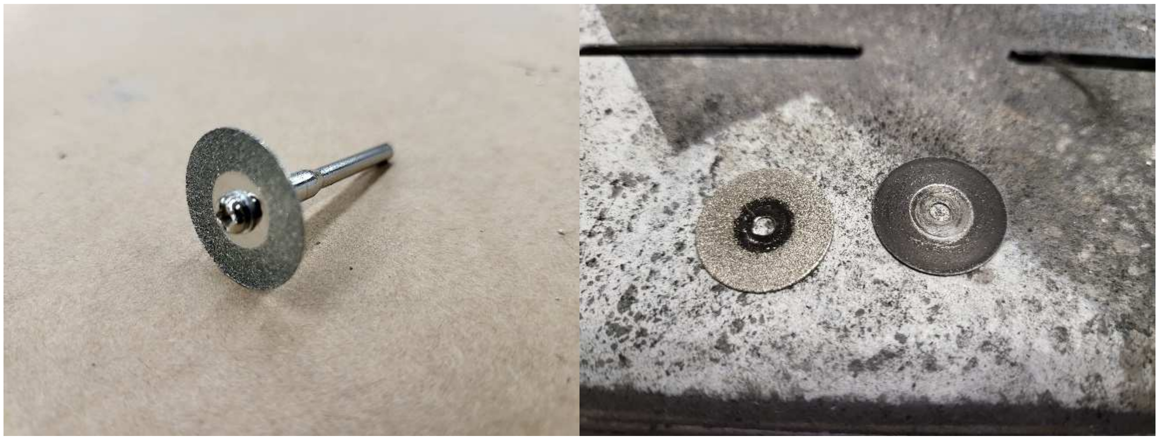


Figure 6. New cutting disc on the left. Worn out cutting disc on the right.

Each test piece was cut in a well-ventilated area with the proper personal protective equipment, clamped onto a vacuum table with the side being cut over the edge of the table. While cutting the carbon fiber, carbon dust and resin dust flies around the area which are both toxic to the lungs, so a well-ventilated area is necessary to protect the body [8]. While cutting the edges of the test pieces with the cutting wheel, there were some areas that were harder to cut than others because of the tape. Test piece number 2 was the most difficult test piece to cut the edges since the tape was folded over the edges of every layer.

Figure 7. Carbon fiber test piece ready to be trimmed on ventilated table.

The diamond cutting wheel worked very well, but it was a little small. The radius of the cutting wheel was bigger than the thickness of the materials, but if the wheel was not held correctly the bolt fastening the wheel to the Dremel would ruin the surface of the test piece. The bolt would remove

Figure 8. Example of the ruined edges due to the Dremel bolt.

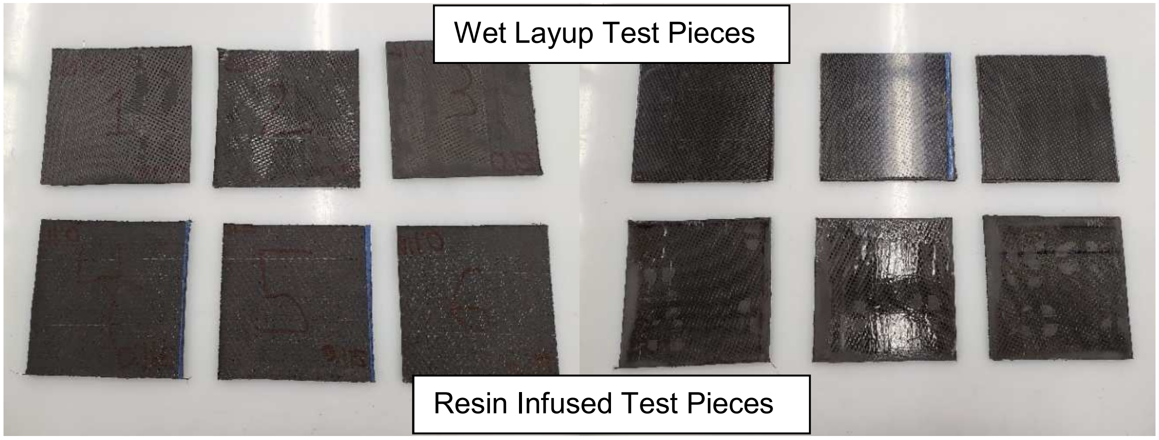


Figure 9. Test pieces after being trimmed with the dremmel.

As for the aluminum and steel test pieces, the only work that had to be done to get them ready for machining was to cut them to size. The aluminum used was a 6061 aluminum because it's one of the most common grade of aluminum used in the world [9]. The aluminum was cut to size using a band saw; the edges for this test piece are only required to be straight for clamping, they do not need to be smooth. The steel test pieces are stainless steel type 304, one of the most common grades of steel used in all different industries [10]. The steel test pieces were also trimmed with a bandsaw and sized to be 5"x5" to fit the cutting program designed for this experiment.

Toolpath Program Design

The cutting program was designed in MasterCam and was designed to fit within a 4"x4" square while machining all the important properties of carbon fiber and the common machining operations. Within the cutting square, there were 7 different operations to test 7 different machining properties of the test pieces. The 7 different machining operations are: a 90° cut to the fiber twill in a single cutting path, a 45° cut to the twill, a 0° cut to the twill, a 90° cut to the twill making a square surface pass, 0° cut to the twill making a square surface pass, a 90° cut to the twill exiting an edge of the test piece to test for surface roughness, and lastly a circular cut with a 1.5” diameter.

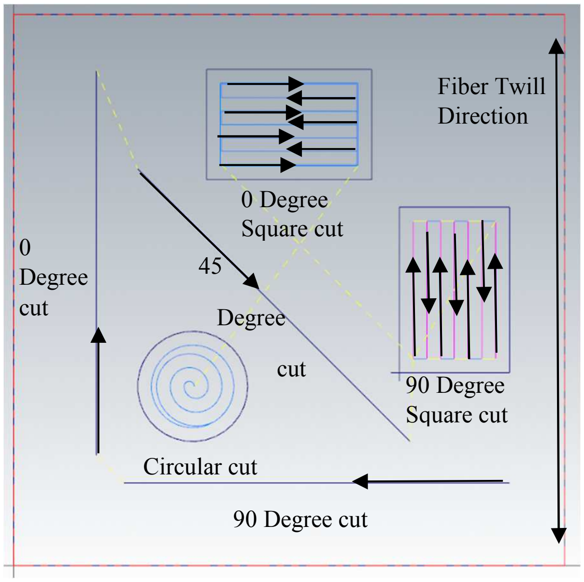


Figure 10. All the toolpaths programmed for each test piece and their direction.

The parameters for the cutting toolpaths are the same for all the machining operations and for all the test pieces. The spindle’s RPM was set to 2500RPM, the endmill feed rate was set to 5 inches per minute (ipm) with a plunge rate of 3ipm. All 7 operations were done with a single depth pass of 0.075” because that is an approximate mid-point of all the carbon fiber test pieces. To be able to test the surface roughness after machining a surface, the surface must have enough clearance around the sides to measure for some distance and for the tool’s head to be free of obstacles.

Data Gathering

To test the cutting forces on the endmill while machining, the CNC recorded the X, Y, and Z spindle load. The spindle load of every cut could not be downloaded from the CNC, instead, the spindle load was video recorded for every operation and test piece. The largest spindle load every 5 seconds for the X, Y, and Z values was recorded and placed in a table, which is demonstrated in the “Results” section of this experiment. Each operation lasted at least 45 seconds, which provides at least 9 data points to test and compare throughout the experiment for each test piece.

Lastly, to check the surface roughness for all the test pieces after machining, a profilometer was used. Surface roughness was checked on the operation that cut the right side of the test piece, on three randomly selected spots of the surface. All the test pieces had completely different values since they were all machined with different endmills. The hypothesis for this experiment is that the resin infused layups would provide the best surface finish as compared to the wet layups, regardless of the endmill. Both carbon fiber layups would be easier to machine than steel, but harder to machine aluminum. Lastly, the endmill that provides the best machineability and surface finish would be the diamond coated endmill over the other two.

Figure 11. Using profilometer example. Checking the surface roughness of wet layup that was machined with the diamond endmill.

Results

Visual

The results of machining resulted in some visual significant differences between the endmills' cutting potential, as well as the machineability of the materials. By a visual inspection, the differences in cuts between the orientation of the material and the direction of the endmill could clearly be distinguished. There was also a significant difference between climb milling and conventional milling while cutting the carbon fiber, climb milling would almost perfectly remove any filaments, while conventional appeared to only remove the resin. Based on a visual inspection, the best way to get a smooth cut while cutting with any endmill is cut at 0° of the fiber twill while climb milling. In other words, cut the fiber in the same direction that the fiber twill is facing and using climb milling to not get any delamination or other cutting defects. See the images below demonstrating the 6 carbon fiber test pieces after being machined.

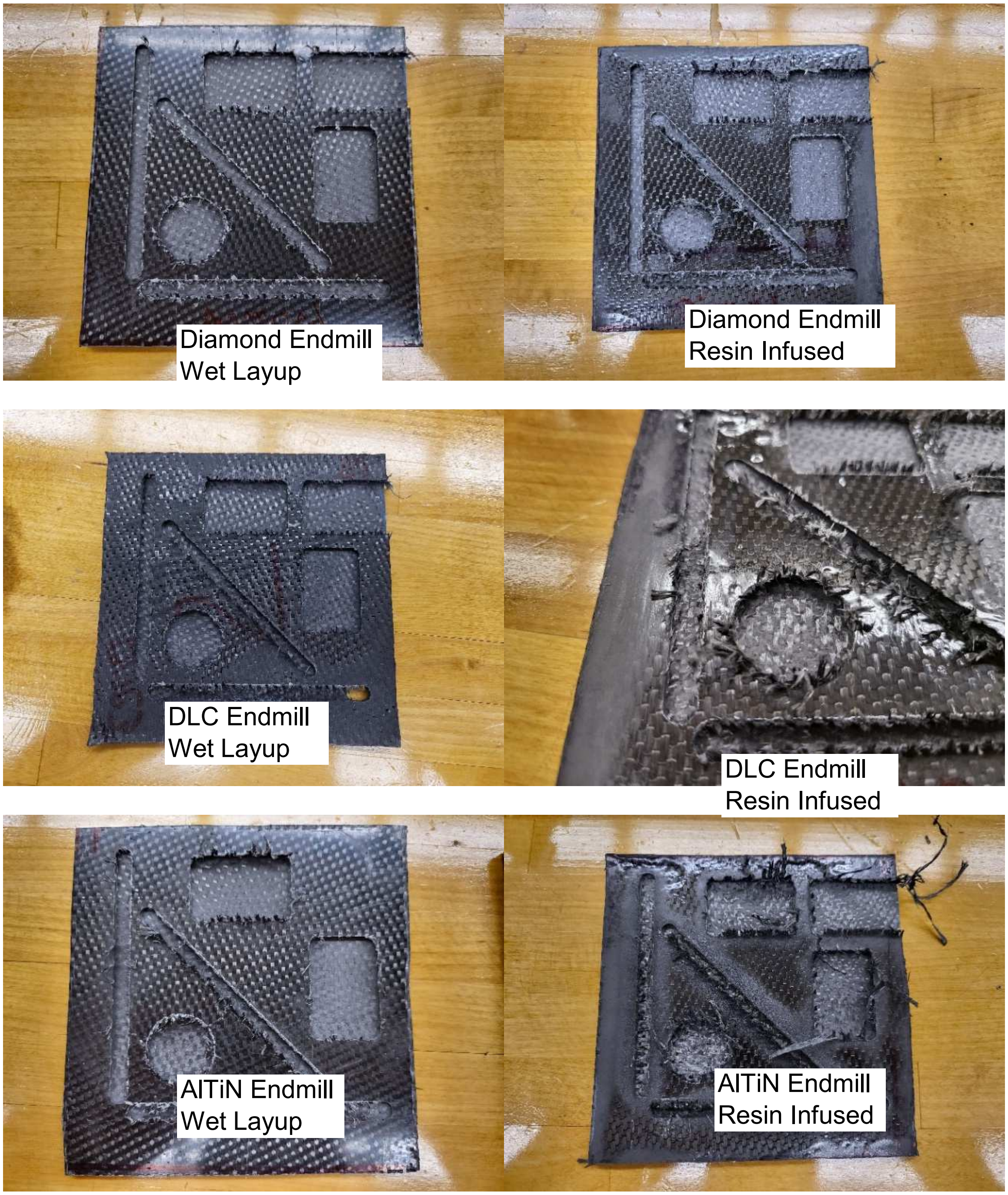
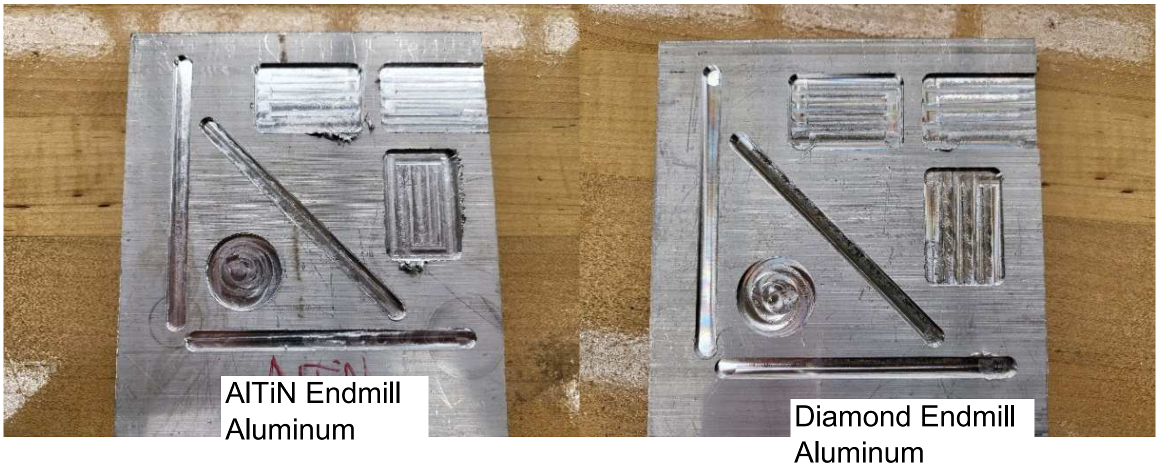


Figure 12. All the carbon fiber pieces after being machined.

From the figure 12 it is seen that for all the three endmills, the layup type matters. The wet layup appears to be more machinable than resin infused layups because there is less delamination on these layups. This could be caused by the amount of resin on the layups, resin infused layups have the least amount of resin possible, while the wet layups have almost an even amount of resin on each layer. The layups demonstrated that the AlTiN endmill provides the worst cutting properties for machining carbon fiber. DLC and Diamond coated endmills appear to be very comparable, but the Diamond coated endmill machines resin infused layups much better than DLC was able to.

Based on a visual inspection, there is not a significant difference between the aluminum and steel test pieces machined by the three endmills with the set feed rate and RPM. Diamond did give aluminum the best surface finish; the surface had a rainbow color after machining. The Diamond endmill though was too brittle for the set feed rates and plunge rates to machine steel, the endmill tip broke; no data was able to be gathered for machining steel with the Diamond endmill. The DLC endmill did have a slight difference in surface finish on both the aluminum and steel test pieces. AlTiN machined steel better than DLC. See figure 13 below.



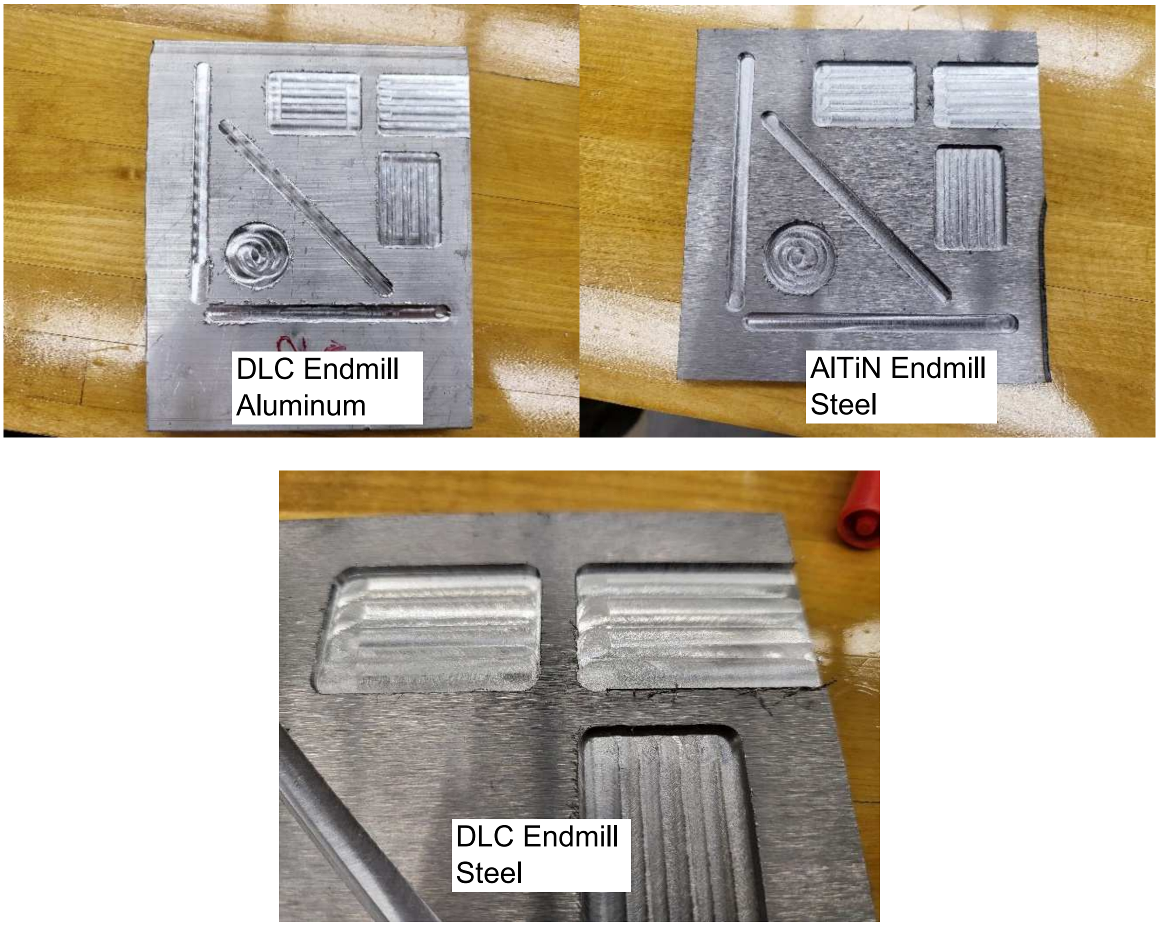


Figure 13. All the aluminum and steel test pieces after being machined. Note: There is no sample for the diamond endmill cutting steel because the endmill snapped.

Surface Finish

Table 3. The combinations of the materials and endmills.

Test Piece	Material	Endmill Used	Material #	Endmill #
1	Wet Layup	AlTiN	1	1
2	Wet Layup	DLC	1	2
3	Wet Layup	Diamond	1	3
4	Infusion	AlTiN	2	1
5	Infusion	DLC	2	2
6	Infusion	Diamond	2	3
7	Aluminum	AlTiN	3	1

8	Aluminum	DLC	3	2
9	Aluminum	Diamond	3	3
10	Steel	AlTiN	4	1
11	Steel	DLC	4	2
12	Steel	Diamond	4	3

The surface finish for each material with each of the three endmills is seen in the table below. From the data, it can be said that aluminum has the best machining capabilities for a smooth surface finish, but all the materials are still very smooth. The values on the table are measured in micrometers, anything below 0.8 micrometers is considered to be a mirror surface finish [12]. The averages of all the surface finish demonstrate that aluminum provides a mirror surface finish with all the endmills, but with the combination of a DLC endmill you can get the best surface finish out of all the endmill options in this experiment. The diamond endmill also provide a great surface finish on all the materials tested, wet layup, resin infusion, and aluminum. There is not a significant difference between the surface roughness mean of the wet layup and the resin infused layup while cutting with the diamond endmill. The DLC endmill does machine with a better surface finish than the AlTiN endmill, but it’s approximately 1.5x rougher than machining with the diamond endmill.

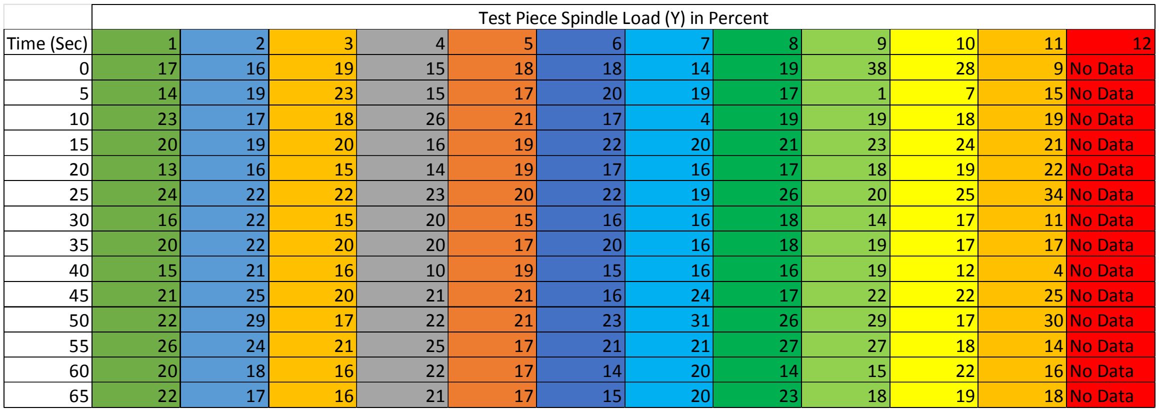
Table 4. Surface finish values, measured with profilometer in micrometers. Refer to table 3 for test pieces' material and endmill matrix.

Test Piece	Location 1	Location 2	Location 3	Average	Rank
1	1.628	1.838	2.19	1.885	10
2	1.4	2.063	1.725	1.729	8
3	1.324	1.134	1.244	1.234	6
4	2.577	3.187	3.151	2.972	11
5	1.882	1.613	1.529	1.675	7
6	0.993	1.211	1.227	1.144	5
7	0.483	0.567	0.468	0.506	2
8	0.318	0.327	0.46	0.368	1
9	0.61	0.55	0.404	0.521	3
10	0.628	0.562	0.781	0.657	4
11	1.948	1.907	1.738	1.864	9
12	No Data	No Data	No Data	No Data	No Data

Spindle Load Data

The table below is an example table of how the data was collected and then analyzed. This table is for load percentage in the Y-axis for cutting the circular pattern. The data could not be exported from the CNC machine, every operation was video recorded and inputted into multiple tables for each operation. Each operation has a table for the X-axis, Y-axis, Z-axis, and the spindle load in percent, which was provided on the CNC's screen. From the recording, the load for each direction was written on the tables every 5 seconds, from the start of that operation until the end of that operation. Some of the materials did not give very accurate data at times, because the load on the screen would fluctuate from 0-40% within 1 second. The materials that did this were both steel samples, and aluminum sample cutting with the AlTiN endmill.

Table 5. Example table for data collection. Circular operation table for the Y-axis load.



	Test Piece Spindle Load (Y) in Percent											
Time (Sec)	1	2	3	4	5	6	7	8	9	10	11	12
0	17	16	19	15	18	18	14	19	38	28	9	No Data
5	14	19	23	15	17	20	19	17	1	7	15	No Data
10	23	17	18	26	21	17	4	19	19	18	19	No Data
15	20	19	20	16	19	22	20	21	23	24	21	No Data
20	13	16	15	14	19	17	16	17	18	19	22	No Data
25	24	22	22	23	20	22	19	26	20	25	34	No Data
30	16	22	15	20	15	16	16	18	14	17	11	No Data
35	20	22	20	20	17	20	16	18	19	17	17	No Data
40	15	21	16	10	19	15	16	16	19	12	4	No Data
45	21	25	20	21	21	16	24	17	22	22	25	No Data
50	22	29	17	22	21	23	31	26	29	17	30	No Data
55	26	24	21	25	17	21	21	27	27	18	14	No Data
60	20	18	16	22	17	14	20	14	15	22	16	No Data
65	22	17	16	21	17	15	20	23	18	19	18	No Data

The data was analyzed with a Generalized Linear Model process of analysis using Minitab to compare all the different polymer structures with the machinability of each combination. After each analysis a post-hoc analysis was performed, specifically a Tukey pairwise comparison of each material, endmill, and their interactions. Each cut has results in the X, Y, Z, and total load; each result was viewed individually for a more detailed view at the full analysis. The carbon fiber twill on all the test pieces is aligned on the Y-Axis; a 0-degree cut means that the endmill is moving along the Y-Axis while machining.

90 Degree Cut

The analysis results for the 90-degree cut test can be found on Appendix A. According to the analysis of variance in the X-Axis (Appendix A: Tables 1-6) there is a significant difference between the machineability of the materials with the 3 different endmills. Based on the Tukey method of comparison, both carbon fiber test pieces provide less resistance load on the endmill while machining than the aluminum and steel no matter the endmill. The endmill that provides the least resistance load while machining is the diamond endmill, whereas the DLC endmill provides the most resistance load while machining. As for the combination of materials and endmills, the worst combinations for machining are aluminum with the DLC endmill, and steel with the AlTiN endmill. The analysis demonstrates that there is no significant difference between the rest of the combinations, but the top 5 combinations in order from best to worst are: aluminum with diamond, wet layup with DLC, resin infused with AlTiN, wet layup with diamond, and resin infused with diamond. The diamond endmill took 3 of 5 positions, and the carbon fiber took 4 of 5 positions; this clearly demonstrates that the least resistance load from machining can be achieved through using carbon fiber and diamond endmills. Even though this was the case, there is no significant difference between the combination of materials and endmill except for two.

According to the analysis of variance in the Y-Axis (Appendix A: Tables 7-12) there is a significant difference between the machineability of the materials, and their combinations with different endmills, but there is no significant difference between endmills. Based on the Tukey method of comparison, both carbon fiber test pieces provide less resistance load on the endmill while machining than the aluminum and steel no matter the endmill. Since there is no significant difference between the endmills, there is no difference in their ranks. As for the combination of materials and endmills, the worst combination for machining is resin infused with the AlTiN endmill. The analysis demonstrates that there are 5 different ranks that are significantly different for the 12 combinations. The best 5 combinations for machining in order from best to worst are: aluminum with diamond, steel with AlTiN, steel with DLC, aluminum with AlTiN, and steel with DLC. As seen the top 5 spots were all taken by the metals; this clearly demonstrates that the least resistance load from machining can be achieved through chip forming. While the endmills moved along the X-Axis, the metals created chips that exited the cutting surfaces, which provided less resistance load on the Y-Axis. Since the carbon fiber had uncut filaments that kept resisting along the X-Axis, this increased the average load values of the carbon fiber test pieces. Therefore, uncut filaments do provide some machining resistance even if they are moving freely around the endmill, and chip forming provides the least resistance on the non-moving axis.

According to the analysis of variance in the Z-Axis (Appendix A: Tables 13-18) there is a significant difference between the machineability combinations materials and endmills, but there is no significant difference between materials and endmills individually. Based on the Tukey method of comparison, the materials are all ranked the same, but in order from best to worst in machining resistance load is steel, resin infused, aluminum, and wet layup. Since there is no significant difference between the endmills as well, there is no difference in their ranks or much of a difference in their mean variance. As for the combination of materials and endmills, the worst combination for machining is resin infused with the diamond endmill. The analysis demonstrates that there is just one combination that is significantly different, which is the steel with diamond endmill; this is also the best combination. The top 5 combinations for machining in order from best to worst are: steel with diamond, aluminum with AlTiN, resin infused with DLC, wet layup with DLC, and resin infused with diamond. As mentioned before, there is no full set of data on the steel and diamond endmill combination, therefore this analysis can be concluded that there is no significant difference between the combinations of materials and endmills' machineability. The steel and diamond endmill data is not completely accurate, which made it seem as if the combination is good, but in reality this material caused the endmill to break.

According to the analysis of variance in the total load (Appendix A: Tables 19-24) there is a significant difference between the machineability of the materials with the 3 different endmills. Based on the Tukey method of comparison, both carbon fiber test pieces provide less resistance load on the endmill while machining than the aluminum and steel no matter the endmill. The endmill that provides the least resistance load while machining is the diamond endmill, whereas the DLC endmill provides the most resistance load while machining. As for the combination of materials and endmills, the worst combination for machining is aluminum with the DLC endmill. The analysis demonstrates that there are 4 different ranks that are significantly different for the 12 combinations. The best 5 combinations for machining in order from best to worst are: resin infused with diamond, wet layup with AlTiN, resin infused with DLC, resin infused with AlTiN, and wet layup with DLC. As seen the top 5 spots were all taken by the carbon fiber pieces; this clearly demonstrates that the polymer matrix composite materials are easier to machine than both aluminum and steel while machining at 90-degrees to the twill. The carbon fiber provided the least total load resistance whether it was wet laid, or resin infused the results were the same, there is no significant difference between either layup.

45 Degree Cut

The analysis results for this 45-degree cut test can be found on Appendix B. According to the analysis of variance in the X-Axis (Appendix B: Tables 1-6) there is a significant difference between the machineability while using different endmills and the material and endmill interaction. Based on the Tukey method of comparison, all the materials provide the same resistance load while machining. The endmill that provides the least resistance load while machining is the AlTiN endmill, whereas the Diamond endmill provides the most resistance while machining. Though this may be the case, the Tukey comparison demonstrates that there is no significant difference between the endmills while machining at 45-degrees. As for the combination of materials and endmills, the worst combinations for machining are steel with the Diamond endmill. The analysis demonstrates that there is no significant difference between most of the combinations, but the top 5 combinations in order from best to worst are: steel with AlTiN, resin infused with AlTiN, steel with DLC, resin infused with DLC, and aluminum with diamond. The only two combinations that are significantly different are the best and the worst: steel with AlTiN and steel with diamond endmill. As mentioned before, steel was a material that fluctuated much while collecting data, in other words, all the combinations may not be significantly different.

According to the analysis of variance in the Y-Axis (Appendix B: Tables 7-12) there is a significant difference between the machineability of the interaction of materials and endmills, but there is no significant difference between materials or endmills alone. Based on the Tukey method of comparison, all the materials provide the same resistance while machining, and the same goes to the endmills. As for the combination of materials and endmills, the worst combination for machining is steel with the diamond endmill. The best 5 combinations for machining in order from best to worst are: steel with DLC, aluminum with AlTiN, resin infusion with AlTiN, wet layup with DLC, and resin infusion with diamond. As seen the top 5 spots were all taken by a mix of materials and endmills; this clearly demonstrates that there may not be a significant difference between the combinations while machining at an angle. The significantly different materials shown in the analysis are those that fluctuated much during the machining process, therefore an untrustworthy result. Even though this is the case, the information is valuable since machineability of the combinations of materials and endmills at a 45-degree angle in the Y-Axis is the same for all the tested combinations.

According to the analysis of variance in the Z-Axis (Appendix B: Tables 13-18) there is a significant difference between the machineability of the materials, as well as the combinations materials and endmills, but there is no significant difference between the endmills individually. Based on the Tukey method of comparison, there is only one material that is significantly different, which is aluminum. The endmills are not significantly different, but from least machining resistance load to most resistance load are shown as diamond, AlTiN, and DLC endmill. As for the combination of materials and endmills, the worst combination for machining is aluminum with DLC endmill. The analysis demonstrates that there are three different ranks in which six of combinations are not significantly different. The six combinations are mostly the carbon fiber test pieces and one steel combination. The top 5 combinations for machining in order from best to worst are: resin infused with AlTiN, steel with diamond, steel with AlTiN, resin infused with diamond, and wet layup with DLC. The top 3 combinations are combinations that fluctuated too much while collecting data, if those combinations are not present, then carbon fiber materials provide the least amount of resistance while machining, no matter the endmill used. This concludes that in the Z-Axis, the material with the best machineability is carbon fiber, whether is wet laid or resin infused.

According to the analysis of variance in the total load (Appendix B: Tables 19-24) there is a significant difference between the machineability of the materials, the endmills, and their combinations. Based on the Tukey method of comparison, both carbon fiber test pieces provide less resistance load on the endmill while machining than the aluminum and steel no matter the endmill. The endmill that provides the least resistance while machining is the DLC endmill, whereas the AlTiN endmill provides the most resistance while machining. As for the combination of materials and endmills, the worst combination for machining is steel with diamond endmill. The analysis demonstrates that there are three different ranks that are significantly different for the 12 combinations. The best 5 combinations for machining in order from best to worst are: resin infused with diamond, resin infused with DLC, aluminum with diamond, wet layup with DLC, and wet layup with diamond. As seen 4 of the top 5 spots were taken by the carbon fiber pieces and all the endmills were DLC and diamond endmills. This clearly demonstrates that the polymer matrix composite materials are easier to machine than both aluminum and steel while machining at 45-degrees to the twill. The DLC and diamond endmills are not very different in terms of machineability of the carbon fiber materials. The carbon fiber provided the least total load resistance whether it was wet laid, or resin infused the results were the same, there is no significant difference between either layup.

0 Degree Cut

The analysis results for this 0-degree cut test can be found on Appendix C. According to the analysis of variance in the X-Axis (Appendix C: Tables 1-6) there is a significant difference between the machineability of the materials, and the material and endmill combination, but there is not a significant difference between the machineability of different endmills. Based on the Tukey method of comparison, both carbon fiber test pieces provide more resistance on the endmill while machining than the aluminum and steel no matter the endmill. The endmill that provides the least resistance load while machining is the AlTiN endmill, whereas the DLC endmill provides the most resistance while machining, even though there is no significant difference between them. As for the combination of materials and endmills, the worst combination for machining is resin infused with AlTiN endmill. The analysis demonstrates that there are five different ranks for the combinations, but the top 5 combinations in order from best to worst are: steel with AlTiN, steel with DLC, aluminum with diamond, steel with diamond, and aluminum with AlTiN. As seen the top 5 spots were all taken by the metals; this clearly demonstrates that the least resistance load from machining can be achieved through chip forming as mentioned on the Y-Axis analysis for the 90-degree cut. While the endmills moved along the Y-Axis, the metals created chips that exited the cutting surfaces, which provided less resistance on the X-Axis. Since the carbon fiber had uncut filaments that kept resisting along the X-Axis, this increased the average load values of the carbon fiber test pieces. Therefore, uncut filaments do provide some machining resistance even if they are moving freely around the endmill, and chip forming provides the least resistance on the non-moving axis.

According to the analysis of variance in the Y-Axis (Appendix C: Tables 7-12) there is no significant difference between the machineability of the materials, the endmills, nor their combinations. Based on the Tukey method of comparison, the material with the least resistance to most resistance are aluminum, wet layup, resin infused, and lastly steel. Since there is no significant difference between the endmills, there is no difference in their ranks, but the AlTiN endmill had the lowest load, while the diamond endmill had the most load. As for the combination of materials and endmills, the worst combination for machining is steel with the diamond endmill, even though there is no significant difference between the combinations. The best 5 combinations for machining in order from best to worst are: aluminum with AlTiN, steel with DLC, wet layup with AlTiN, resin infused with DLC, and aluminum with DLC. The top 5 spots were taken by a different variety of combinations of materials and metals; this makes it unclear to what exactly produces the least load while machining. This is also the result of the analysis, that states that there is no significant difference between all the combinations, while machining in the same direction that the carbon fiber twill is facing.

According to the analysis of variance in the Z-Axis (Appendix C: Tables 13-18) there is a significant difference between the machineability of the materials, the endmills, and their combinations. Based on the Tukey method of comparison, the materials have three different ranks where resin infused is ranked the best, wet laid and steel are ranked the same but wet laid is placed over steel, and aluminum is ranked as the worst material with the most load resistance. The endmills were significantly different, where the diamond endmill was ranked as the best endmill, and the AlTiN endmill was ranked as the worst endmill with the most load resistance. As for the combination of materials and endmills, the worst combination for machining is aluminum with the diamond endmill. The analysis demonstrates that there are five different ranks for the twelve combinations, indicating them to be significantly different. The top 5 combinations for machining in order from best to worst are: resin infused with diamond, steel with diamond, resin infused with DLC, wet layup with DLC, and resin infused with AlTiN. As mentioned before, there is no full set of data on the steel and diamond endmill combination, therefore this analysis can be concluded that the top 5 combinations are all carbon fiber test pieces since ranked 6th is wet laid with diamond endmill. This clearly demonstrates that while machining in the Z-Axis, polymer matrix composites will provide less load resistance than steel and aluminum, making it more machinable.

According to the analysis of variance in the total load (Appendix C: Tables 19-24) there is a significant difference between the machineability of the materials, and the endmills, but there is not a significant difference between their interaction. Based on the Tukey method of comparison, both carbon fiber test pieces provide less resistance on the endmill while machining than the aluminum and steel no matter the endmill. The endmill that provides the least resistance while machining is the diamond endmill, whereas the AlTiN endmill provides the most resistance while machining. As for the combination of materials and endmills, the worst combination for machining is machining steel with the

AlTiN endmill. The best 5 combinations for machining in order from best to worst are: wet laid with diamond, resin infused with DLC, resin infused with diamond, resin infused with AlTiN, and aluminum with diamond. As seen, most of the top 5 spots were taken by the carbon fiber pieces; this clearly demonstrates that the polymer matrix composite materials are easier to machine than both aluminum and steel while machining at 0-degrees to the twill. All the resin infused layups are in the top 5, and are not significantly different, which shows that resin infused layups do provide less resistance load than wet laid carbon fiber while machining 0-degrees to the twill, and no matter which endmill is used.

90 Degree Square Cut

The analysis results for this 90-degree square cut test can be found on Appendix D. According to the analysis of variance in the X-Axis (Appendix D: Tables 1-6) there is a significant difference between the machineability of the materials, the endmills, and their combinations. Based on the Tukey method of comparison, the order of the materials that create the least resistance to the most resistance load while machining the 90-degree square cut is aluminum, resin infused, wet layup, and lastly steel. The endmill that provides the least resistance while machining is the AlTiN endmill, whereas the diamond endmill provides the most resistance while machining. As for the combination of materials and endmills, the worst combination for machining is steel with the diamond endmill which was also the only combination that was significantly different. The analysis demonstrates that there is no significant difference between the rest of the combinations, but the top 5 combinations in order from best to worst are: aluminum with

AlTiN, aluminum with diamond, steel with AlTiN, steel with DLC, and resin infused with diamond. Even though 4 out of 5 of the materials are metals, the composite materials were not significantly different from them, this means that square pockets can be similarly machined with the same resistance load on all the tested materials except steel and diamond endmill. Based on the best to worst analysis though, it can also be said that metal materials are slightly better to pocket while machining at 90 degrees to the twill of the composite materials because they create less resistance load.

According to the analysis of variance in the Y-Axis (Appendix D: Tables 7-12) there is not a significant difference between the machineability of the materials, the endmills, nor their combinations. Based on the Tukey method of comparison, the order of the materials from least to most resistance load is steel, resin infused, aluminum, and lastly wet layups. The order of the endmills from least to most resistance load is diamond, DLC, and AlTiN. As for the combination of materials and endmills, the worst combination for machining is wet layup with the AlTiN endmill. The best 5 combinations for machining in order from best to worst are: steel with diamond, resin infused with diamond, aluminum with DLC, steel with AlTiN, and steel with DLC. As seen the top 5 spots were mostly taken by the metals, this is similar to what was seen before, metals create less resistance load on the axis that the endmill is not moving along on.

According to the analysis of variance in the Z-Axis (Appendix D: Tables 13-18) there is a significant difference between the machineability of the materials, the endmills, and their combinations. Based on the Tukey method of comparison, there is a significant difference between all the materials, there are 4 different ranks, but the order of the most machinable to least machinable material is resin infused, wet laid, steel, and lastly aluminum. All the endmills are also significantly different with 3 different ranks, the endmill with the best machinability properties is diamond, while DLC has the worst machinability properties. The analysis demonstrates that there are eight different ranks for the twelve combinations, indicating them to be significantly different. The top 5 combinations for machining in order from best to worst are: steel with diamond, wet laid with DLC, resin infused with diamond, resin infused with AlTiN, and resin infused with DLC. As mentioned before, there is no full set of data on the steel and diamond endmill combination, therefore this analysis can be concluded that the top 5 combinations are all carbon fiber test pieces since ranked 6th is wet laid with AlTiN endmill. This clearly demonstrates that while machining in the Z-Axis, polymer matrix composites will provide less resistance load than steel and aluminum, making it more machinable.

According to the analysis of variance in the total load (Appendix D: Tables 19-24) there is a significant difference between the machineability of the materials, the endmills, and their combinations. Based on the Tukey method of comparison, both carbon fiber test pieces provide less resistance on the endmill while machining than the aluminum and steel no matter the endmill. The endmill that provides the least resistance while machining is the DLC endmill, whereas the diamond endmill provides the most resistance while machining. As for the combination of materials and endmills, the worst combination for machining is machining steel with the diamond endmill. The analysis demonstrates that there are 4 different ranks that are significantly different for the 12 combinations. The best 5 combinations for machining in order from best to worst are: wet laid with diamond, aluminum with DLC, wet laid with DLC, resin infused with diamond, and wet layup with AlTiN. As seen the top 5 spots were mostly taken by the carbon fiber pieces; this clearly demonstrates that the polymer matrix composite materials are easier to machine than both aluminum and steel while machining a 90-degrees square pocket to the twill. It can also be said that while machining a square pocket that is machined at 90-degrees to the twill, the wet laid composites do provide less resistance load than the resin infused, even though both are not significantly different from each other.

0 Degree Square Cut

The analysis results for this 0-degree square cut test can be found on Appendix E. According to the analysis of variance in the X-Axis (Appendix E: Tables 1-6) there is not a significant difference between the machineability of the materials, the endmills, nor their combinations. Based on the Tukey method of comparison, both carbon fiber test pieces provide less resistance on the endmill while machining than the aluminum and steel no matter the endmill. The endmill that provides the least resistance load while machining is the diamond endmill, whereas the DLC endmill provides the most resistance load while machining. As for the combination of materials and endmills, the worst combination for machining is steel with the AlTiN endmill. The analysis demonstrates that there is no significant difference between all the combinations, but the top 5 combinations in order from best to worst are: steel with diamond, wet layup with AlTiN, resin infused with diamond, wet layup with diamond, and wet laid with DLC. Even with no significantly different results for the combinations, it can also be said that the carbon fiber tests provide less resistance load than that of aluminum and steel, especially the composites that were wet laid.

According to the analysis of variance in the Y-Axis (Appendix E: Tables 7-12) there is a significant difference between the machineability of the materials, and their combinations with different endmills, but there is no significant difference between endmills. Based on the Tukey method of comparison, there is no significant difference between the materials' resistance load, but from the material that creates the least resistance load to the most is aluminum, resin infused, wet laid, and lastly steel. Since there is no significant difference between the endmills, there is no difference in their ranks where the DLC endmill creates the least resistance load, and diamond creates the most resistance load. As for the combination of materials and endmills, the worst combination for machining is steel with the diamond endmill, which was the only combination that was significantly different. The best 5 combinations for machining in order from best to worst are: aluminum with diamond, resin infused with diamond, wet laid with DLC, wet laid with diamond, and resin infused with DLC. With the top combinations not being significantly different, the combinations are scattered with almost no trend. However, it is possible to say that the composite materials have a lower resistance load while machining a square pocket that is machined in the same direction as the fiber twill. It can also be said that diamond and DLC endmills have the least resistance load while machining these pockets.

According to the analysis of variance in the Z-Axis (Appendix E: Tables 13-18) there is a significant difference between the machineability of the materials, the endmills, and their combinations. Based on the Tukey method of comparison, both carbon fiber test pieces provide less resistance on the endmill while machining than the aluminum and steel no matter the endmill. The analysis ranks the diamond endmill as the only significantly different endmill with the least resistance load, whereas the endmill with the most resistance load is the AlTiN endmill. As for the combination of materials and endmills, the worst combination for machining is aluminum with the DLC endmill. The analysis demonstrates that there are five different ranks that are significantly different for the twelve combinations. The top 5 combinations for machining in order from best to worst are: steel with diamond, wet laid with DLC, resin infused with DLC, resin infused with diamond, and resin infused with AlTiN. The comparison demonstrates that most of top 5 combinations are with the composite materials, especially the resin infused layups. This means that the resin infused layups create a lower resistance load while machining pockets along the fiber twill in the Z-Axis than wet layups and metals.

According to the analysis of variance in the total load (Appendix E: Tables 19-24) there is a significant difference between the machineability of the materials, the endmills, and their combinations. Based on the Tukey method of comparison, both carbon fiber test pieces provide less resistance on the endmill while machining than the aluminum and steel no matter the endmill. The endmills were all significantly different from each other, and the endmill that provides the least resistance load while machining is the DLC endmill, whereas the diamond endmill provides the most resistance load while machining. As for the combination of materials and endmills, the worst combination for machining is machining steel with the diamond endmill. The analysis demonstrates that there are five different ranks that are significantly different for the twelve combinations. The top 5 combinations for machining with the least resistance load in order from best to worst are: resin infused with AlTiN, resin infused with DLC, resin infused with diamond, wet layup with DLC, and wet layup with AlTiN. As shown the top 5 spots were all taken by the carbon fiber pieces; this clearly demonstrates that the polymer matrix composite materials are easier to machine than both aluminum and steel while machining a 0-degrees to the fiber twill pocket. Even though the results demonstrate that the composite layups had no significant difference in their values, all the resin infused combinations had a lower resistance load value than the other combinations. Therefore, the resin infused layups are more machinable than the wet layups, the aluminum, and the steel.

Circular Cut

The analysis results for this circular cut test can be found on Appendix F. According to the analysis of variance in the X-Axis (Appendix F: Tables 1-6) there is a significant difference between the machineability of the endmills, but there is no significant difference between the materials, and the combinations. Based on the Tukey method of comparison, both carbon fiber test pieces provide less resistance on the endmill while machining than the aluminum and steel no matter the endmill. The endmill that provides the least resistance load while machining is the AlTiN endmill, whereas the diamond endmill provides the most resistance load while machining. As for the combination of materials and endmills, the worst combination for machining is steel with the diamond endmill, which was the only combination that is demonstrated to be significantly different. The top 5 combinations in order from best to worst are: steel with

AlTiN, resin infused with AlTiN, steel with DLC, wet layup with DLC, and resin infused with DLC. Something to note from the results is that the top five results only have AlTiN and DLC endmills, indicating that they produce less resistance load on the X-Axis while machining a circular pocket. Even though this was the case, there is no significant difference between the combinations of the materials and the endmills, and not much can be said about the results since the top results have a variety of combinations.

According to the analysis of variance in the Y-Axis (Appendix F: Tables 7-12) there is not a significant difference between the machineability of the materials, and the endmills, but there is a significant difference between their combinations. Based on the Tukey method of comparison, all the materials are ranked the same, but in order from least resistance load to most resistance load the results were resin infused, aluminum, wet layups, and lastly steel. Since there is no significant difference between the endmills, there is no difference in their ranks as well, the best endmill with the least resistance load is the AlTiN endmill, while the diamond endmill was the worst endmill with the most resistance load. As for the combination of materials and endmills, there was only one combination that was significantly different, which was the steel with the diamond endmill. In other words, there is not a significant different between the combinations of the materials and endmills on the Y-Axis while machining a circular pocket since the steel and diamond combination is not actual data. The best 5 combinations for machining in order from best to worst are: steel with DLC, aluminum with AlTiN, resin infused with diamond, resin infused with DLC, and wet layup with diamond. These top results truly demonstrate that there is no significant difference between the resistance load of the combinations of materials and endmills on the Y-Axis while machining a circular pocket. The top combinations are from each of the materials and each of the endmills, indicating that the machineability is similar through each of the combinations.

According to the analysis of variance in the Z-Axis (Appendix F: Tables 13-18) there is a significant difference between the machineability of the materials, the endmills, and their combinations. Based on the Tukey method of comparison, all the materials are ranked differently, the order of the materials best to worst in machining resistance load is resin infused, wet layup, steel, and aluminum. The endmill with the least resistance load is the diamond endmill, while the DLC endmill is the endmill with the most resistance load while machining a circular pocket. The analysis demonstrates that there are 5 different ranks for 12 combinations where steel with diamond is has its own rank. The top 5 combinations for machining in order from best to worst are: steel with diamond, resin infused with DLC, wet layup with DLC, resin infused with diamond, and resin infused with AlTiN. As mentioned before, there is no full set of data on the steel and diamond endmill combination, therefore this analysis can be concluded that the composite materials create the lowest resistance load out of all the materials. The steel and diamond endmill data is not completely accurate, which would truly remove it from the top of the list. The top list had three out of three resin infused materials, meaning that the resin infused composite materials have the best machinability over all the test materials in this experiment while machining on Z-Axis.

According to the analysis of variance in the total load (Appendix F: Tables 19-24) there is a significant difference between the machineability of the materials, the endmills, and their combinations. Based on the Tukey method of comparison, the only material that is ranked differently is steel, but the order from best to worst in machining resistance load is resin infused, wet layup, aluminum, and steel. The endmill that provides the least resistance while machining is the AlTiN endmill, whereas the diamond endmill provides the most resistance while machining. As for the combination of materials and endmills, the worst combination for machining is machining steel with the diamond endmill. The analysis demonstrates that there are 3 different ranks that are significantly different for the 12 combinations. The top 5 combinations for machining in order from best to worst are: wet layup with diamond, resin infused with DLC, wet layup with AlTiN, resin infused with diamond, and aluminum with DLC. The top spots were taken by mostly composite materials, and mostly by the DLC and diamond endmill. The carbon fiber provided the least total load resistance whether it was wet laid, or resin infused the results were the same, there is no significant difference between either layup. The DLC and the diamond endmills can equally be said to be the endmills that create the least total resistance load while machining a circular pocket.

Recommendations

This experiment is only the beginning of many more experiments that could be adding more value to this research. There are many different properties and experiments that should be tested to truly know the machining of polymer matrix composites. Some of those properties and tests include items from both sides of the spectrum, the composites side, and the machining side of the experiment. In the composites, there are different types of resins, resin mixtures, fibers, and fiber orientation that should be tested. In the machining side, the endmills could have different feed rates, different spindle RPM, and different cutting depths. Before getting into any of those recommendations, the first recommendation is to fasten the test pieces a different way. The test pieces in this experiment were secured onto the CNC machining using a vise, which slightly warped the material, creating an uneven cut of the material. To fix this it would be best to secure the materials onto the cutting table directly by using a clamping method called “Top Clamping” [11]. This clamping method ensures that the material is completely flat on the CNC bed/table, by clamping the corners or top sides of the material.

The first recommendation within the composite materials perspective is to test the carbon layups with different resin such as epoxy. Epoxy has much a more elastic structure than that of vinyl ester, which means that epoxy can be machined nearly the same as aluminum. As for vinyl ester, it is more brittle than epoxy so it’s machining properties may be similar to that of cast iron or steel. It is expected that epoxy and vinyl ester will both demonstrate different machining properties but will be comparable to those of aluminum and steel. The same experiment would be performed, in other words by using the epoxy resin, a wet layup and a resin infused layup test piece for the three different endmills should be made, and machined.

The next recommendation is to test different resin mixture, with their respective resin hardener, because the resin hardness will differ the machineability of the product. The resin hardness is determined by the resin to hardener mixture; epoxy uses an epoxy hardener that varies the mixture from slow, medium, and fast gel times which all provide a different hardness to the resin. All three resin mixtures should be tested to k if the hardener mixture affects the epoxy’s machineability. Vinyl ester uses Methyl ethyl ketone peroxide (MEKP) to harden the resin, this experiment used 2% of MEKP with the vinyl ester resin. The harder the resin is the more brittle the resin will become, while the softer the resin is the more elastic it will be as well. For vinyl ester it is recommended to test different MEKP mixtures from 1% to 3% MEKP to learn the machineability of the composite materials with different resin and hardener mixture.

Another recommendation with the composite materials perspective is to test different fiber orientation. In the experiment all the carbon fiber layups were manufactured by having all the fiber layers in the same orientation or direction. An ideal test would be to manufacture the test pieces by having every layer with a 90° cross over. For example, if the first layer is set to have a fiber orientation of 0°, then the next layer would be placed over it at 90°, the layer after that would then be placed over it at 0°, and so on. This would create the test pieces to have different cutting properties since the piece is basically being machined at 0° and 90° (relative to the fibers) while machining in the X and Y axis.

The last recommendation with the composite materials perspective is to do all the mentioned recommendations and the tests in the experiment with other polymer matrix composites such as fiberglass and Kevlar, as well as prepreg materials. Prepreg is another type of layup that is widely used everywhere and is considered to be the “perfect” fiber to resin ratio. Both fibers, and prepreg materials will have different properties from the test pieces manufactured in this experiment and will react differently to the endmills, feed rates, resin mixture, which is all important to know. Both materials are also widely used in different industries such as automotive, marine, aerospace, and more. Fiberglass and Kevlar, have their own characteristics that would be interesting to see how they compare to the machining of carbon fiber, aluminum, and steel. The prepreg material should be of the three materials mentioned: carbon fiber, fiberglass, and Kevlar.

As for the machining properties that should be changed and tested are the feed rates and spindle RPM. With the same RPM, the test piece should be machined with different federates to see surface finish and machineability. A good range of feed rates to be test would be from 3ipm to 8ipm, while being cautious of the material and having the same RPM. As mentioned before, the 3ipm plunge of the diamond endmill was too much for the endmill to handle, which made it break. The RPM would also have a range from 2,000RPM to 5,000RPM while keeping the same feed rate. These 2 experiments would add many runs to do, which would be very time consuming, but by the end of the experiment the information will be very educational. These tests would demonstrate what the perfect RPM and feed rate would be for all the materials, fiberglass, carbon fiber, and Kevlar.

Lastly in machining processes, the depth of every cutting path does create a difference in the forces seen on the spindle load. During the experiment, every cutting path had a depth of 0.075”, how would a cutting path of 0.1” be different from 0.075”? A good cutting path depth range to test would be from 0.05” to 0.15” while also testing all the other recommendations mentioned. All these combinations of tests would improve the understanding of polymer matrix composites, by demonstrating how it would be best to machine them. Every machinist wants to know how to machine the material they are machining as efficiently as possible, while still having high quality. All these other tests mentioned in this recommendation section of this research are tests that would give an answer to that efficiency question.

A new way for information gathering of the data is a must. During this experiment it took a long time to place the data from a video into a table or excel document. A software or CNC that can record the spindle loading data and be placed into a table or graph would simplify the process and be more accurate. As mentioned, the steel spindle loading forces may be inaccurate because the load alternated too much every second; a data point could be written down from 0-40%. The accuracy of the steel data is questionable which can give false data, improving this data collection process would highly increase the results of this experiment.

Conclusion

This research is something that I would like to continue in my career or when I complete a Doctorate Degree. There is still much more to learn from the machining of polymer matrix composite materials that have not been established. The gathered data in this experiment did demonstrate some of the machining properties of polymer matrix composites. The most common properties from a visual perspective for machining the carbon fiber are that it's best to climb mill in the direction of the twill for the best cut. The wet layups are more machinable than resin infused layups because they had less fiber delamination after machining no matter which endmill was used. The diamond endmill did machine much better than the AlTiN endmill by having less delamination, but the DLC endmill was not far off from the same results as the diamond endmill.

The surfaces of the materials demonstrated that aluminum has the best machining capabilities for a smooth surface finish, but all the materials are still very smooth. The averages of all the surface finish demonstrate that aluminum provides a mirror surface finish with all the endmills, but with the combination of a DLC endmill you can get the best surface finish out of all the endmill options in this experiment. The diamond endmill also provides a great surface finish on all the materials tested, wet layup, resin infusion, and aluminum. The DLC endmill had similar results to that of the diamond endmill, except that the diamond endmill provides a better surface finish for both composite layups, while the AlTiN endmill provides a worst surface finish overall.

The resistance load analysis demonstrated which materials, endmills, and combinations have the least resistance, indicating the best machineability possible between materials and the endmills. The results indicated that this is case by case, and that it's important to know the direction that the endmill is cutting as well as the direction of the fiber twill. While machining at 90-degrees to the fiber twill, whether that's a straight cut or a square cut the polymer matrix composite materials are more machinable than both aluminum and steel while machining at 90-degrees to the fiber twill. The carbon fiber provided the least total load resistance whether it was wet laid, or resin infused the results were the same, there is no significant difference between either layup. While machining at 0-degrees to the fiber twill, the results are different from the 90-degree cut, the polymer matrix composite materials are easier to machine than both aluminum and steel as well, but resin infused materials are clearly over wet laid composites. Even though the results demonstrate that the composite layups had no significant difference in their values, all the resin infused combinations had a lower resistance load value than the other combinations. Therefore, the resin infused layups are more machinable than the wet layups, the aluminum, and the steel while machining in the same direction that the fiber twill is waved. Lastly, the circular cut analysis demonstrated the same results about the materials that the polymer matrix composite materials have a lower resistance load value than aluminum and steel. As for the endmills, the two endmills that had very similar results were the DLC and diamond endmill; these endmills equally be said to be the endmills that create the least total resistance load while machining a circular pocket.

Overall, this experiment has demonstrated the machinability properties of polymer matrix composite materials as compared to common aluminum and steel. Resin infused and wet laid composite materials do have slightly different cutting properties even at different cutting angles, the materials are also fairly similar to metals at different cutting directions and cutting angles to the fiber twill. When deciding the endmill to use on a specific material that was used in this experiment, it is important to also consider the machining program operation in order to reduce the stress on the endmill.

There are multiple other tests that would add more knowledge to this experiment such as machining at different RPMs, feed rates, depths, as well as testing other materials such as pre-preg composite materials. This experiment is a steppingstone to many more potential experiments that would add more value to the body of knowledge in polymer matrix composite materials.

Citations

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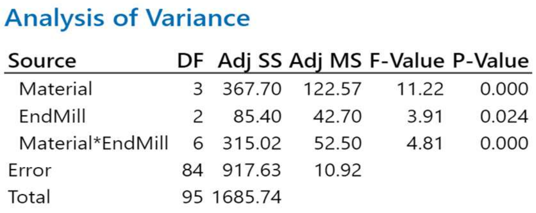
Appendixes

Appendix A – 90 Degree Analysis Results

X-Axis Analysis:

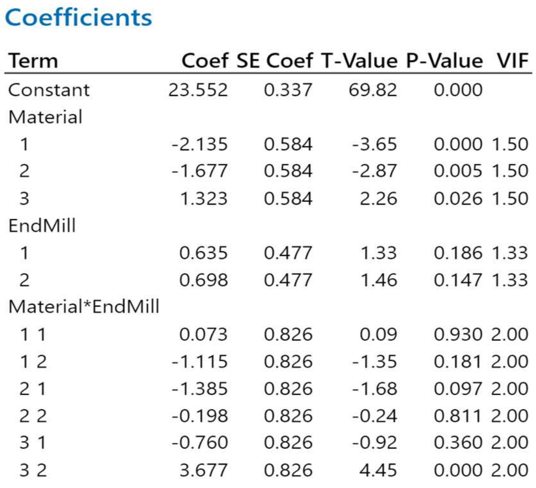
Table 1.



Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Material	3	367.70	122.57	11.22	0.000
EndMill	2	85.40	42.70	3.91	0.024
Material*EndMill	6	315.02	52.50	4.81	0.000
Error	84	917.63	10.92		
Total	95	1685.74			

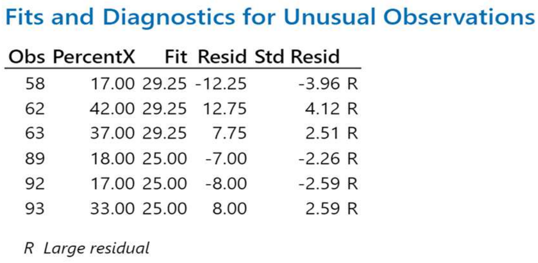
Table 2.



Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	23.552	0.337	69.82	0.000	
Material					
1	-2.135	0.584	-3.65	0.000	1.50
2	-1.677	0.584	-2.87	0.005	1.50
3	1.323	0.584	2.26	0.026	1.50
EndMill					
1	0.635	0.477	1.33	0.186	1.33
2	0.698	0.477	1.46	0.147	1.33
Material*EndMill					
1 1	0.073	0.826	0.09	0.930	2.00
1 2	-1.115	0.826	-1.35	0.181	2.00
2 1	-1.385	0.826	-1.68	0.097	2.00
2 2	-0.198	0.826	-0.24	0.811	2.00
3 1	-0.760	0.826	-0.92	0.360	2.00
3 2	3.677	0.826	4.45	0.000	2.00

Table 3.

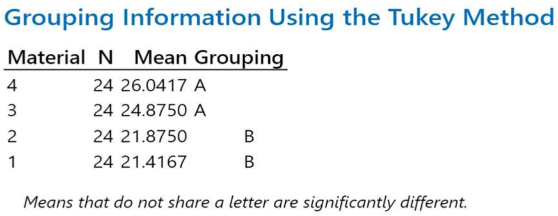


Fits and Diagnostics for Unusual Observations

Obs	PercentX	Fit	Resid	Std Resid	
58	17.00	29.25	-12.25	-3.96	R
62	42.00	29.25	12.75	4.12	R
63	37.00	29.25	7.75	2.51	R
89	18.00	25.00	-7.00	-2.26	R
92	17.00	25.00	-8.00	-2.59	R
93	33.00	25.00	8.00	2.59	R

R Large residual

Table 4.

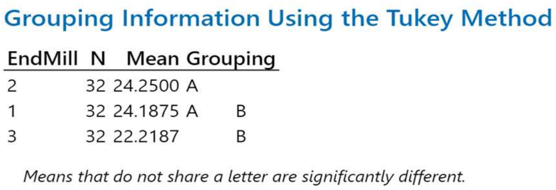


Grouping Information Using the Tukey Method

Material	N	Mean	Grouping	
4	24	26.0417	A	
3	24	24.8750	A	
2	24	21.8750		B
1	24	21.4167		B

Means that do not share a letter are significantly different.

Table 5.

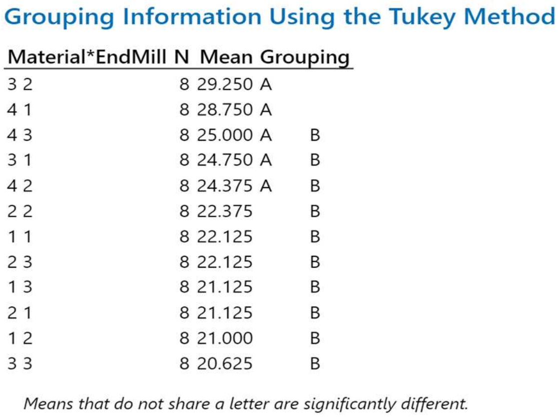


Grouping Information Using the Tukey Method

EndMill	N	Mean	Grouping	
2	32	24.2500	A	
1	32	24.1875	A	B
3	32	22.2187		B

Means that do not share a letter are significantly different.

Table 6.



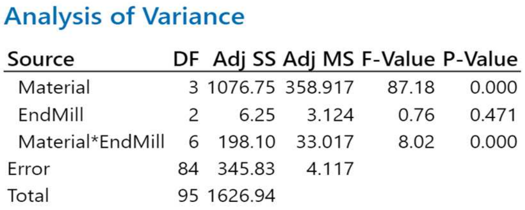
Grouping Information Using the Tukey Method

Material*EndMill	N	Mean	Grouping	
3 2	8	29.250	A	
4 1	8	28.750	A	
4 3	8	25.000	A	B
3 1	8	24.750	A	B
4 2	8	24.375	A	B
2 2	8	22.375		B
1 1	8	22.125		B
2 3	8	22.125		B
1 3	8	21.125		B
2 1	8	21.125		B
1 2	8	21.000		B
3 3	8	20.625		B

Means that do not share a letter are significantly different.

Y-Axis Analysis:

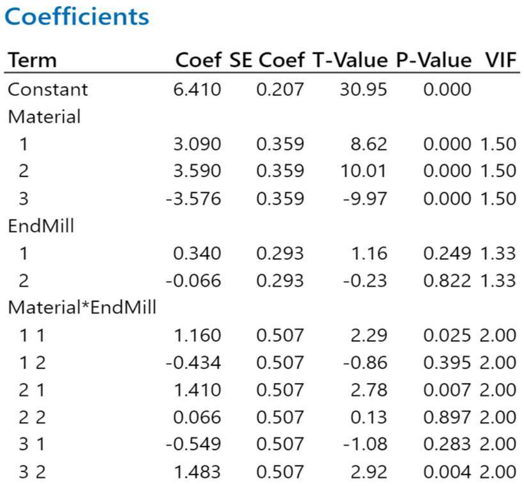
Table 7.



Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Material	3	1076.75	358.917	87.18	0.000
EndMill	2	6.25	3.124	0.76	0.471
Material*EndMill	6	198.10	33.017	8.02	0.000
Error	84	345.83	4.117		
Total	95	1626.94			

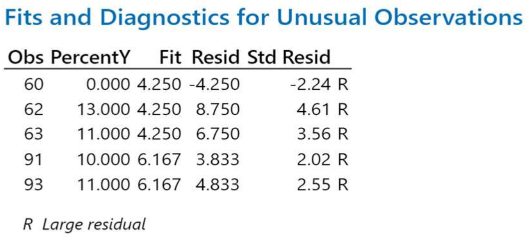
Table 8.



Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	6.410	0.207	30.95	0.000	
Material					
1	3.090	0.359	8.62	0.000	1.50
2	3.590	0.359	10.01	0.000	1.50
3	-3.576	0.359	-9.97	0.000	1.50
EndMill					
1	0.340	0.293	1.16	0.249	1.33
2	-0.066	0.293	-0.23	0.822	1.33
Material*EndMill					
1 1	1.160	0.507	2.29	0.025	2.00
1 2	-0.434	0.507	-0.86	0.395	2.00
2 1	1.410	0.507	2.78	0.007	2.00
2 2	0.066	0.507	0.13	0.897	2.00
3 1	-0.549	0.507	-1.08	0.283	2.00
3 2	1.483	0.507	2.92	0.004	2.00

Table 9.

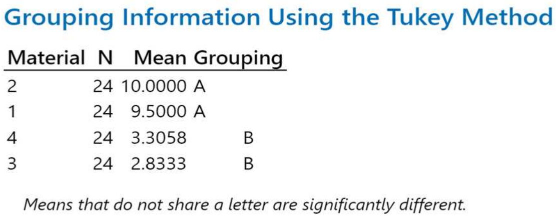


Fits and Diagnostics for Unusual Observations

Obs	PercentY	Fit	Resid	Std Resid	
60	0.000	4.250	-4.250	-2.24	R
62	13.000	4.250	8.750	4.61	R
63	11.000	4.250	6.750	3.56	R
91	10.000	6.167	3.833	2.02	R
93	11.000	6.167	4.833	2.55	R

R Large residual

Table 10.

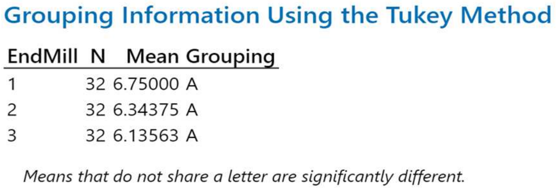


Grouping Information Using the Tukey Method

Material	N	Mean	Grouping
2	24	10.0000	A
1	24	9.5000	A
4	24	3.3058	B
3	24	2.8333	B

Means that do not share a letter are significantly different.

Table 11.

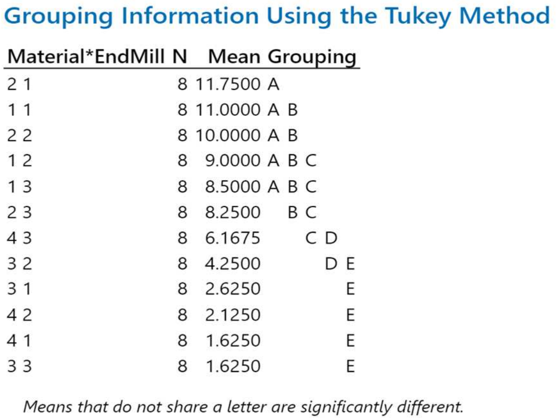


Grouping Information Using the Tukey Method

EndMill	N	Mean	Grouping
1	32	6.75000	A
2	32	6.34375	A
3	32	6.13563	A

Means that do not share a letter are significantly different.

Table 12.



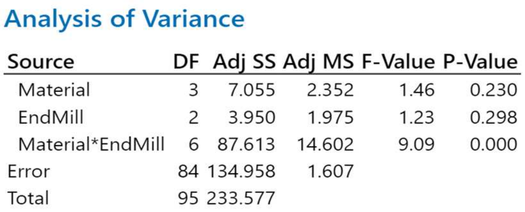
Grouping Information Using the Tukey Method

Material*EndMill	N	Mean	Grouping
2 1	8	11.7500	A
1 1	8	11.0000	A B
2 2	8	10.0000	A B
1 2	8	9.0000	A B C
1 3	8	8.5000	A B C
2 3	8	8.2500	B C
4 3	8	6.1675	C D
3 2	8	4.2500	D E
3 1	8	2.6250	E
4 2	8	2.1250	E
4 1	8	1.6250	E
3 3	8	1.6250	E

Means that do not share a letter are significantly different.

Z-Axis Aalysis:

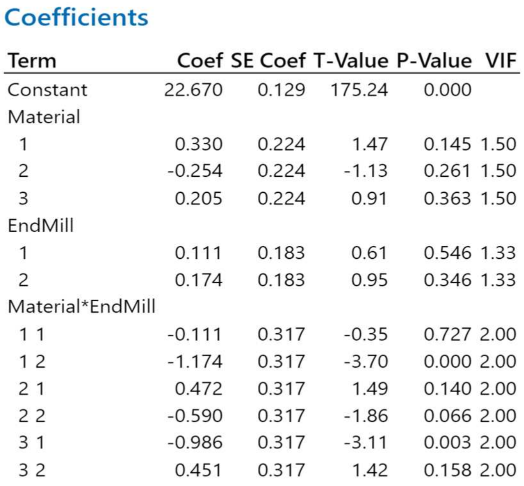
Table 13.



Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Material	3	7.055	2.352	1.46	0.230
EndMill	2	3.950	1.975	1.23	0.298
Material*EndMill	6	87.613	14.602	9.09	0.000
Error	84	134.958	1.607		
Total	95	233.577			

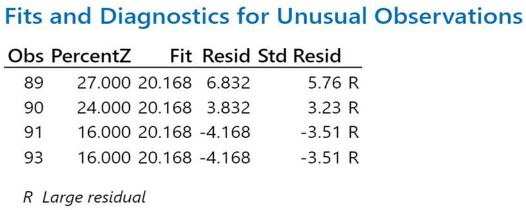
Table 14.



Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	22.670	0.129	175.24	0.000	
Material					
1	0.330	0.224	1.47	0.145	1.50
2	-0.254	0.224	-1.13	0.261	1.50
3	0.205	0.224	0.91	0.363	1.50
EndMill					
1	0.111	0.183	0.61	0.546	1.33
2	0.174	0.183	0.95	0.346	1.33
Material*EndMill					
1 1	-0.111	0.317	-0.35	0.727	2.00
1 2	-1.174	0.317	-3.70	0.000	2.00
2 1	0.472	0.317	1.49	0.140	2.00
2 2	-0.590	0.317	-1.86	0.066	2.00
3 1	-0.986	0.317	-3.11	0.003	2.00
3 2	0.451	0.317	1.42	0.158	2.00

Table 15.

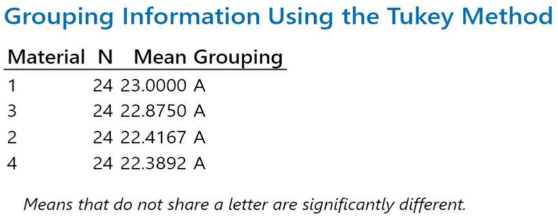


Fits and Diagnostics for Unusual Observations

Obs	PercentZ	Fit	Resid	Std Resid	
89	27.000	20.168	6.832	5.76	R
90	24.000	20.168	3.832	3.23	R
91	16.000	20.168	-4.168	-3.51	R
93	16.000	20.168	-4.168	-3.51	R

R Large residual

Table 16.

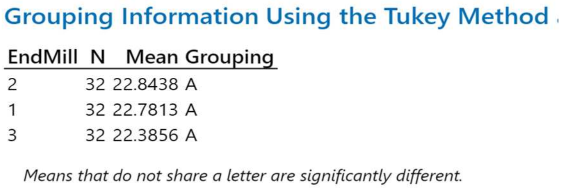


Grouping Information Using the Tukey Method

Material	N	Mean	Grouping
1	24	23.0000	A
3	24	22.8750	A
2	24	22.4167	A
4	24	22.3892	A

Means that do not share a letter are significantly different.

Table 17.

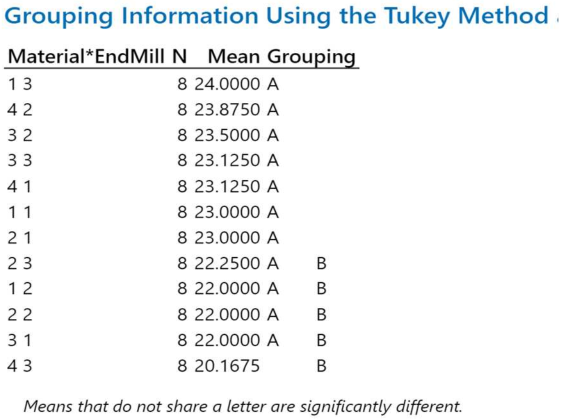


Grouping Information Using the Tukey Method

EndMill	N	Mean	Grouping
2	32	22.8438	A
1	32	22.7813	A
3	32	22.3856	A

Means that do not share a letter are significantly different.

Table 18.



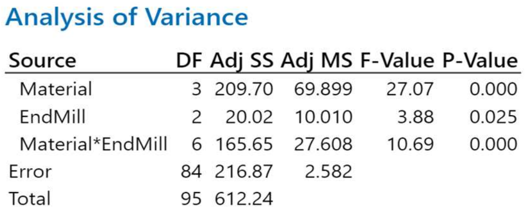
Grouping Information Using the Tukey Method

Material*EndMill	N	Mean	Grouping	
1 3	8	24.0000	A	
4 2	8	23.8750	A	
3 2	8	23.5000	A	
3 3	8	23.1250	A	
4 1	8	23.1250	A	
1 1	8	23.0000	A	
2 1	8	23.0000	A	
2 3	8	22.2500	A	B
1 2	8	22.0000	A	B
2 2	8	22.0000	A	B
3 1	8	22.0000	A	B
4 3	8	20.1675		B

Means that do not share a letter are significantly different.

Total Load Analysis:

Table 19.



Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Material	3	209.70	69.899	27.07	0.000
EndMill	2	20.02	10.010	3.88	0.025
Material*EndMill	6	165.65	27.608	10.69	0.000
Error	84	216.87	2.582		
Total	95	612.24			

Table 20.

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	4.385	0.164	26.74	0.000	
Material					
1	-1.427	0.284	-5.02	0.000	1.50
2	-1.510	0.284	-5.32	0.000	1.50
3	1.698	0.284	5.98	0.000	1.50
EndMill					
1	-0.135	0.232	-0.58	0.561	1.33
2	0.615	0.232	2.65	0.010	1.33
Material*EndMill					
1 1	-0.073	0.402	-0.18	0.856	2.00
1 2	-0.573	0.402	-1.43	0.158	2.00
2 1	0.260	0.402	0.65	0.519	2.00
2 2	-0.490	0.402	-1.22	0.226	2.00
3 1	-0.698	0.402	-1.74	0.086	2.00
3 2	2.927	0.402	7.29	0.000	2.00

Table 21.

Fits and Diagnostics for Unusual Observations

Obs	PercentL	Fit	Resid	Std Resid	
57	6.000	9.625	-3.625	-2.41	R
59	6.000	9.625	-3.625	-2.41	R
60	6.000	9.625	-3.625	-2.41	R
62	19.000	9.625	9.375	6.24	R
63	14.000	9.625	4.375	2.91	R

R Large residual

Table 22.

Grouping Information Using the Tukey Method

Material	N	Mean	Grouping	
3	24	6.08333	A	
4	24	5.62500	A	
1	24	2.95833		B
2	24	2.87500		B

Means that do not share a letter are significantly different.

Table 23.

Grouping Information Using the Tukey Method

EndMill	N	Mean	Grouping	
2	32	5.00000	A	
1	32	4.25000	A	B
3	32	3.90625		B

Means that do not share a letter are significantly different.

Table 24.

Grouping Information Using the Tukey Method

Material*EndMill	N	Mean	Grouping			
3 2	8	9.625	A			
4 3	8	6.500		B		
4 1	8	6.000		B	C	
3 1	8	5.250		B	C	D
4 2	8	4.375		B	C	D
3 3	8	3.375			C	D
1 3	8	3.125				D
1 2	8	3.000				D
2 1	8	3.000				D
2 2	8	3.000				D
1 1	8	2.750				D
2 3	8	2.625				D

Means that do not share a letter are significantly different.

Appendix B – 45 Degree Analysis Results

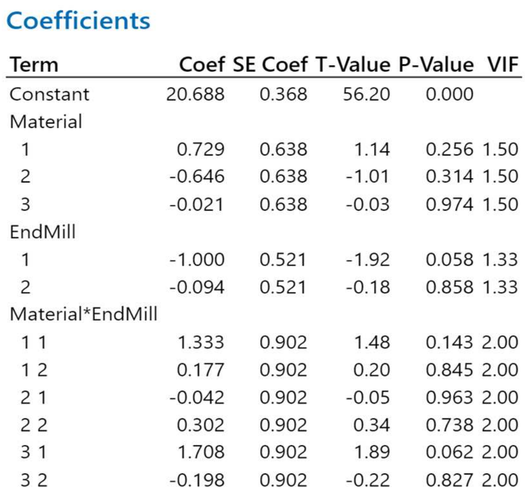
X-Axis Analysis:

Table 1.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Material	3	22.87	7.625	0.59	0.626
EndMill	2	70.56	35.281	2.71	0.072
Material*EndMill	6	234.69	39.115	3.01	0.010
Error	84	1092.50	13.006		
Total	95	1420.62			

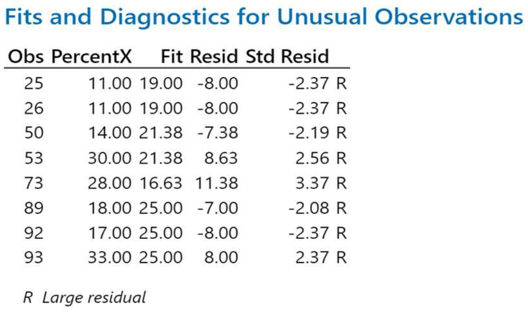
Table 2.



Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	20.688	0.368	56.20	0.000	
Material					
1	0.729	0.638	1.14	0.256	1.50
2	-0.646	0.638	-1.01	0.314	1.50
3	-0.021	0.638	-0.03	0.974	1.50
EndMill					
1	-1.000	0.521	-1.92	0.058	1.33
2	-0.094	0.521	-0.18	0.858	1.33
Material*EndMill					
1 1	1.333	0.902	1.48	0.143	2.00
1 2	0.177	0.902	0.20	0.845	2.00
2 1	-0.042	0.902	-0.05	0.963	2.00
2 2	0.302	0.902	0.34	0.738	2.00
3 1	1.708	0.902	1.89	0.062	2.00
3 2	-0.198	0.902	-0.22	0.827	2.00

Table 3.

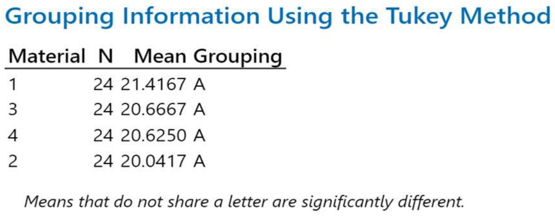


Fits and Diagnostics for Unusual Observations

Obs	PercentX	Fit	Resid	Std Resid	
25	11.00	19.00	-8.00	-2.37	R
26	11.00	19.00	-8.00	-2.37	R
50	14.00	21.38	-7.38	-2.19	R
53	30.00	21.38	8.63	2.56	R
73	28.00	16.63	11.38	3.37	R
89	18.00	25.00	-7.00	-2.08	R
92	17.00	25.00	-8.00	-2.37	R
93	33.00	25.00	8.00	2.37	R

R Large residual

Table 4.

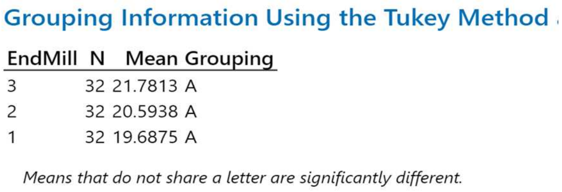


Grouping Information Using the Tukey Method

Material	N	Mean	Grouping
1	24	21.4167	A
3	24	20.6667	A
4	24	20.6250	A
2	24	20.0417	A

Means that do not share a letter are significantly different.

Table 5.

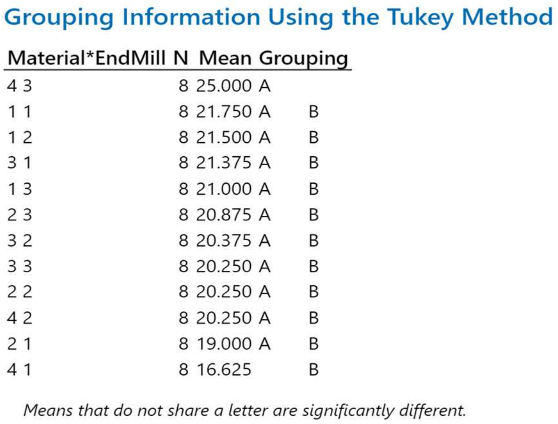


Grouping Information Using the Tukey Method

EndMill	N	Mean	Grouping
3	32	21.7813	A
2	32	20.5938	A
1	32	19.6875	A

Means that do not share a letter are significantly different.

Table 6.



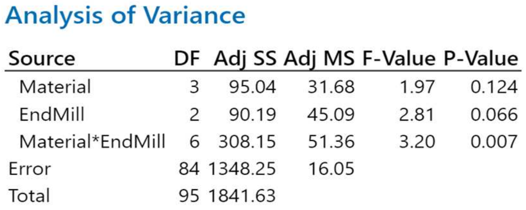
Grouping Information Using the Tukey Method

Material*EndMill	N	Mean	Grouping	
4 3	8	25.000	A	
1 1	8	21.750	A	B
1 2	8	21.500	A	B
3 1	8	21.375	A	B
1 3	8	21.000	A	B
2 3	8	20.875	A	B
3 2	8	20.375	A	B
3 3	8	20.250	A	B
2 2	8	20.250	A	B
4 2	8	20.250	A	B
2 1	8	19.000	A	B
4 1	8	16.625		B

Means that do not share a letter are significantly different.

Y-Axis Analysis:

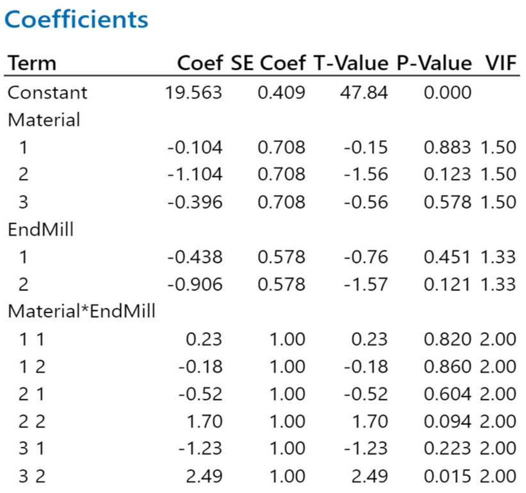
Table 7.



Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Material	3	95.04	31.68	1.97	0.124
EndMill	2	90.19	45.09	2.81	0.066
Material*EndMill	6	308.15	51.36	3.20	0.007
Error	84	1348.25	16.05		
Total	95	1841.63			

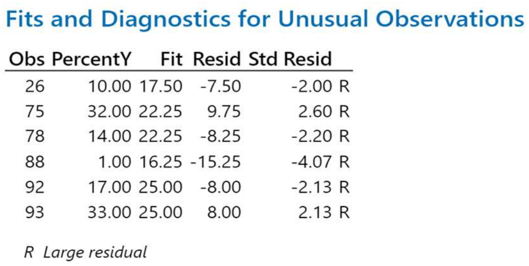
Table 8.



Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	19.563	0.409	47.84	0.000	
Material					
1	-0.104	0.708	-0.15	0.883	1.50
2	-1.104	0.708	-1.56	0.123	1.50
3	-0.396	0.708	-0.56	0.578	1.50
EndMill					
1	-0.438	0.578	-0.76	0.451	1.33
2	-0.906	0.578	-1.57	0.121	1.33
Material*EndMill					
1 1	0.23	1.00	0.23	0.820	2.00
1 2	-0.18	1.00	-0.18	0.860	2.00
2 1	-0.52	1.00	-0.52	0.604	2.00
2 2	1.70	1.00	1.70	0.094	2.00
3 1	-1.23	1.00	-1.23	0.223	2.00
3 2	2.49	1.00	2.49	0.015	2.00

Table 9.

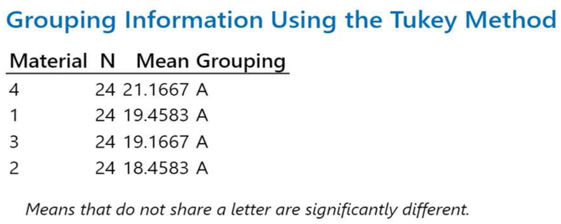


Fits and Diagnostics for Unusual Observations

Obs	PercentY	Fit	Resid	Std Resid	
26	10.00	17.50	-7.50	-2.00	R
75	32.00	22.25	9.75	2.60	R
78	14.00	22.25	-8.25	-2.20	R
88	1.00	16.25	-15.25	-4.07	R
92	17.00	25.00	-8.00	-2.13	R
93	33.00	25.00	8.00	2.13	R

R Large residual

Table 10.

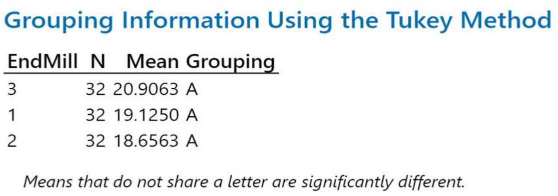


Grouping Information Using the Tukey Method

Material	N	Mean	Grouping
4	24	21.1667	A
1	24	19.4583	A
3	24	19.1667	A
2	24	18.4583	A

Means that do not share a letter are significantly different.

Table 11.

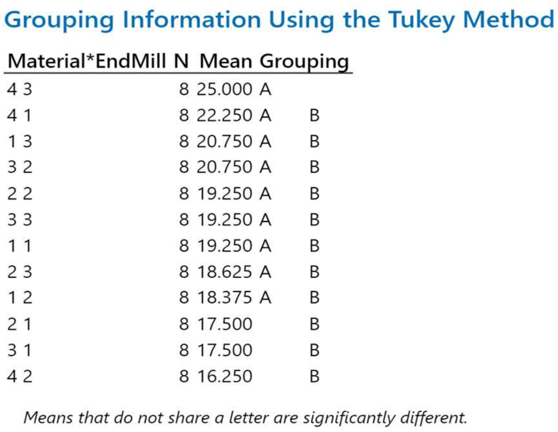


Grouping Information Using the Tukey Method

EndMill	N	Mean	Grouping
3	32	20.9063	A
1	32	19.1250	A
2	32	18.6563	A

Means that do not share a letter are significantly different.

Table 12.



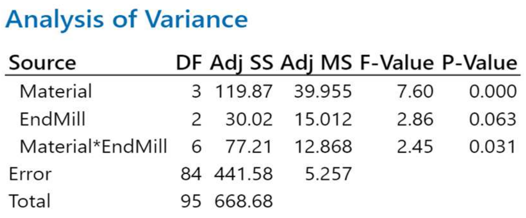
Grouping Information Using the Tukey Method

Material*EndMill	N	Mean	Grouping	
4 3	8	25.000	A	
4 1	8	22.250	A	B
1 3	8	20.750	A	B
3 2	8	20.750	A	B
2 2	8	19.250	A	B
3 3	8	19.250	A	B
1 1	8	19.250	A	B
2 3	8	18.625	A	B
1 2	8	18.375	A	B
2 1	8	17.500		B
3 1	8	17.500		B
4 2	8	16.250		B

Means that do not share a letter are significantly different.

Z-Axis Analysis:

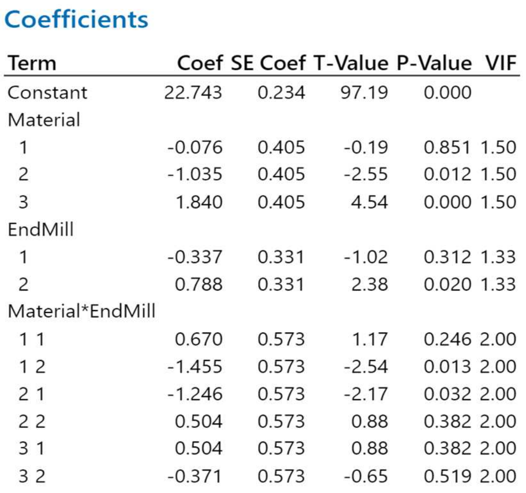
Table 13.



Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Material	3	119.87	39.955	7.60	0.000
EndMill	2	30.02	15.012	2.86	0.063
Material*EndMill	6	77.21	12.868	2.45	0.031
Error	84	441.58	5.257		
Total	95	668.68			

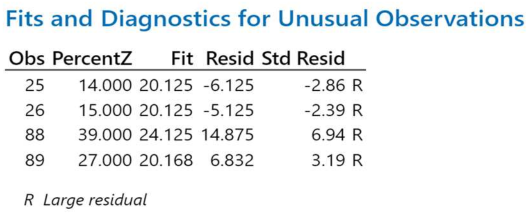
Table 14.



Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	22.743	0.234	97.19	0.000	
Material					
1	-0.076	0.405	-0.19	0.851	1.50
2	-1.035	0.405	-2.55	0.012	1.50
3	1.840	0.405	4.54	0.000	1.50
EndMill					
1	-0.337	0.331	-1.02	0.312	1.33
2	0.788	0.331	2.38	0.020	1.33
Material*EndMill					
1 1	0.670	0.573	1.17	0.246	2.00
1 2	-1.455	0.573	-2.54	0.013	2.00
2 1	-1.246	0.573	-2.17	0.032	2.00
2 2	0.504	0.573	0.88	0.382	2.00
3 1	0.504	0.573	0.88	0.382	2.00
3 2	-0.371	0.573	-0.65	0.519	2.00

Table 15.

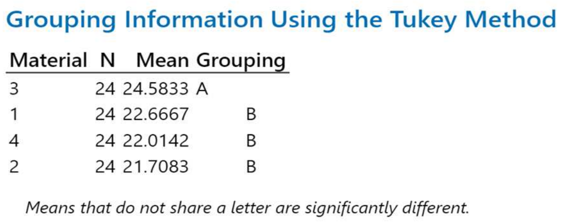


Fits and Diagnostics for Unusual Observations

Obs	PercentZ	Fit	Resid	Std Resid	
25	14.000	20.125	-6.125	-2.86	R
26	15.000	20.125	-5.125	-2.39	R
88	39.000	24.125	14.875	6.94	R
89	27.000	20.168	6.832	3.19	R

R Large residual

Table 16.

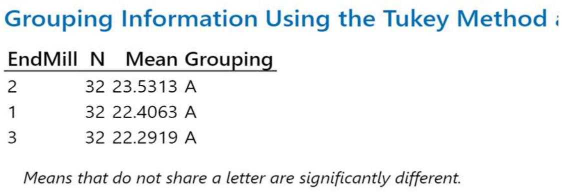


Grouping Information Using the Tukey Method

Material	N	Mean	Grouping	
3	24	24.5833	A	
1	24	22.6667		B
4	24	22.0142		B
2	24	21.7083		B

Means that do not share a letter are significantly different.

Table 17.

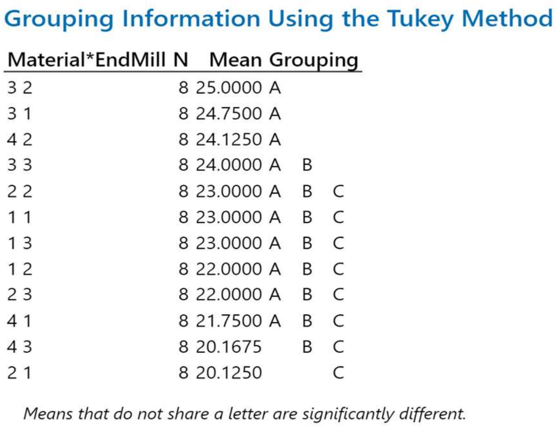


Grouping Information Using the Tukey Method

EndMill	N	Mean	Grouping
2	32	23.5313	A
1	32	22.4063	A
3	32	22.2919	A

Means that do not share a letter are significantly different.

Table 18.



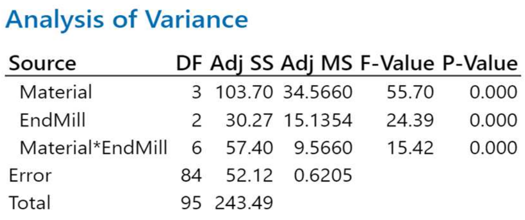
Grouping Information Using the Tukey Method

Material*EndMill	N	Mean	Grouping		
3 2	8	25.0000	A		
3 1	8	24.7500	A		
4 2	8	24.1250	A		
3 3	8	24.0000	A	B	
2 2	8	23.0000	A	B	C
1 1	8	23.0000	A	B	C
1 3	8	23.0000	A	B	C
1 2	8	22.0000	A	B	C
2 3	8	22.0000	A	B	C
4 1	8	21.7500	A	B	C
4 3	8	20.1675		B	C
2 1	8	20.1250			C

Means that do not share a letter are significantly different.

Total Load Analysis:

Table 19.



Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Material	3	103.70	34.5660	55.70	0.000
EndMill	2	30.27	15.1354	24.39	0.000
Material*EndMill	6	57.40	9.5660	15.42	0.000
Error	84	52.12	0.6205		
Total	95	243.49			

Table 20.

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	3.5104	0.0804	43.66	0.000	
Material					
1	-0.760	0.139	-5.46	0.000	1.50
2	-0.927	0.139	-6.66	0.000	1.50
3	-0.010	0.139	-0.07	0.941	1.50
EndMill					
1	0.677	0.114	5.95	0.000	1.33
2	-0.698	0.114	-6.14	0.000	1.33
Material*EndMill					
1 1	-0.677	0.197	-3.44	0.001	2.00
1 2	0.698	0.197	3.54	0.001	2.00
2 1	-0.260	0.197	-1.32	0.190	2.00
2 2	0.615	0.197	3.12	0.002	2.00
3 1	0.573	0.197	2.91	0.005	2.00
3 2	0.323	0.197	1.64	0.105	2.00

Table 21.

Fits and Diagnostics for Unusual Observations

Obs	PercentL	Fit	Resid	Std Resid	
4	1.000	2.750	-1.750	-2.37	R
5	1.000	2.750	-1.750	-2.37	R
89	5.000	6.500	-1.500	-2.04	R
91	5.000	6.500	-1.500	-2.04	R
93	8.000	6.500	1.500	2.04	R
94	8.000	6.500	1.500	2.04	R

R Large residual

Table 22.

Grouping Information Using the Tukey Method

Material	N	Mean	Grouping		
4	24	5.20833	A		
3	24	3.50000		B	
1	24	2.75000			C
2	24	2.58333			C

Means that do not share a letter are significantly different.

Table 23.

Grouping Information Using the Tukey Method

EndMill	N	Mean	Grouping		
1	32	4.18750	A		
3	32	3.53125		B	
2	32	2.81250			C

Means that do not share a letter are significantly different.

Table 24.

Grouping Information Using the Tukey Method

Material*EndMill	N	Mean	Grouping		
4 3	8	6.500	A		
4 1	8	6.250	A		
3 1	8	4.750		B	
3 2	8	3.125			C
2 1	8	3.000			C
4 2	8	2.875			C
1 1	8	2.750			C
1 3	8	2.750			C
1 2	8	2.750			C
3 3	8	2.625			C
2 2	8	2.500			C
2 3	8	2.250			C

Means that do not share a letter are significantly different.

Appendix C – 0 Degree Analysis Results

X-Axis Analysis:

Table 1.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Material	3	946.95	315.651	132.19	0.000
EndMill	2	2.25	1.126	0.47	0.626
Material*EndMill	6	86.45	14.408	6.03	0.000
Error	84	200.58	2.388		
Total	95	1236.24			

Table 2.

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	8.910	0.158	56.49	0.000	
Material					
1	2.965	0.273	10.85	0.000	1.50
2	2.799	0.273	10.24	0.000	1.50
3	-1.118	0.273	-4.09	0.000	1.50
EndMill					
1	-0.129	0.223	-0.58	0.566	1.33
2	0.215	0.223	0.96	0.337	1.33
Material*EndMill					
1 1	0.129	0.386	0.33	0.740	2.00
1 2	-0.340	0.386	-0.88	0.381	2.00
2 1	0.545	0.386	1.41	0.162	2.00
2 2	0.076	0.386	0.20	0.844	2.00
3 1	0.462	0.386	1.20	0.235	2.00
3 2	1.118	0.386	2.89	0.005	2.00

Table 3.

Fits and Diagnostics for Unusual Observations

Obs	PercentX	Fit	Resid	Std Resid	
5	4.000	11.875	-7.875	-5.45	R
86	7.000	3.625	3.375	2.33	R
89	3.000	6.168	-3.168	-2.19	R
90	3.000	6.168	-3.168	-2.19	R
91	10.000	6.168	3.832	2.65	R
93	11.000	6.168	4.832	3.34	R

R Large residual

Table 4.

Grouping Information Using the Tukey Method

Material	N	Mean	Grouping		
1	24	11.8750	A		
2	24	11.7083	A		
3	24	7.7917		B	
4	24	4.2642			C

Means that do not share a letter are significantly different.

Table 5.

Grouping Information Using the Tukey Method

EndMill	N	Mean	Grouping
2	32	9.12500	A
3	32	8.82312	A
1	32	8.78125	A

Means that do not share a letter are significantly different.

Table 6.

Grouping Information Using the Tukey Method

Material*EndMill	N	Mean	Grouping					
2 1	8	12.1250	A					
2 2	8	12.0000	A					
1 3	8	12.0000	A					
1 1	8	11.8750	A					
1 2	8	11.7500	A					
2 3	8	11.0000	A	B				
3 2	8	9.1250		B	C			
3 1	8	8.1250			C	D		
4 3	8	6.1675				D	E	
3 3	8	6.1250				D	E	
4 2	8	3.6250					E	F
4 1	8	3.0000						F

Means that do not share a letter are significantly different.

Y-Axis Analysis:

Table 7.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Material	3	31.58	10.53	0.72	0.543
EndMill	2	45.81	22.91	1.56	0.215
Material*EndMill	6	123.10	20.52	1.40	0.224
Error	84	1229.50	14.64		
Total	95	1430.00			

Table 8.

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	22.500	0.390	57.62	0.000	
Material					
1	-0.208	0.676	-0.31	0.759	1.50
2	0.125	0.676	0.18	0.854	1.50
3	-0.750	0.676	-1.11	0.271	1.50
EndMill					
1	-0.594	0.552	-1.08	0.285	1.33
2	-0.375	0.552	-0.68	0.499	1.33
Material*EndMill					
1 1	-0.698	0.956	-0.73	0.468	2.00
1 2	1.208	0.956	1.26	0.210	2.00
2 1	0.844	0.956	0.88	0.380	2.00
2 2	-0.125	0.956	-0.13	0.896	2.00
3 1	-1.656	0.956	-1.73	0.087	2.00
3 2	1.125	0.956	1.18	0.243	2.00

Table 9.

Fits and Diagnostics for Unusual Observations

Obs	PercentY	Fit	Resid	Std Resid	
5	13.00	21.00	-8.00	-2.24	R
78	14.00	24.25	-10.25	-2.86	R
80	36.00	24.25	11.75	3.28	R
84	13.00	20.75	-7.75	-2.17	R
87	28.00	20.75	7.25	2.03	R
92	17.00	25.00	-8.00	-2.24	R
93	33.00	25.00	8.00	2.24	R

R Large residual

Table 10.

Grouping Information Using the Tukey Method

Material	N	Mean	Grouping
4	24	23.3333	A
2	24	22.6250	A
1	24	22.2917	A
3	24	21.7500	A

Means that do not share a letter are significantly different.

Table 11.

Grouping Information Using the Tukey Method

EndMill	N	Mean	Grouping
3	32	23.4688	A
2	32	22.1250	A
1	32	21.9063	A

Means that do not share a letter are significantly different.

Table 12.

Grouping Information Using the Tukey Method

Material*EndMill	N	Mean	Grouping
4 3	8	25.000	A
4 1	8	24.250	A
3 3	8	23.250	A
1 2	8	23.125	A
2 1	8	22.875	A
2 3	8	22.875	A
1 3	8	22.750	A
3 2	8	22.500	A
2 2	8	22.125	A
1 1	8	21.000	A
4 2	8	20.750	A
3 1	8	19.500	A

Means that do not share a letter are significantly different.

Z-Axis Analysis:

Table 13.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Material	3	124.68	41.561	30.14	0.000
EndMill	2	37.83	18.916	13.72	0.000
Material*EndMill	6	139.33	23.222	16.84	0.000
Error	84	115.83	1.379		
Total	95	417.68			

Table 14.

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	23.118	0.120	192.89	0.000	
Material					
1	-0.368	0.208	-1.77	0.080	1.50
2	-1.451	0.208	-6.99	0.000	1.50
3	1.715	0.208	8.26	0.000	1.50
EndMill					
1	0.694	0.169	4.10	0.000	1.33
2	0.132	0.169	0.78	0.439	1.33
Material*EndMill					
1 1	-0.194	0.294	-0.66	0.510	2.00
1 2	-0.882	0.294	-3.00	0.004	2.00
2 1	0.639	0.294	2.18	0.032	2.00
2 2	0.201	0.294	0.69	0.494	2.00
3 1	-0.903	0.294	-3.07	0.003	2.00
3 2	-1.090	0.294	-3.71	0.000	2.00

Table 15.

Fits and Diagnostics for Unusual Observations

Obs	PercentZ	Fit	Resid	Std Resid	
89	27.000	20.168	6.832	6.22	R
90	24.000	20.168	3.832	3.49	R
91	16.000	20.168	-4.168	-3.79	R
93	16.000	20.168	-4.168	-3.79	R

R Large residual

Table 16.

Grouping Information Using the Tukey Method

Material	N	Mean	Grouping
3	24	24.8333	A
4	24	23.2225	B
1	24	22.7500	B
2	24	21.6667	C

Means that do not share a letter are significantly different.

Table 17.

Grouping Information Using the Tukey Method

EndMill	N	Mean	Grouping
1	32	23.8125	A
2	32	23.2500	A
3	32	22.2919	B

Means that do not share a letter are significantly different.

Table 18.

Grouping Information Using the Tukey Method

Material*EndMill	N	Mean	Grouping
3 3	8	26.0000	A
4 2	8	25.1250	A B
3 1	8	24.6250	A B C
4 1	8	24.3750	A B C
3 2	8	23.8750	B C D
1 1	8	23.2500	B C D
1 3	8	23.0000	C D
2 1	8	23.0000	C D
1 2	8	22.0000	D E
2 2	8	22.0000	D E
4 3	8	20.1675	E F
2 3	8	20.0000	F

Means that do not share a letter are significantly different.

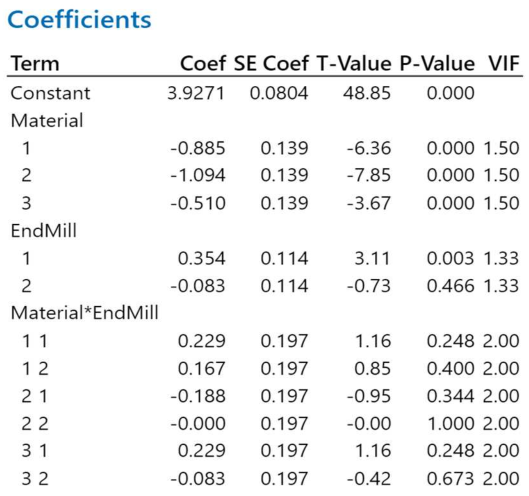
Total Load Analysis:

Table 19.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Material	3	202.531	67.5104	108.79	0.000
EndMill	2	6.583	3.2917	5.30	0.007
Material*EndMill	6	4.750	0.7917	1.28	0.277
Error	84	52.125	0.6205		
Total	95	265.990			

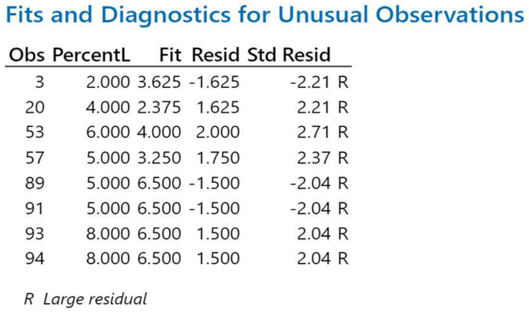
Table 20.



Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	3.9271	0.0804	48.85	0.000	
Material					
1	-0.885	0.139	-6.36	0.000	1.50
2	-1.094	0.139	-7.85	0.000	1.50
3	-0.510	0.139	-3.67	0.000	1.50
EndMill					
1	0.354	0.114	3.11	0.003	1.33
2	-0.083	0.114	-0.73	0.466	1.33
Material*EndMill					
1 1	0.229	0.197	1.16	0.248	2.00
1 2	0.167	0.197	0.85	0.400	2.00
2 1	-0.188	0.197	-0.95	0.344	2.00
2 2	-0.000	0.197	-0.00	1.000	2.00
3 1	0.229	0.197	1.16	0.248	2.00
3 2	-0.083	0.197	-0.42	0.673	2.00

Table 21.

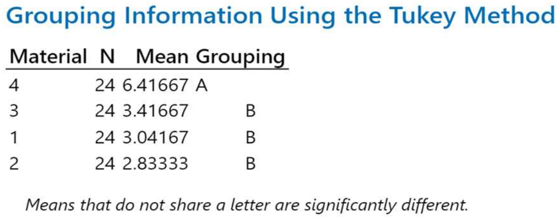


Fits and Diagnostics for Unusual Observations

Obs	PercentL	Fit	Resid	Std Resid	
3	2.000	3.625	-1.625	-2.21	R
20	4.000	2.375	1.625	2.21	R
53	6.000	4.000	2.000	2.71	R
57	5.000	3.250	1.750	2.37	R
89	5.000	6.500	-1.500	-2.04	R
91	5.000	6.500	-1.500	-2.04	R
93	8.000	6.500	1.500	2.04	R
94	8.000	6.500	1.500	2.04	R

R Large residual

Table 22.

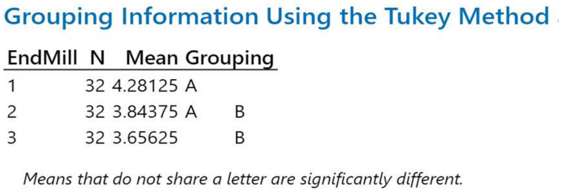


Grouping Information Using the Tukey Method

Material	N	Mean	Grouping
4	24	6.41667	A
3	24	3.41667	B
1	24	3.04167	B
2	24	2.83333	B

Means that do not share a letter are significantly different.

Table 23.

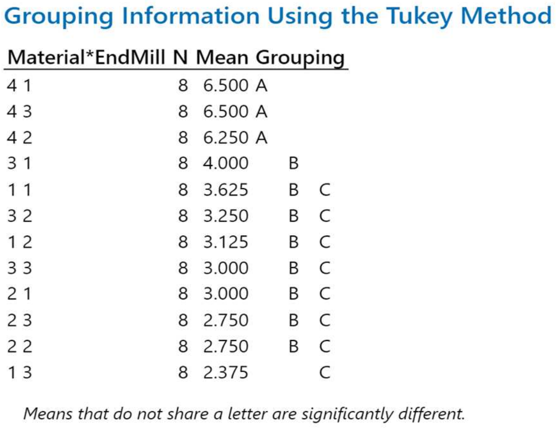


Grouping Information Using the Tukey Method

EndMill	N	Mean	Grouping
1	32	4.28125	A
2	32	3.84375	A B
3	32	3.65625	B

Means that do not share a letter are significantly different.

Table 24.



Grouping Information Using the Tukey Method

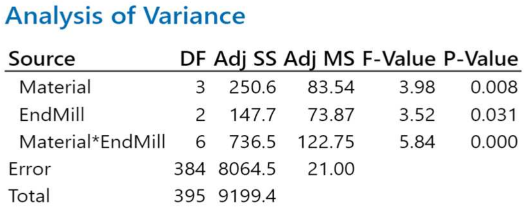
Material*EndMill	N	Mean	Grouping
4 1	8	6.500	A
4 3	8	6.500	A
4 2	8	6.250	A
3 1	8	4.000	B
1 1	8	3.625	B C
3 2	8	3.250	B C
1 2	8	3.125	B C
3 3	8	3.000	B C
2 1	8	3.000	B C
2 3	8	2.750	B C
2 2	8	2.750	B C
1 3	8	2.375	C

Means that do not share a letter are significantly different.

Appendix D – 90 Degree Square Analysis Results

X-Axis Analysis:

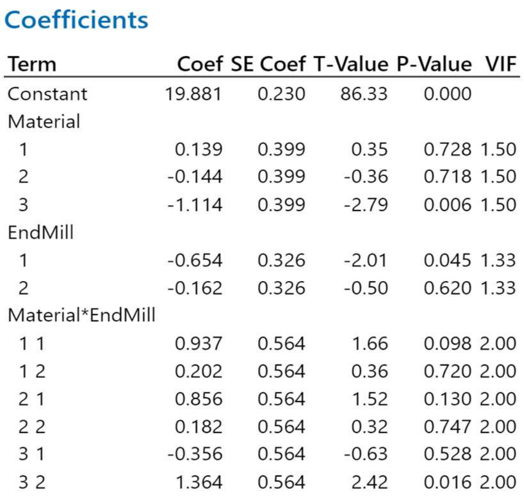
Table 1.



Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Material	3	250.6	83.54	3.98	0.008
EndMill	2	147.7	73.87	3.52	0.031
Material*EndMill	6	736.5	122.75	5.84	0.000
Error	384	8064.5	21.00		
Total	395	9199.4			

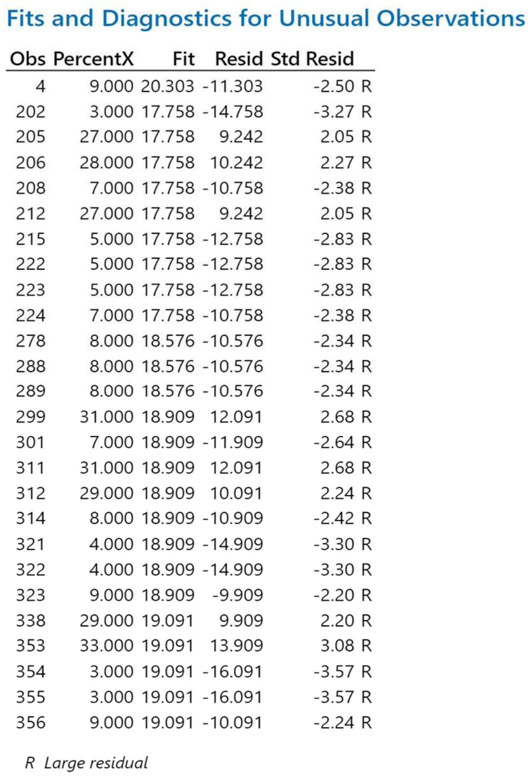
Table 2.



Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	19.881	0.230	86.33	0.000	
Material					
1	0.139	0.399	0.35	0.728	1.50
2	-0.144	0.399	-0.36	0.718	1.50
3	-1.114	0.399	-2.79	0.006	1.50
EndMill					
1	-0.654	0.326	-2.01	0.045	1.33
2	-0.162	0.326	-0.50	0.620	1.33
Material*EndMill					
1 1	0.937	0.564	1.66	0.098	2.00
1 2	0.202	0.564	0.36	0.720	2.00
2 1	0.856	0.564	1.52	0.130	2.00
2 2	0.182	0.564	0.32	0.747	2.00
3 1	-0.356	0.564	-0.63	0.528	2.00
3 2	1.364	0.564	2.42	0.016	2.00

Table 3.

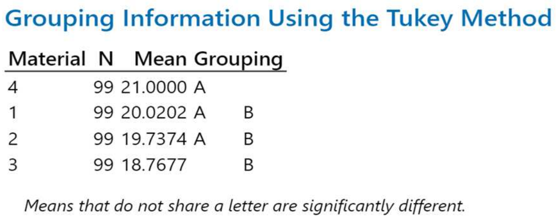


Fits and Diagnostics for Unusual Observations

Obs	PercentX	Fit	Resid	Std Resid
4	9.000	20.303	-11.303	-2.50 R
202	3.000	17.758	-14.758	-3.27 R
205	27.000	17.758	9.242	2.05 R
206	28.000	17.758	10.242	2.27 R
208	7.000	17.758	-10.758	-2.38 R
212	27.000	17.758	9.242	2.05 R
215	5.000	17.758	-12.758	-2.83 R
222	5.000	17.758	-12.758	-2.83 R
223	5.000	17.758	-12.758	-2.83 R
224	7.000	17.758	-10.758	-2.38 R
278	8.000	18.576	-10.576	-2.34 R
288	8.000	18.576	-10.576	-2.34 R
289	8.000	18.576	-10.576	-2.34 R
299	31.000	18.909	12.091	2.68 R
301	7.000	18.909	-11.909	-2.64 R
311	31.000	18.909	12.091	2.68 R
312	29.000	18.909	10.091	2.24 R
314	8.000	18.909	-10.909	-2.42 R
321	4.000	18.909	-14.909	-3.30 R
322	4.000	18.909	-14.909	-3.30 R
323	9.000	18.909	-9.909	-2.20 R
338	29.000	19.091	9.909	2.20 R
353	33.000	19.091	13.909	3.08 R
354	3.000	19.091	-16.091	-3.57 R
355	3.000	19.091	-16.091	-3.57 R
356	9.000	19.091	-10.091	-2.24 R

R Large residual

Table 4.

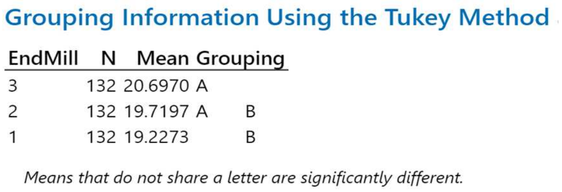


Grouping Information Using the Tukey Method

Material	N	Mean	Grouping	
4	99	21.0000	A	
1	99	20.0202	A	B
2	99	19.7374	A	B
3	99	18.7677		B

Means that do not share a letter are significantly different.

Table 5.

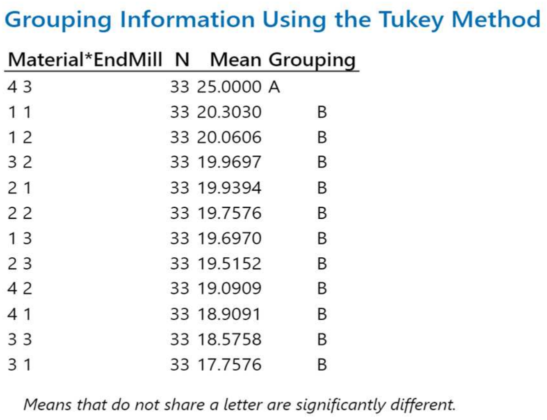


Grouping Information Using the Tukey Method

EndMill	N	Mean	Grouping	
3	132	20.6970	A	
2	132	19.7197	A	B
1	132	19.2273		B

Means that do not share a letter are significantly different.

Table 6.



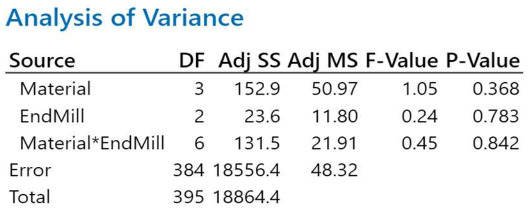
Grouping Information Using the Tukey Method

Material*EndMill	N	Mean	Grouping	
4 3	33	25.0000	A	
1 1	33	20.3030		B
1 2	33	20.0606		B
3 2	33	19.9697		B
2 1	33	19.9394		B
2 2	33	19.7576		B
1 3	33	19.6970		B
2 3	33	19.5152		B
4 2	33	19.0909		B
4 1	33	18.9091		B
3 3	33	18.5758		B
3 1	33	17.7576		B

Means that do not share a letter are significantly different.

Y-Axis Analysis:

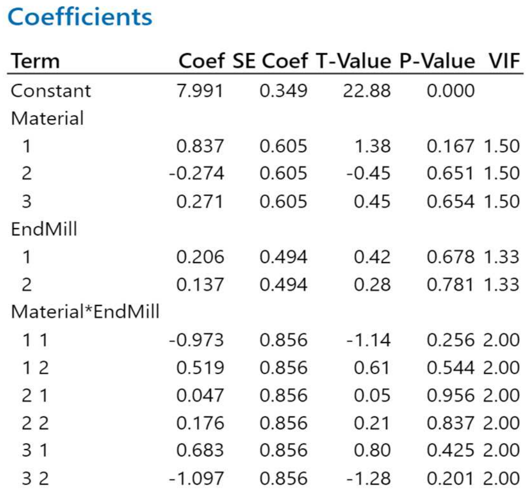
Table 7.



Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Material	3	152.9	50.97	1.05	0.368
EndMill	2	23.6	11.80	0.24	0.783
Material*EndMill	6	131.5	21.91	0.45	0.842
Error	384	18556.4	48.32		
Total	395	18864.4			

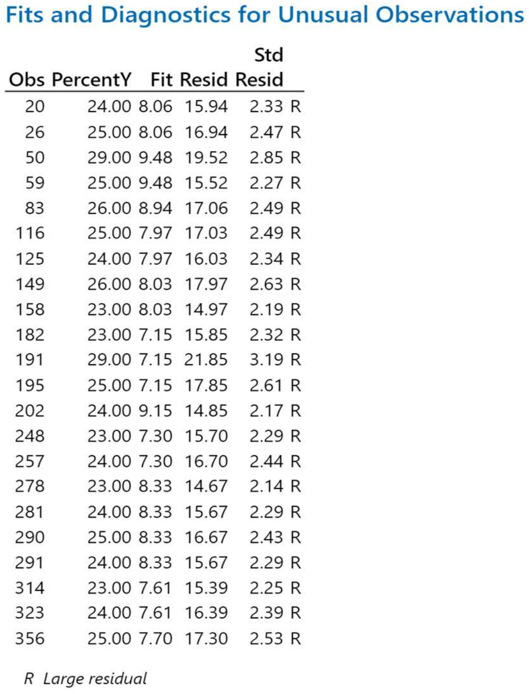
Table 8.



Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	7.991	0.349	22.88	0.000	
Material					
1	0.837	0.605	1.38	0.167	1.50
2	-0.274	0.605	-0.45	0.651	1.50
3	0.271	0.605	0.45	0.654	1.50
EndMill					
1	0.206	0.494	0.42	0.678	1.33
2	0.137	0.494	0.28	0.781	1.33
Material*EndMill					
1 1	-0.973	0.856	-1.14	0.256	2.00
1 2	0.519	0.856	0.61	0.544	2.00
2 1	0.047	0.856	0.05	0.956	2.00
2 2	0.176	0.856	0.21	0.837	2.00
3 1	0.683	0.856	0.80	0.425	2.00
3 2	-1.097	0.856	-1.28	0.201	2.00

Table 9.

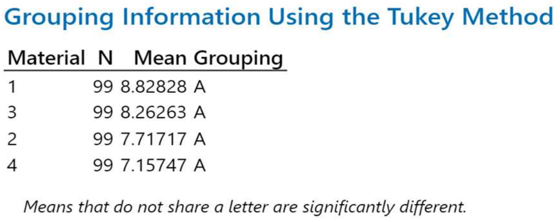


Fits and Diagnostics for Unusual Observations

Obs	PercentY	Fit	Resid	Std Resid	
20	24.00	8.06	15.94	2.33	R
26	25.00	8.06	16.94	2.47	R
50	29.00	9.48	19.52	2.85	R
59	25.00	9.48	15.52	2.27	R
83	26.00	8.94	17.06	2.49	R
116	25.00	7.97	17.03	2.49	R
125	24.00	7.97	16.03	2.34	R
149	26.00	8.03	17.97	2.63	R
158	23.00	8.03	14.97	2.19	R
182	23.00	7.15	15.85	2.32	R
191	29.00	7.15	21.85	3.19	R
195	25.00	7.15	17.85	2.61	R
202	24.00	9.15	14.85	2.17	R
248	23.00	7.30	15.70	2.29	R
257	24.00	7.30	16.70	2.44	R
278	23.00	8.33	14.67	2.14	R
281	24.00	8.33	15.67	2.29	R
290	25.00	8.33	16.67	2.43	R
291	24.00	8.33	15.67	2.29	R
314	23.00	7.61	15.39	2.25	R
323	24.00	7.61	16.39	2.39	R
356	25.00	7.70	17.30	2.53	R

R Large residual

Table 10.

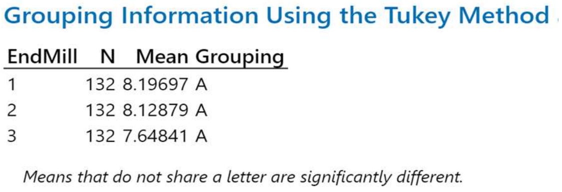


Grouping Information Using the Tukey Method

Material	N	Mean	Grouping
1	99	8.82828	A
3	99	8.26263	A
2	99	7.71717	A
4	99	7.15747	A

Means that do not share a letter are significantly different.

Table 11.

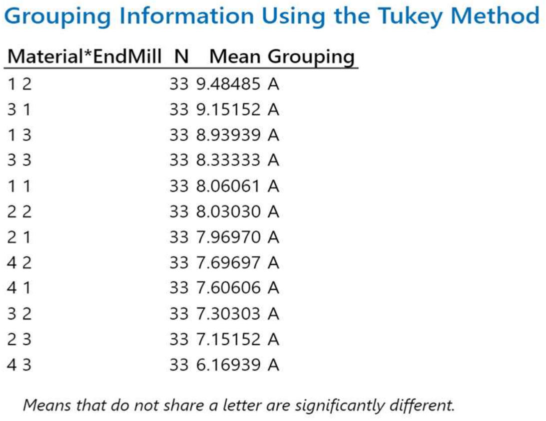


Grouping Information Using the Tukey Method

EndMill	N	Mean	Grouping
1	132	8.19697	A
2	132	8.12879	A
3	132	7.64841	A

Means that do not share a letter are significantly different.

Table 12.



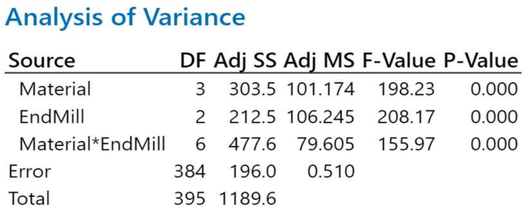
Grouping Information Using the Tukey Method

Material*EndMill	N	Mean	Grouping
1 2	33	9.48485	A
3 1	33	9.15152	A
1 3	33	8.93939	A
3 3	33	8.33333	A
1 1	33	8.06061	A
2 2	33	8.03030	A
2 1	33	7.96970	A
4 2	33	7.69697	A
4 1	33	7.60606	A
3 2	33	7.30303	A
2 3	33	7.15152	A
4 3	33	6.16939	A

Means that do not share a letter are significantly different.

Z-Axis Analysis:

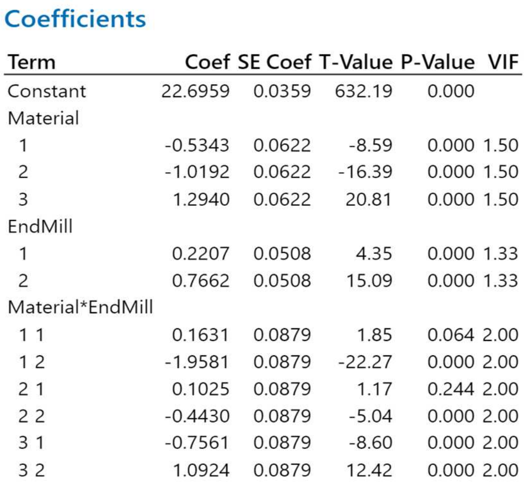
Table 13.



Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Material	3	303.5	101.174	198.23	0.000
EndMill	2	212.5	106.245	208.17	0.000
Material*EndMill	6	477.6	79.605	155.97	0.000
Error	384	196.0	0.510		
Total	395	1189.6			

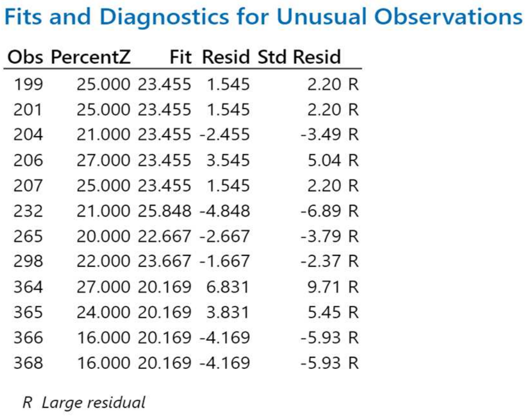
Table 14.



Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	22.6959	0.0359	632.19	0.000	
Material					
1	-0.5343	0.0622	-8.59	0.000	1.50
2	-1.0192	0.0622	-16.39	0.000	1.50
3	1.2940	0.0622	20.81	0.000	1.50
EndMill					
1	0.2207	0.0508	4.35	0.000	1.33
2	0.7662	0.0508	15.09	0.000	1.33
Material*EndMill					
1 1	0.1631	0.0879	1.85	0.064	2.00
1 2	-1.9581	0.0879	-22.27	0.000	2.00
2 1	0.1025	0.0879	1.17	0.244	2.00
2 2	-0.4430	0.0879	-5.04	0.000	2.00
3 1	-0.7561	0.0879	-8.60	0.000	2.00
3 2	1.0924	0.0879	12.42	0.000	2.00

Table 15.

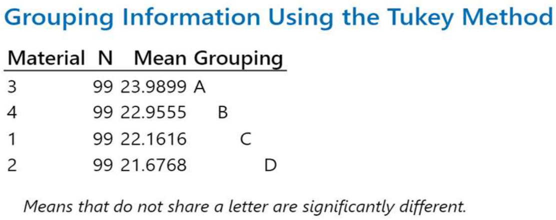


Fits and Diagnostics for Unusual Observations

Obs	PercentZ	Fit	Resid	Std Resid	
199	25.000	23.455	1.545	2.20	R
201	25.000	23.455	1.545	2.20	R
204	21.000	23.455	-2.455	-3.49	R
206	27.000	23.455	3.545	5.04	R
207	25.000	23.455	1.545	2.20	R
232	21.000	25.848	-4.848	-6.89	R
265	20.000	22.667	-2.667	-3.79	R
298	22.000	23.667	-1.667	-2.37	R
364	27.000	20.169	6.831	9.71	R
365	24.000	20.169	3.831	5.45	R
366	16.000	20.169	-4.169	-5.93	R
368	16.000	20.169	-4.169	-5.93	R

R Large residual

Table 16.

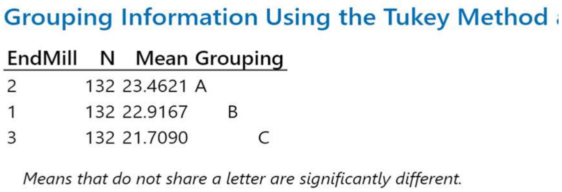


Grouping Information Using the Tukey Method

Material	N	Mean	Grouping
3	99	23.9899	A
4	99	22.9555	B
1	99	22.1616	C
2	99	21.6768	D

Means that do not share a letter are significantly different.

Table 17.

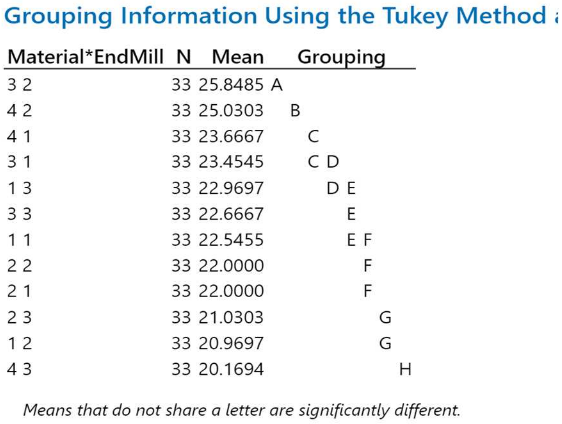


Grouping Information Using the Tukey Method

EndMill	N	Mean	Grouping
2	132	23.4621	A
1	132	22.9167	B
3	132	21.7090	C

Means that do not share a letter are significantly different.

Table 18.



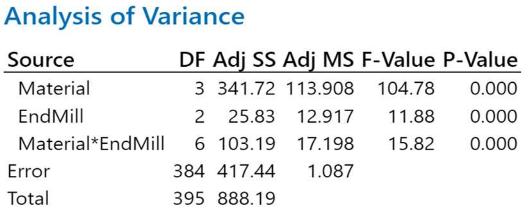
Grouping Information Using the Tukey Method

Material*EndMill	N	Mean	Grouping
3 2	33	25.8485	A
4 2	33	25.0303	B
4 1	33	23.6667	C
3 1	33	23.4545	C D
1 3	33	22.9697	D E
3 3	33	22.6667	E
1 1	33	22.5455	E F
2 2	33	22.0000	F
2 1	33	22.0000	F
2 3	33	21.0303	G
1 2	33	20.9697	G
4 3	33	20.1694	H

Means that do not share a letter are significantly different.

Total Load Analysis:

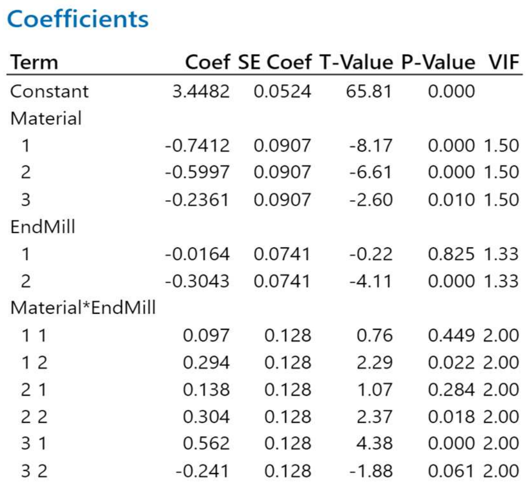
Table 19.



Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Material	3	341.72	113.908	104.78	0.000
EndMill	2	25.83	12.917	11.88	0.000
Material*EndMill	6	103.19	17.198	15.82	0.000
Error	384	417.44	1.087		
Total	395	888.19			

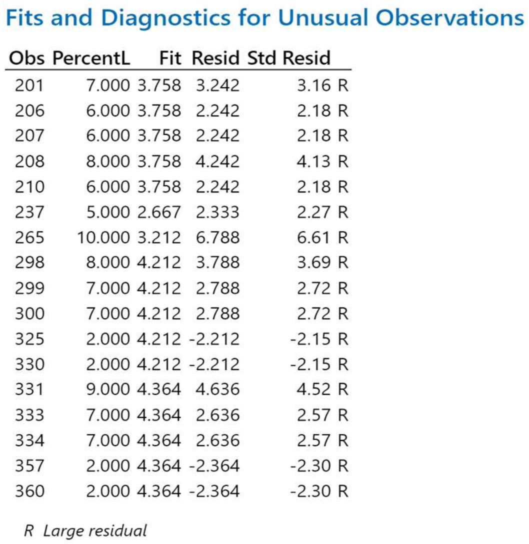
Table 20.



Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	3.4482	0.0524	65.81	0.000	
Material					
1	-0.7412	0.0907	-8.17	0.000	1.50
2	-0.5997	0.0907	-6.61	0.000	1.50
3	-0.2361	0.0907	-2.60	0.010	1.50
EndMill					
1	-0.0164	0.0741	-0.22	0.825	1.33
2	-0.3043	0.0741	-4.11	0.000	1.33
Material*EndMill					
1 1	0.097	0.128	0.76	0.449	2.00
1 2	0.294	0.128	2.29	0.022	2.00
2 1	0.138	0.128	1.07	0.284	2.00
2 2	0.304	0.128	2.37	0.018	2.00
3 1	0.562	0.128	4.38	0.000	2.00
3 2	-0.241	0.128	-1.88	0.061	2.00

Table 21.

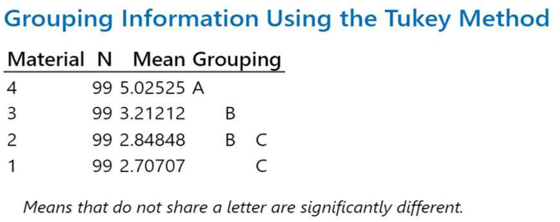


Fits and Diagnostics for Unusual Observations

Obs	PercentL	Fit	Resid	Std Resid	
201	7.000	3.758	3.242	3.16	R
206	6.000	3.758	2.242	2.18	R
207	6.000	3.758	2.242	2.18	R
208	8.000	3.758	4.242	4.13	R
210	6.000	3.758	2.242	2.18	R
237	5.000	2.667	2.333	2.27	R
265	10.000	3.212	6.788	6.61	R
298	8.000	4.212	3.788	3.69	R
299	7.000	4.212	2.788	2.72	R
300	7.000	4.212	2.788	2.72	R
325	2.000	4.212	-2.212	-2.15	R
330	2.000	4.212	-2.212	-2.15	R
331	9.000	4.364	4.636	4.52	R
333	7.000	4.364	2.636	2.57	R
334	7.000	4.364	2.636	2.57	R
357	2.000	4.364	-2.364	-2.30	R
360	2.000	4.364	-2.364	-2.30	R

R Large residual

Table 22.

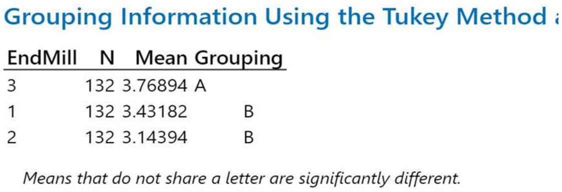


Grouping Information Using the Tukey Method

Material	N	Mean	Grouping		
4	99	5.02525	A		
3	99	3.21212		B	
2	99	2.84848		B	C
1	99	2.70707			C

Means that do not share a letter are significantly different.

Table 23.

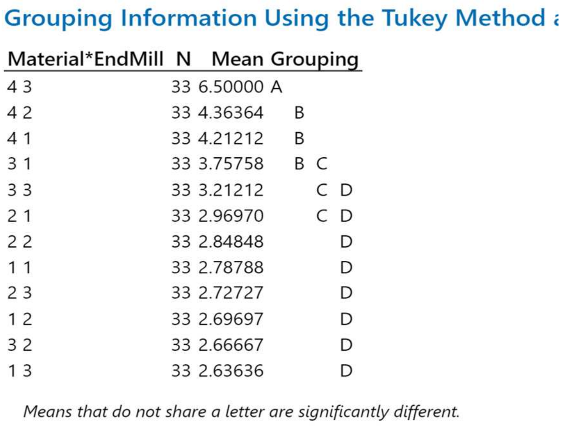


Grouping Information Using the Tukey Method

EndMill	N	Mean	Grouping	
3	132	3.76894	A	
1	132	3.43182		B
2	132	3.14394		B

Means that do not share a letter are significantly different.

Table 24.



Grouping Information Using the Tukey Method

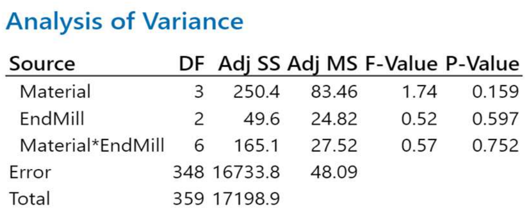
Material*EndMill	N	Mean	Grouping			
4 3	33	6.50000	A			
4 2	33	4.36364		B		
4 1	33	4.21212		B		
3 1	33	3.75758		B	C	
3 3	33	3.21212			C	D
2 1	33	2.96970			C	D
2 2	33	2.84848				D
1 1	33	2.78788				D
2 3	33	2.72727				D
1 2	33	2.69697				D
3 2	33	2.66667				D
1 3	33	2.63636				D

Means that do not share a letter are significantly different.

Appendix E – 0 Degree Square Analysis Results

X-Axis Analysis:

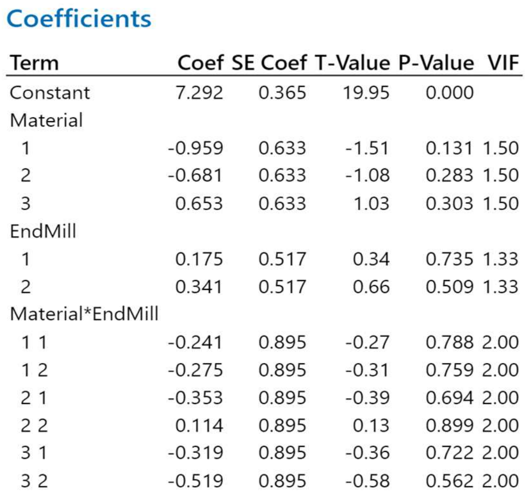
Table 1.



Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Material	3	250.4	83.46	1.74	0.159
EndMill	2	49.6	24.82	0.52	0.597
Material*EndMill	6	165.1	27.52	0.57	0.752
Error	348	16733.8	48.09		
Total	359	17198.9			

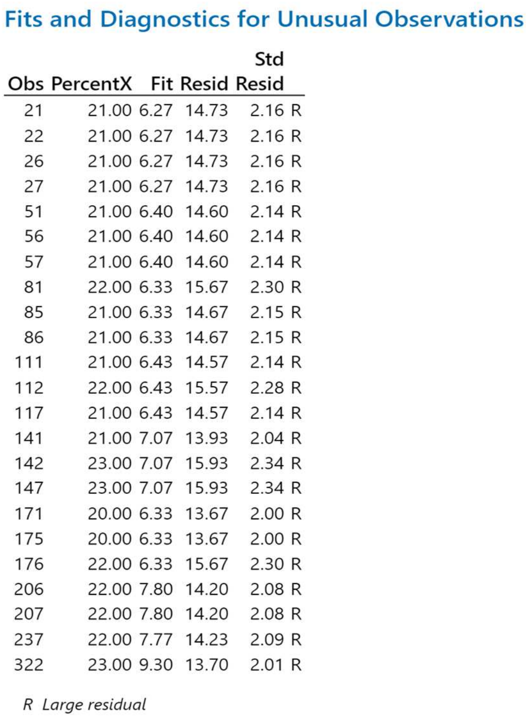
Table 2.



Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	7.292	0.365	19.95	0.000	
Material					
1	-0.959	0.633	-1.51	0.131	1.50
2	-0.681	0.633	-1.08	0.283	1.50
3	0.653	0.633	1.03	0.303	1.50
EndMill					
1	0.175	0.517	0.34	0.735	1.33
2	0.341	0.517	0.66	0.509	1.33
Material*EndMill					
1 1	-0.241	0.895	-0.27	0.788	2.00
1 2	-0.275	0.895	-0.31	0.759	2.00
2 1	-0.353	0.895	-0.39	0.694	2.00
2 2	0.114	0.895	0.13	0.899	2.00
3 1	-0.319	0.895	-0.36	0.722	2.00
3 2	-0.519	0.895	-0.58	0.562	2.00

Table 3.

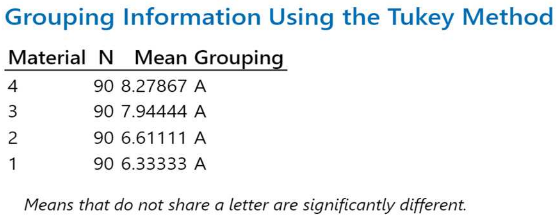


Fits and Diagnostics for Unusual Observations

Obs	PercentX	Fit	Resid	Std Resid	
21	21.00	6.27	14.73	2.16	R
22	21.00	6.27	14.73	2.16	R
26	21.00	6.27	14.73	2.16	R
27	21.00	6.27	14.73	2.16	R
51	21.00	6.40	14.60	2.14	R
56	21.00	6.40	14.60	2.14	R
57	21.00	6.40	14.60	2.14	R
81	22.00	6.33	15.67	2.30	R
85	21.00	6.33	14.67	2.15	R
86	21.00	6.33	14.67	2.15	R
111	21.00	6.43	14.57	2.14	R
112	22.00	6.43	15.57	2.28	R
117	21.00	6.43	14.57	2.14	R
141	21.00	7.07	13.93	2.04	R
142	23.00	7.07	15.93	2.34	R
147	23.00	7.07	15.93	2.34	R
171	20.00	6.33	13.67	2.00	R
175	20.00	6.33	13.67	2.00	R
176	22.00	6.33	15.67	2.30	R
206	22.00	7.80	14.20	2.08	R
207	22.00	7.80	14.20	2.08	R
237	22.00	7.77	14.23	2.09	R
322	23.00	9.30	13.70	2.01	R

R Large residual

Table 4.

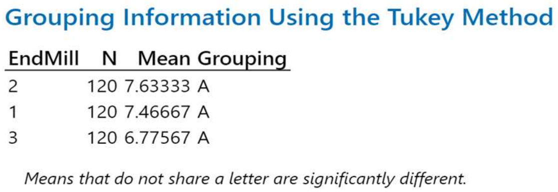


Grouping Information Using the Tukey Method

Material	N	Mean	Grouping
4	90	8.27867	A
3	90	7.94444	A
2	90	6.61111	A
1	90	6.33333	A

Means that do not share a letter are significantly different.

Table 5.

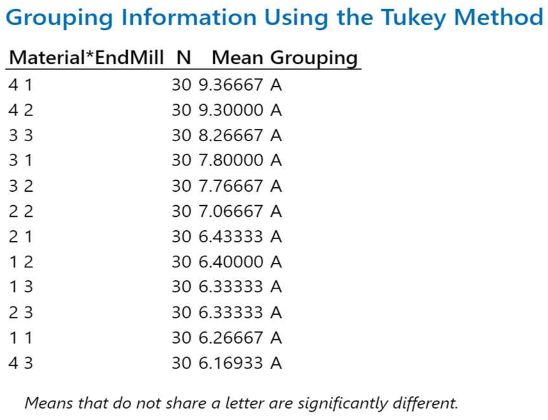


Grouping Information Using the Tukey Method

EndMill	N	Mean	Grouping
2	120	7.63333	A
1	120	7.46667	A
3	120	6.77567	A

Means that do not share a letter are significantly different.

Table 6.



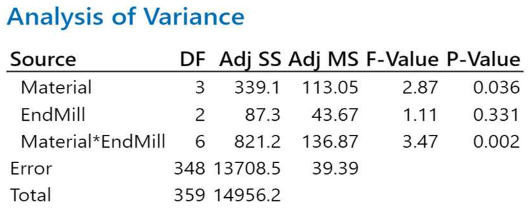
Grouping Information Using the Tukey Method

Material*EndMill	N	Mean	Grouping
4 1	30	9.36667	A
4 2	30	9.30000	A
3 3	30	8.26667	A
3 1	30	7.80000	A
3 2	30	7.76667	A
2 2	30	7.06667	A
2 1	30	6.43333	A
1 2	30	6.40000	A
1 3	30	6.33333	A
2 3	30	6.33333	A
1 1	30	6.26667	A
4 3	30	6.16933	A

Means that do not share a letter are significantly different.

Y-Axis Analysis:

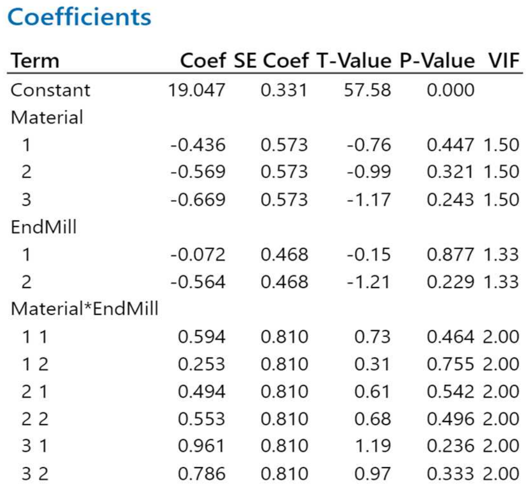
Table 7.



Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Material	3	339.1	113.05	2.87	0.036
EndMill	2	87.3	43.67	1.11	0.331
Material*EndMill	6	821.2	136.87	3.47	0.002
Error	348	13708.5	39.39		
Total	359	14956.2			

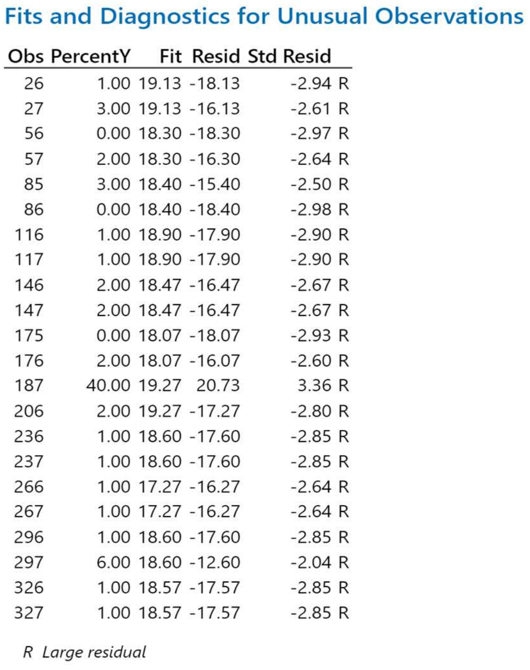
Table 8.



Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	19.047	0.331	57.58	0.000	
Material					
1	-0.436	0.573	-0.76	0.447	1.50
2	-0.569	0.573	-0.99	0.321	1.50
3	-0.669	0.573	-1.17	0.243	1.50
EndMill					
1	-0.072	0.468	-0.15	0.877	1.33
2	-0.564	0.468	-1.21	0.229	1.33
Material*EndMill					
1 1	0.594	0.810	0.73	0.464	2.00
1 2	0.253	0.810	0.31	0.755	2.00
2 1	0.494	0.810	0.61	0.542	2.00
2 2	0.553	0.810	0.68	0.496	2.00
3 1	0.961	0.810	1.19	0.236	2.00
3 2	0.786	0.810	0.97	0.333	2.00

Table 9.

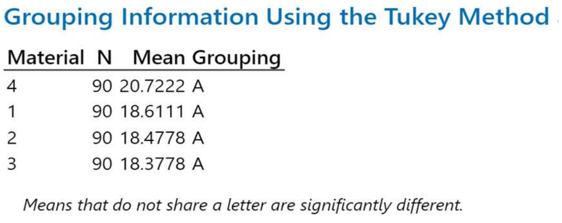


Fits and Diagnostics for Unusual Observations

Obs	PercentY	Fit	Resid	Std Resid	
26	1.00	19.13	-18.13	-2.94	R
27	3.00	19.13	-16.13	-2.61	R
56	0.00	18.30	-18.30	-2.97	R
57	2.00	18.30	-16.30	-2.64	R
85	3.00	18.40	-15.40	-2.50	R
86	0.00	18.40	-18.40	-2.98	R
116	1.00	18.90	-17.90	-2.90	R
117	1.00	18.90	-17.90	-2.90	R
146	2.00	18.47	-16.47	-2.67	R
147	2.00	18.47	-16.47	-2.67	R
175	0.00	18.07	-18.07	-2.93	R
176	2.00	18.07	-16.07	-2.60	R
187	40.00	19.27	20.73	3.36	R
206	2.00	19.27	-17.27	-2.80	R
236	1.00	18.60	-17.60	-2.85	R
237	1.00	18.60	-17.60	-2.85	R
266	1.00	17.27	-16.27	-2.64	R
267	1.00	17.27	-16.27	-2.64	R
296	1.00	18.60	-17.60	-2.85	R
297	6.00	18.60	-12.60	-2.04	R
326	1.00	18.57	-17.57	-2.85	R
327	1.00	18.57	-17.57	-2.85	R

R Large residual

Table 10.

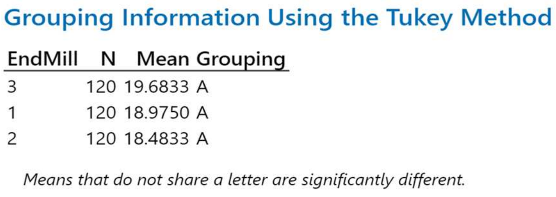


Grouping Information Using the Tukey Method

Material	N	Mean	Grouping
4	90	20.7222	A
1	90	18.6111	A
2	90	18.4778	A
3	90	18.3778	A

Means that do not share a letter are significantly different.

Table 11.



Grouping Information Using the Tukey Method

EndMill	N	Mean	Grouping
3	120	19.6833	A
1	120	18.9750	A
2	120	18.4833	A

Means that do not share a letter are significantly different.

Table 12.

Grouping Information Using the Tukey Method

Material*EndMill	N	Mean	Grouping	
4 3	30	25.0000	A	
3 1	30	19.2667		B
1 1	30	19.1333		B
2 1	30	18.9000		B
3 2	30	18.6000		B
4 1	30	18.6000		B
4 2	30	18.5667		B
2 2	30	18.4667		B
1 3	30	18.4000		B
1 2	30	18.3000		B
2 3	30	18.0667		B
3 3	30	17.2667		B

Means that do not share a letter are significantly different.

Z-Axis Analysis:

Table 13.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Material	3	114.17	38.058	12.35	0.000
EndMill	2	77.92	38.958	12.65	0.000
Material*EndMill	6	342.06	57.010	18.51	0.000
Error	348	1072.07	3.081		
Total	359	1606.22			

Table 14.

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	22.3502	0.0925	241.61	0.000	
Material					
1	-0.261	0.160	-1.63	0.104	1.50
2	-0.661	0.160	-4.13	0.000	1.50
3	0.872	0.160	5.44	0.000	1.50
EndMill					
1	0.491	0.131	3.76	0.000	1.33
2	0.133	0.131	1.02	0.310	1.33
Material*EndMill					
1 1	0.086	0.227	0.38	0.703	2.00
1 2	-1.689	0.227	-7.45	0.000	2.00
2 1	-0.347	0.227	-1.53	0.127	2.00
2 2	-0.322	0.227	-1.42	0.156	2.00
3 1	-0.080	0.227	-0.35	0.723	2.00
3 2	0.745	0.227	3.29	0.001	2.00

Table 15.

Fits and Diagnostics for Unusual Observations

Obs	PercentZ	Fit	Resid	Std Resid	
1	14.000	22.667	-8.667	-5.02	R
31	17.000	20.533	-3.533	-2.05	R
91	18.000	21.833	-3.833	-2.22	R
121	14.000	21.500	-7.500	-4.35	R
151	14.000	21.733	-7.733	-4.48	R
181	13.000	23.633	-10.633	-6.16	R
200	18.000	23.633	-5.633	-3.26	R
241	6.000	21.933	-15.933	-9.23	R
331	27.000	20.169	6.831	3.96	R
332	24.000	20.169	3.831	2.22	R
333	16.000	20.169	-4.169	-2.42	R
335	16.000	20.169	-4.169	-2.42	R

R Large residual

Table 16.

Grouping Information Using the Tukey Method

Material	N	Mean	Grouping		
3	90	23.2222	A		
4	90	22.4009		B	
1	90	22.0889		B	C
2	90	21.6889			C

Means that do not share a letter are significantly different.

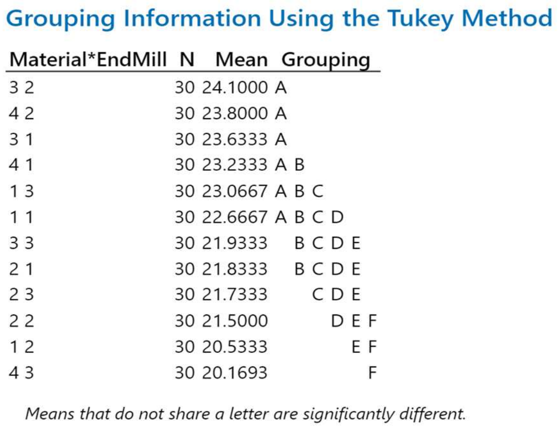
Table 17.

Grouping Information Using the Tukey Method

EndMill	N	Mean	Grouping	
1	120	22.8417	A	
2	120	22.4833	A	
3	120	21.7257		B

Means that do not share a letter are significantly different.

Table 18.



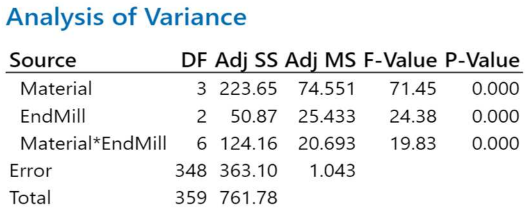
Grouping Information Using the Tukey Method

Material*EndMill	N	Mean	Grouping
3 2	30	24.1000	A
4 2	30	23.8000	A
3 1	30	23.6333	A
4 1	30	23.2333	A B
1 3	30	23.0667	A B C
1 1	30	22.6667	A B C D
3 3	30	21.9333	B C D E
2 1	30	21.8333	B C D E
2 3	30	21.7333	C D E
2 2	30	21.5000	D E F
1 2	30	20.5333	E F
4 3	30	20.1693	F

Means that do not share a letter are significantly different.

Total Load Analysis:

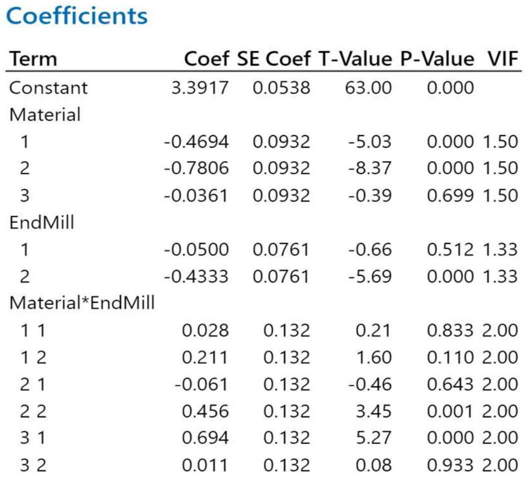
Table 19.



Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Material	3	223.65	74.551	71.45	0.000
EndMill	2	50.87	25.433	24.38	0.000
Material*EndMill	6	124.16	20.693	19.83	0.000
Error	348	363.10	1.043		
Total	359	761.78			

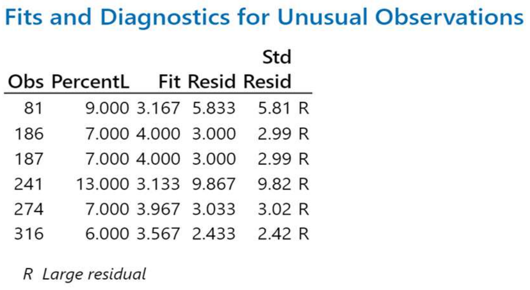
Table 20.



Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	3.3917	0.0538	63.00	0.000	
Material					
1	-0.4694	0.0932	-5.03	0.000	1.50
2	-0.7806	0.0932	-8.37	0.000	1.50
3	-0.0361	0.0932	-0.39	0.699	1.50
EndMill					
1	-0.0500	0.0761	-0.66	0.512	1.33
2	-0.4333	0.0761	-5.69	0.000	1.33
Material*EndMill					
1 1	0.028	0.132	0.21	0.833	2.00
1 2	0.211	0.132	1.60	0.110	2.00
2 1	-0.061	0.132	-0.46	0.643	2.00
2 2	0.456	0.132	3.45	0.001	2.00
3 1	0.694	0.132	5.27	0.000	2.00
3 2	0.011	0.132	0.08	0.933	2.00

Table 21.

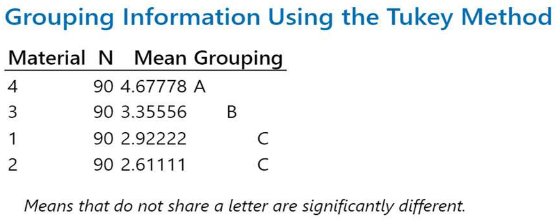


Fits and Diagnostics for Unusual Observations

Obs	PercentL	Fit	Resid	Std Resid	
81	9.000	3.167	5.833	5.81	R
186	7.000	4.000	3.000	2.99	R
187	7.000	4.000	3.000	2.99	R
241	13.000	3.133	9.867	9.82	R
274	7.000	3.967	3.033	3.02	R
316	6.000	3.567	2.433	2.42	R

R Large residual

Table 22.

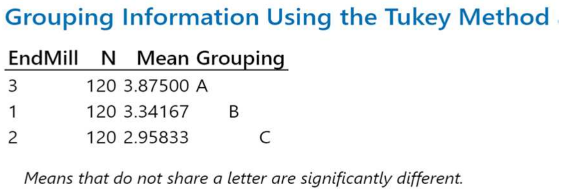


Grouping Information Using the Tukey Method

Material	N	Mean	Grouping
4	90	4.67778	A
3	90	3.35556	B
1	90	2.92222	C
2	90	2.61111	C

Means that do not share a letter are significantly different.

Table 23.

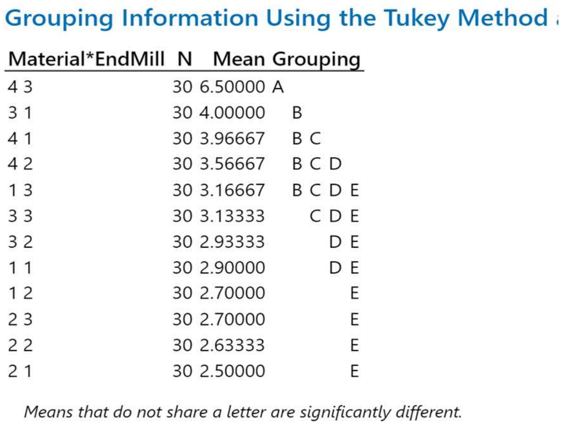


Grouping Information Using the Tukey Method

EndMill	N	Mean	Grouping
3	120	3.87500	A
1	120	3.34167	B
2	120	2.95833	C

Means that do not share a letter are significantly different.

Table 24.



Grouping Information Using the Tukey Method

Material*EndMill	N	Mean	Grouping
4 3	30	6.50000	A
3 1	30	4.00000	B
4 1	30	3.96667	B C
4 2	30	3.56667	B C D
1 3	30	3.16667	B C D E
3 3	30	3.13333	C D E
3 2	30	2.93333	D E
1 1	30	2.90000	D E
1 2	30	2.70000	E
2 3	30	2.70000	E
2 2	30	2.63333	E
2 1	30	2.50000	E

Means that do not share a letter are significantly different.

Appendix F – Circular Analysis Results

X-Axis Analysis:

Table 1.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Material	3	32.98	10.99	0.68	0.565
EndMill	2	126.15	63.08	3.91	0.022
Material*EndMill	6	205.56	34.26	2.12	0.054
Error	156	2516.43	16.13		
Total	167	2881.12			

Table 2.

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	21.298	0.310	68.73	0.000	
Material					
1	-0.107	0.537	-0.20	0.842	1.50
2	-0.607	0.537	-1.13	0.260	1.50
3	0.631	0.537	1.18	0.242	1.50
EndMill					
1	-0.708	0.438	-1.62	0.108	1.33
2	-0.512	0.438	-1.17	0.245	1.33
Material*EndMill					
1 1	1.589	0.759	2.09	0.038	2.00
1 2	-0.250	0.759	-0.33	0.742	2.00
2 1	-0.268	0.759	-0.35	0.725	2.00
2 2	0.893	0.759	1.18	0.241	2.00
3 1	-0.006	0.759	-0.01	0.994	2.00
3 2	0.440	0.759	0.58	0.563	2.00

Table 3.

Fits and Diagnostics for Unusual Observations

Obs	PercentX	Fit	Resid	Std Resid	
27	5.00	20.43	-15.43	-3.99	R
47	5.00	19.71	-14.71	-3.80	R
87	33.00	21.21	11.79	3.05	R
114	35.00	22.71	12.29	3.17	R
128	30.00	19.36	10.64	2.75	R
150	37.00	19.79	17.21	4.45	R
151	12.00	19.79	-7.79	-2.01	R
158	17.00	25.00	-8.00	-2.07	R
159	33.00	25.00	8.00	2.07	R

R Large residual

Table 4.

Grouping Information Using the Tukey Method

Material	N	Mean	Grouping
3	42	21.9286	A
4	42	21.3810	A
1	42	21.1905	A
2	42	20.6905	A

Means that do not share a letter are significantly different.

Table 5.

Grouping Information Using the Tukey Method

EndMill	N	Mean	Grouping	
3	56	22.5179	A	
2	56	20.7857	A	B
1	56	20.5893		B

Means that do not share a letter are significantly different.

Table 6.

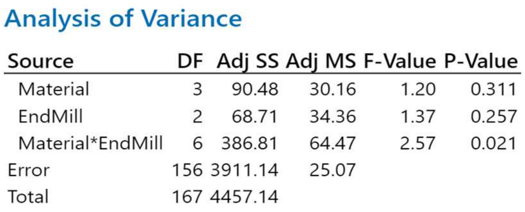
Grouping Information Using the Tukey Method

Material*EndMill	N	Mean	Grouping	
4 3	14	25.0000	A	
3 3	14	22.7143	A	B
1 1	14	22.0714	A	B
3 2	14	21.8571	A	B
2 3	14	21.2857	A	B
3 1	14	21.2143	A	B
1 3	14	21.0714	A	B
2 2	14	21.0714	A	B
1 2	14	20.4286	A	B
4 2	14	19.7857		B
2 1	14	19.7143		B
4 1	14	19.3571		B

Means that do not share a letter are significantly different.

Y-Axis Analysis:

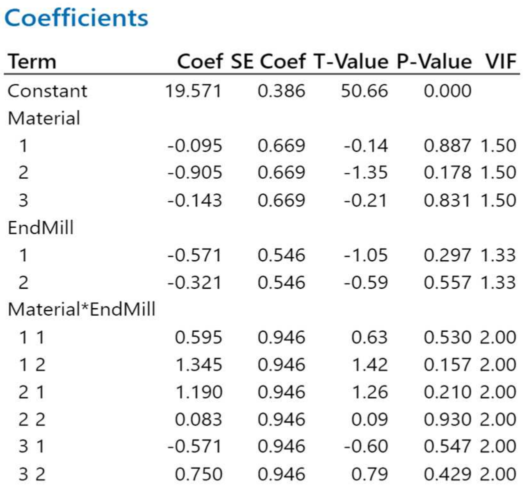
Table 6.



Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Material	3	90.48	30.16	1.20	0.311
EndMill	2	68.71	34.36	1.37	0.257
Material*EndMill	6	386.81	64.47	2.57	0.021
Error	156	3911.14	25.07		
Total	167	4457.14			

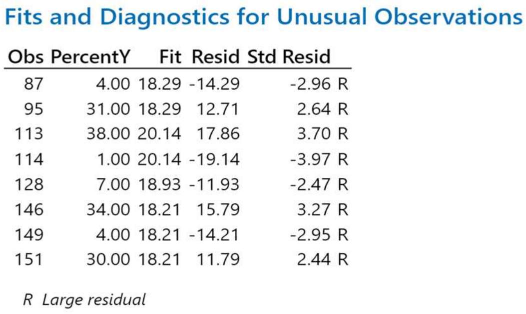
Table 7.



Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	19.571	0.386	50.66	0.000	
Material					
1	-0.095	0.669	-0.14	0.887	1.50
2	-0.905	0.669	-1.35	0.178	1.50
3	-0.143	0.669	-0.21	0.831	1.50
EndMill					
1	-0.571	0.546	-1.05	0.297	1.33
2	-0.321	0.546	-0.59	0.557	1.33
Material*EndMill					
1 1	0.595	0.946	0.63	0.530	2.00
1 2	1.345	0.946	1.42	0.157	2.00
2 1	1.190	0.946	1.26	0.210	2.00
2 2	0.083	0.946	0.09	0.930	2.00
3 1	-0.571	0.946	-0.60	0.547	2.00
3 2	0.750	0.946	0.79	0.429	2.00

Table 8.

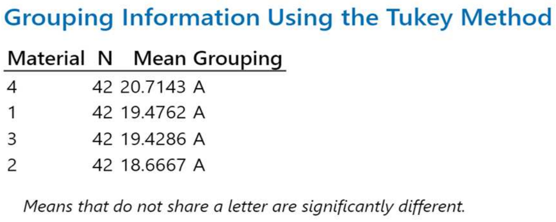


Fits and Diagnostics for Unusual Observations

Obs	PercentY	Fit	Resid	Std Resid	
87	4.00	18.29	-14.29	-2.96	R
95	31.00	18.29	12.71	2.64	R
113	38.00	20.14	17.86	3.70	R
114	1.00	20.14	-19.14	-3.97	R
128	7.00	18.93	-11.93	-2.47	R
146	34.00	18.21	15.79	3.27	R
149	4.00	18.21	-14.21	-2.95	R
151	30.00	18.21	11.79	2.44	R

R Large residual

Table 9.

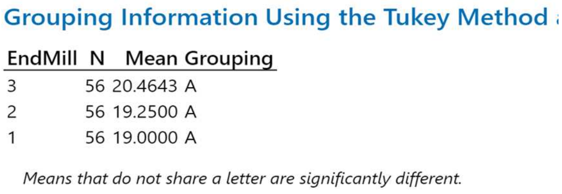


Grouping Information Using the Tukey Method

Material	N	Mean	Grouping
4	42	20.7143	A
1	42	19.4762	A
3	42	19.4286	A
2	42	18.6667	A

Means that do not share a letter are significantly different.

Table 10.

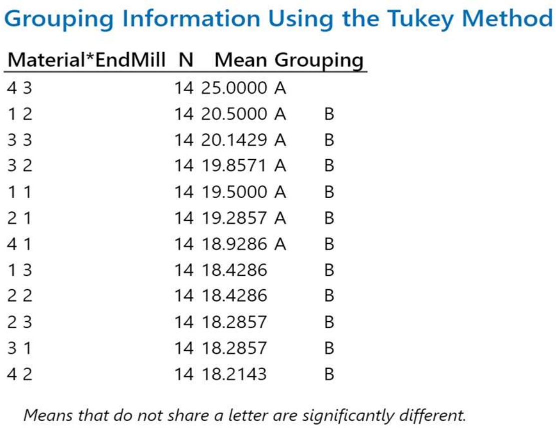


Grouping Information Using the Tukey Method

EndMill	N	Mean	Grouping
3	56	20.4643	A
2	56	19.2500	A
1	56	19.0000	A

Means that do not share a letter are significantly different.

Table 11.



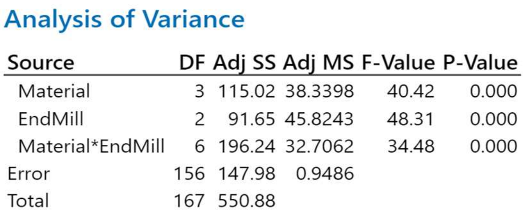
Grouping Information Using the Tukey Method

Material*EndMill	N	Mean	Grouping	
4 3	14	25.0000	A	
1 2	14	20.5000	A	B
3 3	14	20.1429	A	B
3 2	14	19.8571	A	B
1 1	14	19.5000	A	B
2 1	14	19.2857	A	B
4 1	14	18.9286	A	B
1 3	14	18.4286		B
2 2	14	18.4286		B
2 3	14	18.2857		B
3 1	14	18.2857		B
4 2	14	18.2143		B

Means that do not share a letter are significantly different.

Z-Axis Analysis:

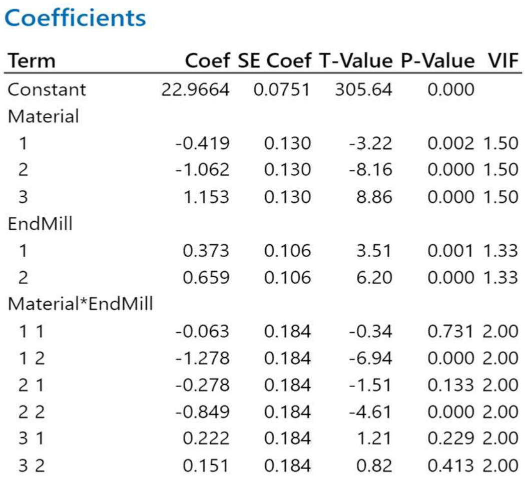
Table 13.



Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Material	3	115.02	38.3398	40.42	0.000
EndMill	2	91.65	45.8243	48.31	0.000
Material*EndMill	6	196.24	32.7062	34.48	0.000
Error	156	147.98	0.9486		
Total	167	550.88			

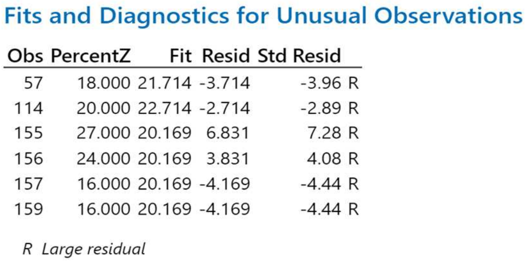
Table 14.



Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	22.9664	0.0751	305.64	0.000	
Material					
1	-0.419	0.130	-3.22	0.002	1.50
2	-1.062	0.130	-8.16	0.000	1.50
3	1.153	0.130	8.86	0.000	1.50
EndMill					
1	0.373	0.106	3.51	0.001	1.33
2	0.659	0.106	6.20	0.000	1.33
Material*EndMill					
1 1	-0.063	0.184	-0.34	0.731	2.00
1 2	-1.278	0.184	-6.94	0.000	2.00
2 1	-0.278	0.184	-1.51	0.133	2.00
2 2	-0.849	0.184	-4.61	0.000	2.00
3 1	0.222	0.184	1.21	0.229	2.00
3 2	0.151	0.184	0.82	0.413	2.00

Table 15.

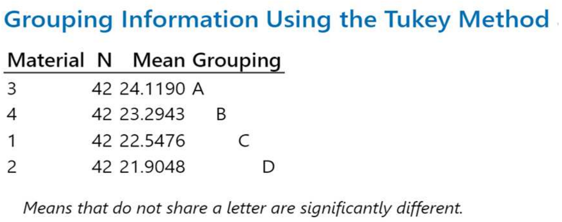


Fits and Diagnostics for Unusual Observations

Obs	PercentZ	Fit	Resid	Std Resid	
57	18.000	21.714	-3.714	-3.96	R
114	20.000	22.714	-2.714	-2.89	R
155	27.000	20.169	6.831	7.28	R
156	24.000	20.169	3.831	4.08	R
157	16.000	20.169	-4.169	-4.44	R
159	16.000	20.169	-4.169	-4.44	R

R Large residual

Table 16.

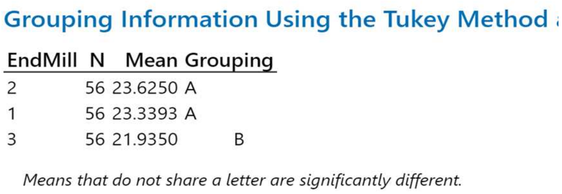


Grouping Information Using the Tukey Method

Material	N	Mean	Grouping
3	42	24.1190	A
4	42	23.2943	B
1	42	22.5476	C
2	42	21.9048	D

Means that do not share a letter are significantly different.

Table 17.

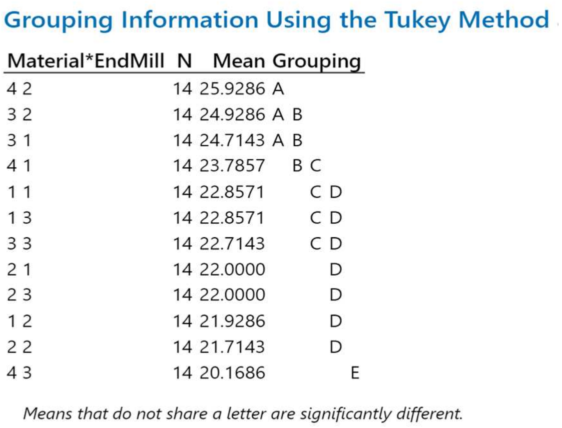


Grouping Information Using the Tukey Method

EndMill	N	Mean	Grouping
2	56	23.6250	A
1	56	23.3393	A
3	56	21.9350	B

Means that do not share a letter are significantly different.

Table 18.



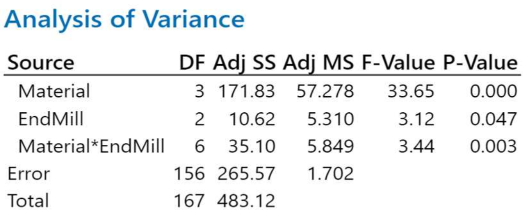
Grouping Information Using the Tukey Method

Material*EndMill	N	Mean	Grouping
4 2	14	25.9286	A
3 2	14	24.9286	A B
3 1	14	24.7143	A B
4 1	14	23.7857	B C
1 1	14	22.8571	C D
1 3	14	22.8571	C D
3 3	14	22.7143	C D
2 1	14	22.0000	D
2 3	14	22.0000	D
1 2	14	21.9286	D
2 2	14	21.7143	D
4 3	14	20.1686	E

Means that do not share a letter are significantly different.

Total Load Analysis:

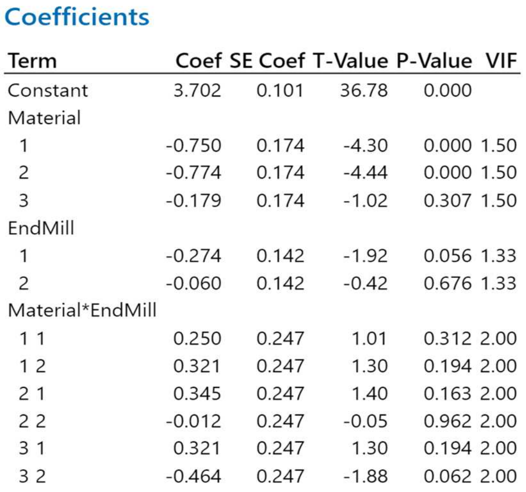
Table 19.



Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Material	3	171.83	57.278	33.65	0.000
EndMill	2	10.62	5.310	3.12	0.047
Material*EndMill	6	35.10	5.849	3.44	0.003
Error	156	265.57	1.702		
Total	167	483.12			

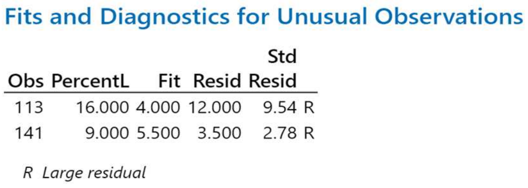
Table 20.



Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	3.702	0.101	36.78	0.000	
Material					
1	-0.750	0.174	-4.30	0.000	1.50
2	-0.774	0.174	-4.44	0.000	1.50
3	-0.179	0.174	-1.02	0.307	1.50
EndMill					
1	-0.274	0.142	-1.92	0.056	1.33
2	-0.060	0.142	-0.42	0.676	1.33
Material*EndMill					
1 1	0.250	0.247	1.01	0.312	2.00
1 2	0.321	0.247	1.30	0.194	2.00
2 1	0.345	0.247	1.40	0.163	2.00
2 2	-0.012	0.247	-0.05	0.962	2.00
3 1	0.321	0.247	1.30	0.194	2.00
3 2	-0.464	0.247	-1.88	0.062	2.00

Table 21.

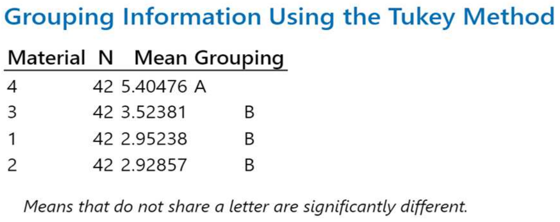


Fits and Diagnostics for Unusual Observations

Obs	PercentL	Fit	Resid	Std Resid	
113	16.000	4.000	12.000	9.54	R
141	9.000	5.500	3.500	2.78	R

R Large residual

Table 22.

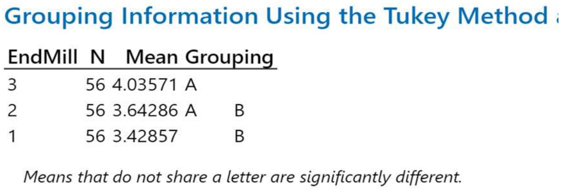


Grouping Information Using the Tukey Method

Material	N	Mean	Grouping
4	42	5.40476	A
3	42	3.52381	B
1	42	2.95238	B
2	42	2.92857	B

Means that do not share a letter are significantly different.

Table 23.

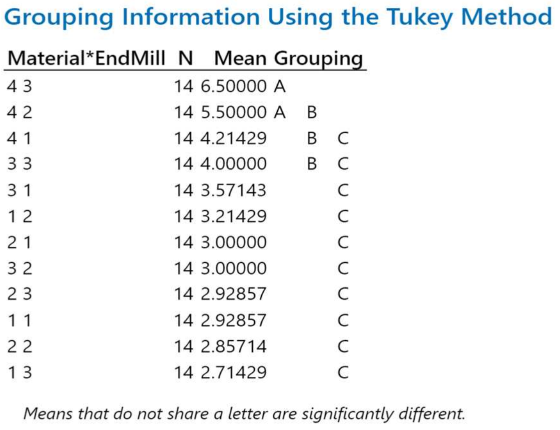


Grouping Information Using the Tukey Method

EndMill	N	Mean	Grouping
3	56	4.03571	A
2	56	3.64286	A B
1	56	3.42857	B

Means that do not share a letter are significantly different.

Table 24.



Grouping Information Using the Tukey Method

Material*EndMill	N	Mean	Grouping
4 3	14	6.50000	A
4 2	14	5.50000	A B
4 1	14	4.21429	B C
3 3	14	4.00000	B C
3 1	14	3.57143	C
1 2	14	3.21429	C
2 1	14	3.00000	C
3 2	14	3.00000	C
2 3	14	2.92857	C
1 1	14	2.92857	C
2 2	14	2.85714	C
1 3	14	2.71429	C

Means that do not share a letter are significantly different.