

Position Verification in a GD&T Course: A Longitudinal Study

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Abstract

A Geometric Dimensioning and Tolerancing (GD&T) course has been offered at Illinois State University since the Fall of 2016. This course was added as an elective to the Engineering Technology curriculum at the recommendation of the industrial advisory board to help give students a better understanding of dimensioning and tolerancing through the design, manufacturing, and product inspection processes. The course includes weekly study of GD&T concepts, measurement/inspection activities, and CAD modeling and drawing activities. A critical topic in GD&T is locating holes using the position tolerance rather than conventional plus/minus dimensioning. The position tolerance and position verification/inspection are covered as part of the GD&T concepts. To master position verification, students must be able to read information from a drawing and produced part, determine the maximum material condition (MMC) of a hole, determine the actual size of a hole, calculate the allowed position tolerance, determine the X & Y deviations of the hole, calculate the actual position tolerance, and make an accurate decision whether to accept or reject the position. This paper will give an overview of locating holes with the position tolerance vs. conventional tolerancing, present data from the GD&T class over a seven-year period and describe trends in student performance related to position verification.

Introduction / Review of Literature

The Engineering Technology program at Illinois State University has offered a stand-alone GD&T course since the fall of 2016. Faculty and industrial advisory board members had been discussing adding the course in prior years with the goal of providing students more experience in dimensioning and tolerancing and precision measurement methods. The course covers GD&T content based on the current ASME Standards for Dimensioning & Tolerancing [1], which is supported by workbook content and exercises [2], measuring activities (calipers and coordinate measuring machines), and modeling and drawing activities. Grades are based on laboratory activities (30%), weekly online quizzes (20%), two tests (30%), and an exam (20%). Lab activities consist of modeling and drawing assignments using Siemens NX as well as measuring exercises using calipers, a Romer Arm coordinate measuring machine (CMM), and a Brown & Sharpe CMM.

One of the key concepts of GD&T, and covered in this course, is position tolerancing. It is important for students to understand how it can be applied to cylindrical features and how material condition modifiers influence the tolerance [3]. It is also critical that students can determine if parts pass or fail based on the given documentation (drawings) and inspection data. The goal of all concepts within GD&T, including the position tolerance, is to pass parts that work and fail parts that do not work.

GD&T textbooks/workbooks typically do a good job presenting the position tolerance, but some fall short in assessing students' understanding of interpreting inspection data related to the tolerance [4]-[6]. There are some workbooks that include exercises where students are required to calculate bonus tolerances based on produced parts and then make decisions about whether the

parts pass or fail inspection [2], [7]. These exercises give students a much deeper understanding of the position tolerance since they are required to work with more pieces of data.

Review of Conventional Tolerancing vs. the Position Tolerancing

Conventional tolerancing is a two-dimensional system and is subject to many interpretations (e.g., location of datum features or relationships between features). These types of dimensions are very good for specifying features with size such as holes, cylinders, slots, tabs, etc. They are not very good for locating holes or cylinders [2]. During the design phase, worst-case scenarios are used to determine size and location dimensions. Typically, this starts by determining the type of fit necessary between mating features and then calculating the location dimensions when the features are at MMC (largest pin and smallest hole) [6]. Fig. 1 displays an example assembly and drawings of two parts – one part with holes and one part with pins. The sizes of the holes and pins were specified to create a clearance fit. The location dimensions were then determined by examining a worst-case scenario along the X or Y axis (largest pin and smallest hole). To maintain the clearance fit, the features were located by $1.125 \pm .005$ dimensions. These location dimensions create square tolerance zones (Fig. 2). Fig. 2 also shows example hole and pins locations that will be further analyzed in Fig. 3.

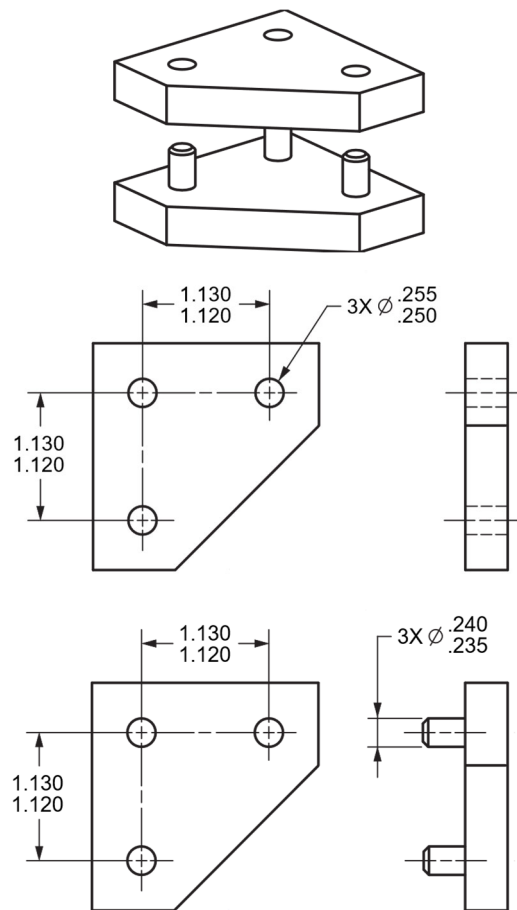


Fig. 1. Example of conventional tolerancing to locate features.

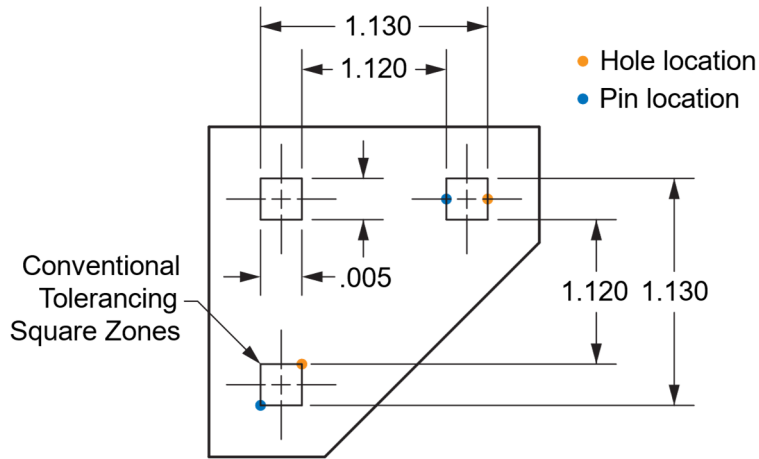


Fig. 2. Conventional tolerancing creates square tolerance zones.

Fig. 3(a) shows what happens when the pins and holes are created on opposite sides of the square tolerance zone as highlighted at the top right location in Fig. 2. In this case, the clearance fit is maintained. Fig. 3(b) shows the result when the pins and holes are machined so their locations are at the opposite corners of the square zone (bottom left location in Fig. 2). In this case an interference exists, and the assembly will not function. To avoid passing parts that satisfy the original $1.125 \pm .005$ location dimensions but do not function, the location dimensions must be reduced to $1.125 \pm .004$. Unfortunately, this will create situations where parts will be rejected that still function.

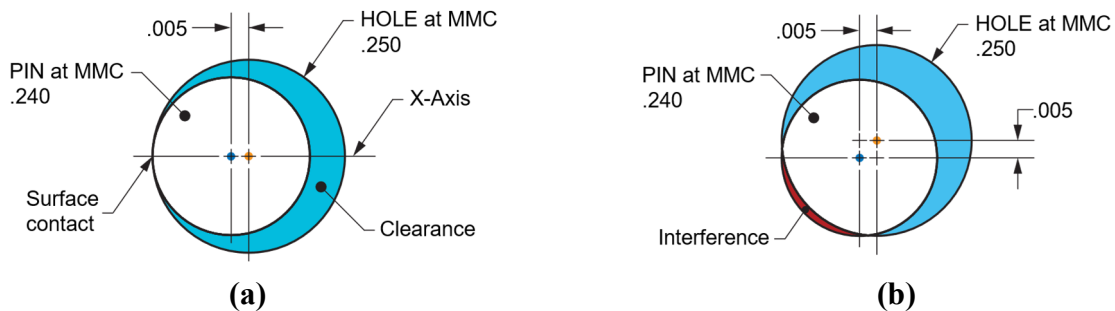


Fig. 3. (a) Potential hole and (b) pin locations with conventional tolerancing.

The position tolerance within GD&T creates cylindrical tolerance zones at theoretically exact locations. When material condition modifiers are applied (such as MMC or LMC), designers can be sure that parts that work will pass inspection and parts that do not work will fail inspection. Fig. 4 displays an example of the part with holes controlled by the position tolerance. The size of the holes is still specified using a limit dimension. The holes are located with basic dimensions (theoretically exact – no tolerance), and the position tolerance specifies a .005 cylindrical zone at MMC (M within the circle). The MMC modifier allows the position zone to be larger if the hole departs from MMC. To calculate the allowed position tolerance when the MMC modifier is applied to hole features, the formula is:

$$\text{Allowed Position Tolerance} = (\text{Actual Hole Size} - \text{MMC Size}) + \text{Position Tolerance}$$

For example, if the actual size of a hole is .253, the allowed position would be calculated:

$$\text{Allowed Position Tolerance} = (.253 - .250) + .005 = .008$$

Fig. 5 shows the potential tolerance zones that are the results of using conventional tolerances to locate the holes (square zones) and the smallest and largest cylindrical zones that are possible based on the actual size of each feature (hole or pin). Position 1 in Fig. 5 shows a hole or pin location that would pass inspection based on the original $1.125 \pm .005$ location dimensions and a feature at MMC specified with the position tolerance. It would not pass inspection with the modified $1.125 \pm .004$ location dimensions. Position 2 in Fig. 5 illustrates a hole or pin location that would pass inspection with the original $1.125 \pm .005$ location dimensions but might not necessarily function. It would pass inspection based on the actual size of the features specified with the position tolerance. Position 3 illustrates a hole or pin location that would fail inspection with the original $1.125 \pm .005$ and modified $1.125 \pm .004$ location dimensions but could potentially pass inspection based on the size of the feature with the position tolerance.

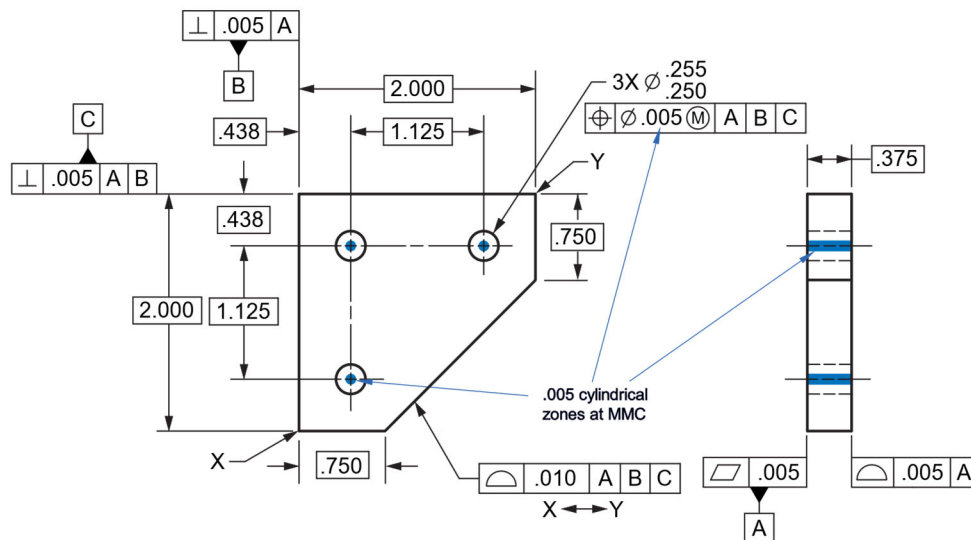


Fig. 4. Geometric dimensioning & tolerancing applied to a part.

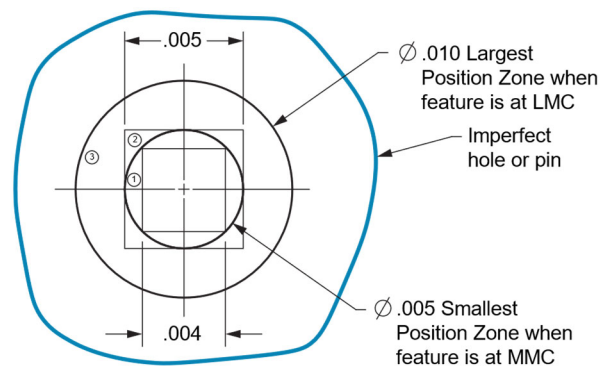
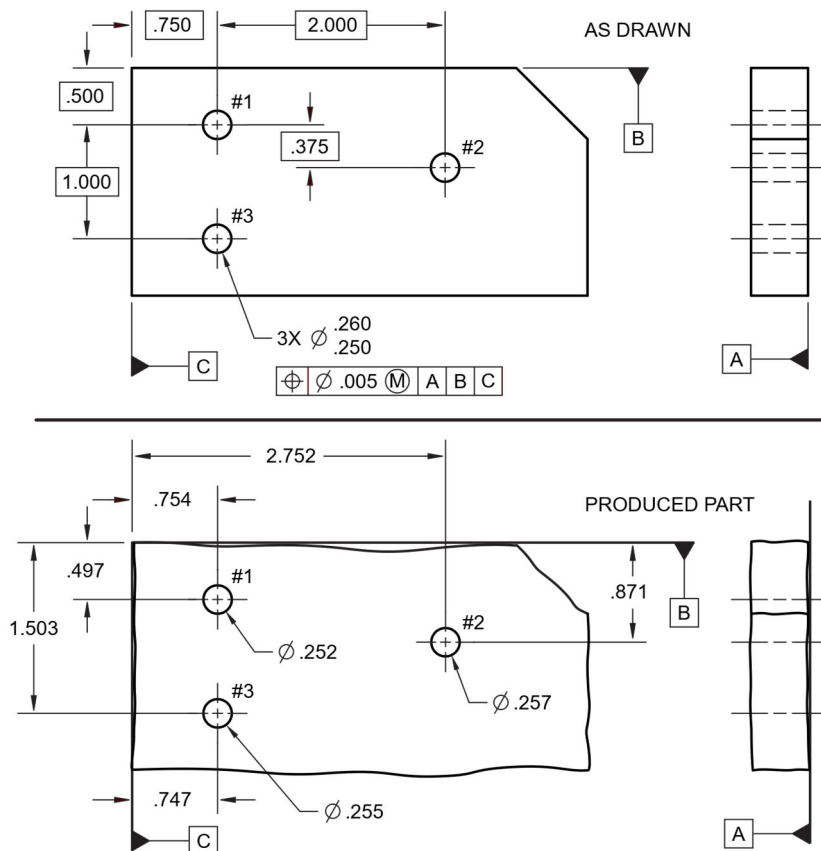


Fig. 5. Potential tolerance zones.

Position Verification Exercise

From the first semester the GD&T course was offered, position tolerance exercises were included where students were required to evaluate data from a produced part and determine if the locations of holes would pass inspection based on the given drawing. Fig. 6 displays an example of the type of position verification exercise that has been integrated into the GD&T course over the last 7 years.

Students are given a production drawing with the required dimensioning and tolerancing, a produced part drawing with actual size and location information for the holes, and a table to complete where they must identify or calculate key parts of the position verification process. Students complete practice versions of this activity during the fourth week of classes and are assessed using equivalent versions on a subsequent learning management system (LMS) quiz, the first test, and the exam.



Hole #	MMC Size	Actual Size	Allowed Position	X Dev	Y Dev	Actual Position	Accept	Reject
1								
2								
3								

Fig. 6. Sample position verification problem.

During the Fall 2016 through Fall 2022 semesters, students were asked to complete problems like Fig. 6 on the first test and the exam in the course. These assessments were administered via paper and pencil test except for the Fall 2020 semester exam. During this semester, all exams at the university were administered online via the LMS due to the COVID-19 pandemic. To examine trends in students' success, the following research questions were developed.

Research Questions

1. Are students able to determine maximum material condition (MMC) better at the end of the course than at the beginning of the course?
2. Do students calculate allowed position better at the end of the course than at the beginning of the course?
3. Do students calculate actual position better at the end of the course than at the beginning of the course?
4. Do students make more accurate accept/reject decisions at the end of the course than at the beginning of the course?

Method

Participants

From Fall 2016 to Fall 2022, ninety students were enrolled in the GD&T course. Tables 1-4 summarize the demographic information on all students.

Table 1. Participants by semester.

Semester	Frequency	Percent
Fall 2016	12	13.3%
Fall 2017	19	21.1%
Fall 2018	10	11.1%
Fall 2019	11	12.2%
Fall 2020	18	20.0%
Fall 2021	12	13.3%
Fall 2022	8	8.9%
TOTAL	90	100.0%

Table 2. Participants by academic year.

Semester	Frequency	Percent
Freshmen	1	1.1%
Sophomore	2	2.2%
Junior	27	30.0%
Senior	56	62.2%
Graduate	4	4.4%
TOTAL	90	100.0%

Table 3. Participants by gender.

Semester	Frequency	Percent
Female	7	7.8%
Male	83	92.2%
TOTAL	90	100.0%

Table 4. Participants by ethnicity.

Semester	Frequency	Percent
Asian	4	4.4%
Black	11	12.2%
Hispanic	7	7.8%
White	68	75.6%
TOTAL	90	100.0%

Enrollment ranged from 8-19 students each semester. Most students were white males in their senior year of the Engineering Technology program.

Results

To better understand how students' scores differed from the beginning of the semester to the end, data from the position verification questions on the first test and the exam were recorded. The questions on each of these assessments consisted of verifying the data on a part with 3 holes like the problem in Fig. 6. Each student could potentially get three items correct on the first test and 3 items correct on the exam. Tables 5-8 display these data.

Table 5. Determining MMC.

Correct MMC identified?	Test 1		Exam	
	Frequency	Percent	Frequency	Percent
No	10	11.1%	12	13.3%
Yes	80	88.9%	78	86.7%
TOTAL	90	100.0%	90	100.0%

Table 6. Calculating allowed position.

Number Correct	Test 1		Exam	
	Frequency	Percent	Frequency	Percent
0	18	20.0%	19	21.1%
1	6	6.7%	1	1.1%
2	5	5.6%	4	4.4%
3	61	67.8%	66	73.3%
TOTAL	90	100.0%	90	100.0%

Table 7. Calculating actual position.

Number Correct	Test 1		Exam	
	Frequency	Percent	Frequency	Percent
0	8	8.9%	4	4.4%
1	7	7.8%	12	13.3%
2	14	15.6%	3	3.3%
3	61	67.8%	71	78.9%
TOTAL	90	100.0%	90	100.0%

Table 8. Making the correct accept/reject decision.

Number Correct	Test 1		Exam	
	Frequency	Percent	Frequency	Percent
0	5	5.6%	2	2.2%
1	19	21.1%	16	17.8%
2	14	15.6%	16	17.8%
3	52	57.8%	56	62.2%
TOTAL	90	100.0%	90	100.0%

Eighty students correctly identified the MMC on all items on the first test compared to 78 on the exam (Table 5). Sixty-one students were able to calculate the allowed position on all three holes on the first test correctly, while 66 students calculated the allowed position correctly on all three holes on the exam (Table 6). Sixty-one students calculated the actual position of the holes correctly for the three holes on test 1, and 71 students did so on the exam (Table 7). Finally, fifty-two students accurately accepted or rejected the position for the three holes on test 1, while 56 students accurately determined the position of the holes on the exam (Table 8).

To determine if any of these results were significant, non-parametric Wilcoxon Signed Ranked tests were run. Table 9 displays the results of these tests.

Table 9. Wilcoxon Signed Rank tests.

Assessment	Test 1 Correct MMC vs. Exam Correct MMC	Test 1 Correct Allowed Position Vs. Exam Correct Allowed Position	Test 1 Correct Actual Position Vs. Exam Correct Actual Position	Test 1 Correct Decision Vs. Exam Correct Decision
Z	-.447 ^a	-.420 ^b	-.814 ^b	-1.231 ^b
Asymp. Sig. (2-tailed)	.655	.674	.415	.218

- a. Based on positive ranks.
- b. Based on negative ranks.

None of the tests revealed significant differences between data from the first test and data from the exam. To investigate changes over the last 7 years, data were charted by semester. Table 9 displays the results of the correct identification of the MMC, allowed position, actual position,

and accept/reject decisions, and Figs. 7-10 show these results graphically. All results are displayed by the percentage of items correctly answered each semester.

Table 9. Correctly answered items by semester.

Semester	Correct MMC Percentage		Correct Allowed Position Percentage		Correct Actual Position Percentage		Correct Accept/Reject Decision Percentage	
	Test 1	Exam	Test 1	Exam	Test 1	Exam	Test 1	Exam
Fall 2016	91.7%	83.3%	75.0%	88.9%	80.6%	100.0%	75.0%	80.6%
Fall 2017	94.7%	79.0%	84.2%	77.2%	93.0%	86.0%	91.2%	91.2%
Fall 2018	100.0%	100.0%	83.3%	90.0%	86.7%	100.0%	63.3%	76.7%
Fall 2019	100.0%	91.9%	78.8%	72.7%	81.8%	93.9%	75.8%	78.8%
Fall 2020	83.3%	83.3%	66.7%	79.6%	88.9%	70.4%	75.9%	90.7%
Fall 2021	75.0%	83.3%	50.0%	61.1%	58.3%	72.2%	63.9%	61.1%
Fall 2022	75.0%	100.0%	79.2%	62.5%	58.3%	87.5%	66.7%	62.5%
Overall	88.9%	86.7%	73.7%	76.7%	80.7%	85.6%	75.2%	80.0%

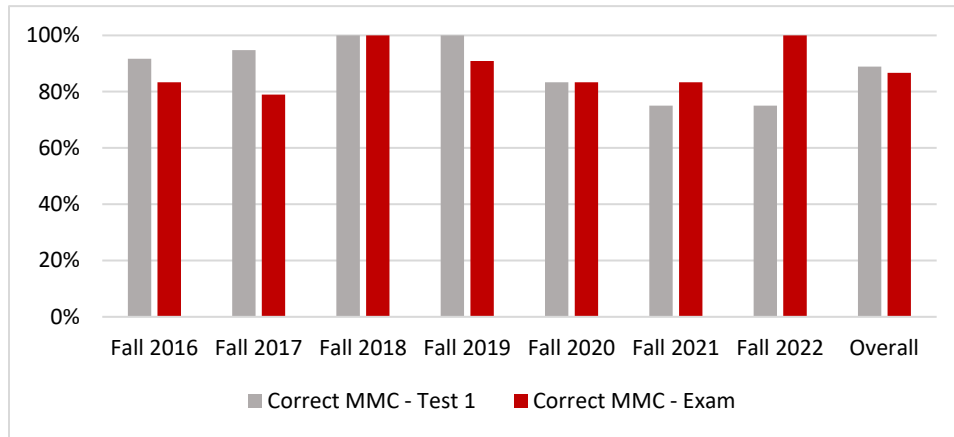


Fig. 7. Correct MMC by semester.

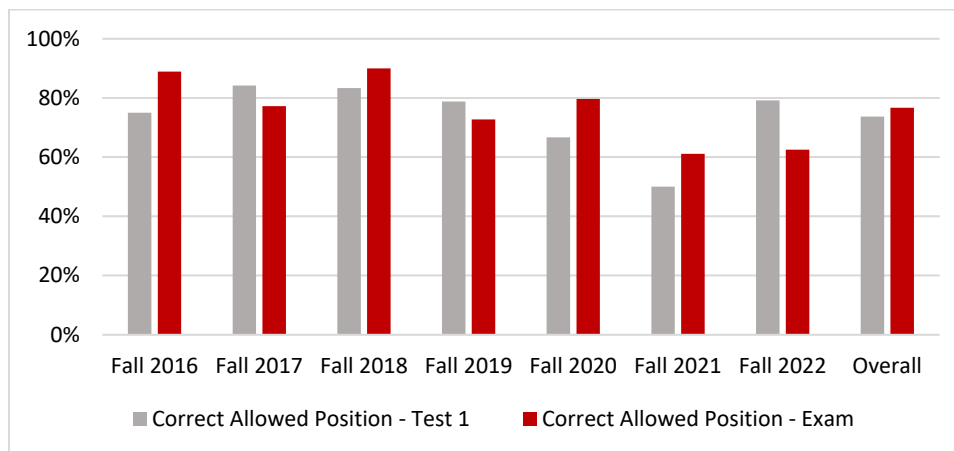


Fig. 8. Correct allowed position by semester.

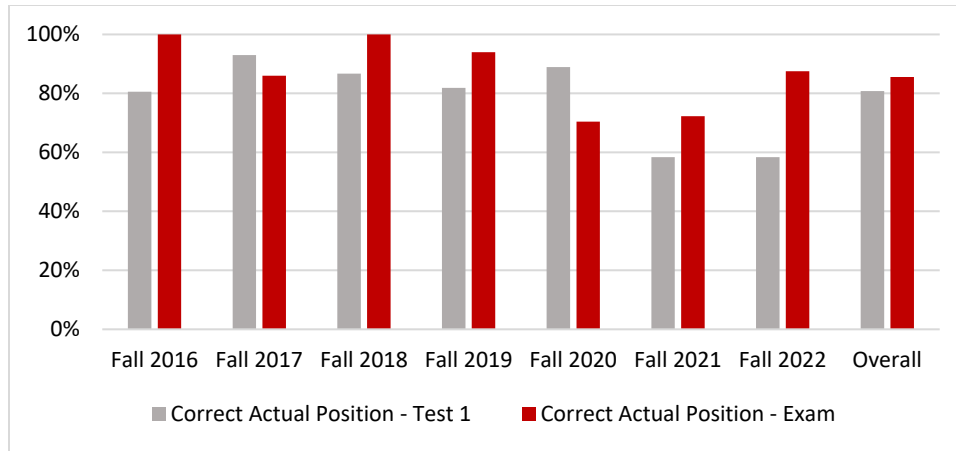


Fig. 9. Correct actual position by semester.

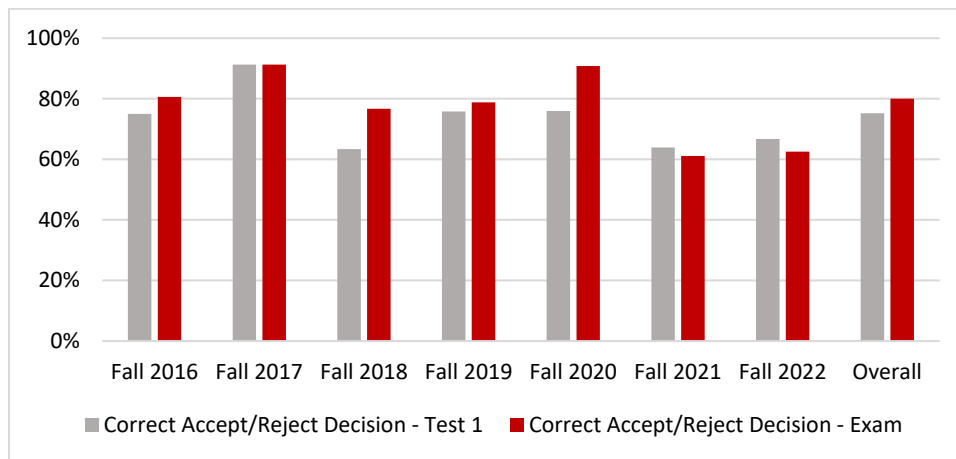


Fig. 10. Correct accept/reject decision by semester.

Overall, students correctly determined the MMC more often on the first test (88.9%) than on the final exam (86.7%). This trend changed during the fall 2021 and fall 2022 semesters where students performed better on the exam than on the first test. The allowed position, in general, was calculated correctly more on the exam (76.7%) than on the first test (73.7%). It was not consistent semester by semester. Students performed better on the exam than on test 1 during 2016, 2018, 2020, and 2021 semester. Allowed position was calculated correctly less frequently on the exam than on test 1 during the 2017, 2019, and 2022 semesters. Students tended to calculate the actual position of holes better on the exam (85.6%) than on the first test (80.7%), but there were two semesters (2017 and 2020) where students performed better on test 1 than the exam. Finally, students tended to make the correct accept/reject decision on the exam (80.0%) more often than on the first test (75.2%). This was not true for the 2021 and 2022 semesters, where students performed better on the first test than on the exam.

Conclusions

Although the data revealed no significant performance improvements from test 1 to the exam, there are items which are worth noting from the study. First, students' ability to determine the MMC of a hole feature decreased (although not significantly) from the first test to the exam. Ten students (11.1%) could not correctly identify the MMC on test 1, but this increased to 12 students (13.3%) on the exam. Since identifying the correct MMC directly affects being able to calculate the allowed position (which also affects accurately accepting or rejecting the hole location), it is critical students determine this correctly at the beginning of the process. Too often students immediately assume the MMC is the largest value in a limit dimension instead of realizing the MMC of a hole is the smallest hole. Fig. 11 displays an example of a student's response that illustrates this result.

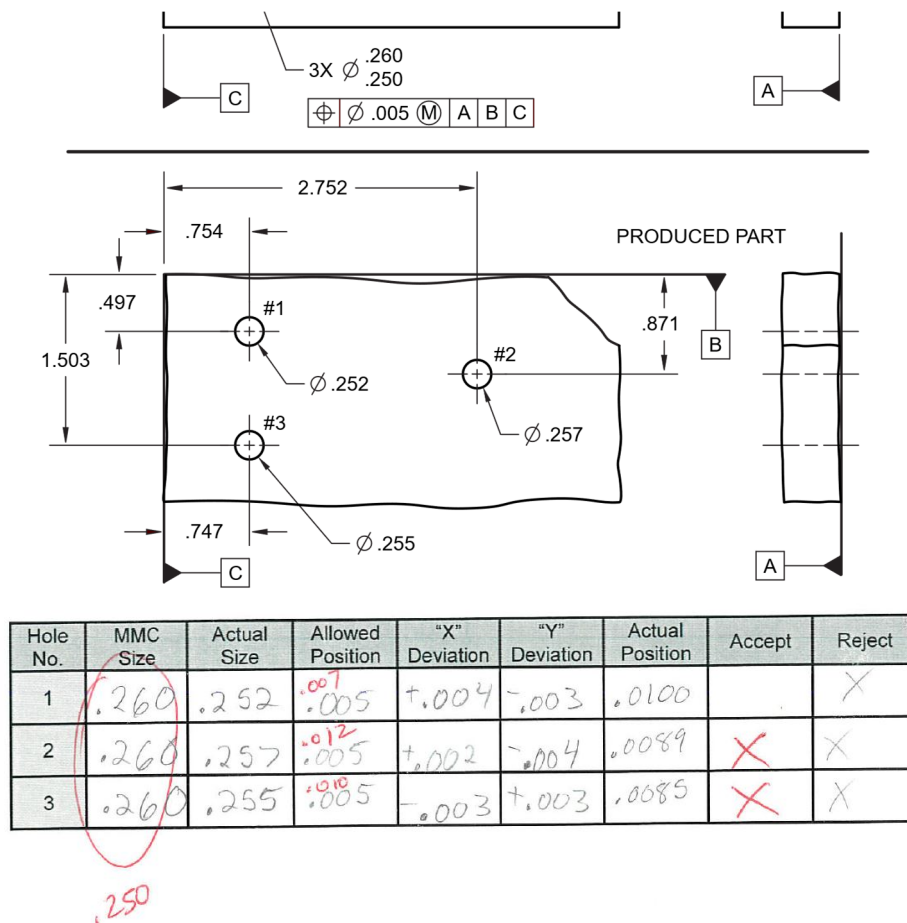


Fig. 11. Example of incorrect MMC.

The number of students who calculated the allowed position correctly increased from the first test to the exam. The difference was not significant. Those who had incorrect values may have identified the wrong MMC or made calculation errors like the example shown in Fig. 12. The allowed position should have been determined by subtracting the MMC (.250) from the actual hole size (.252 for hole #1) and then adding the position tolerance (.005). $(.252 - .250) + .005 =$

.007. What is interesting in this example is the student's calculations on the right side of the problem indicate the correct allowed position values for actual hole sizes.

Correct values for the actual position tolerance also increased from test 1 to the exam, but the difference was not significant. On all assessments, students were given a table to help them determine the actual position from the X & Y deviations. The table displayed results based on the formula:

$$\text{Actual position} = 2\sqrt{x^2 + y^2}$$

Incorrect responses were the result of not reading the correct X & Y deviations or the result of misreading the provided table for determining the actual position. The example in Fig. 12 shows the Y deviation for hole #2 should have been .004 (.875 - .871), and the X deviation for hole #3 should have been .003 (.750 - .747). These mistakes caused the actual position calculation to be incorrect.

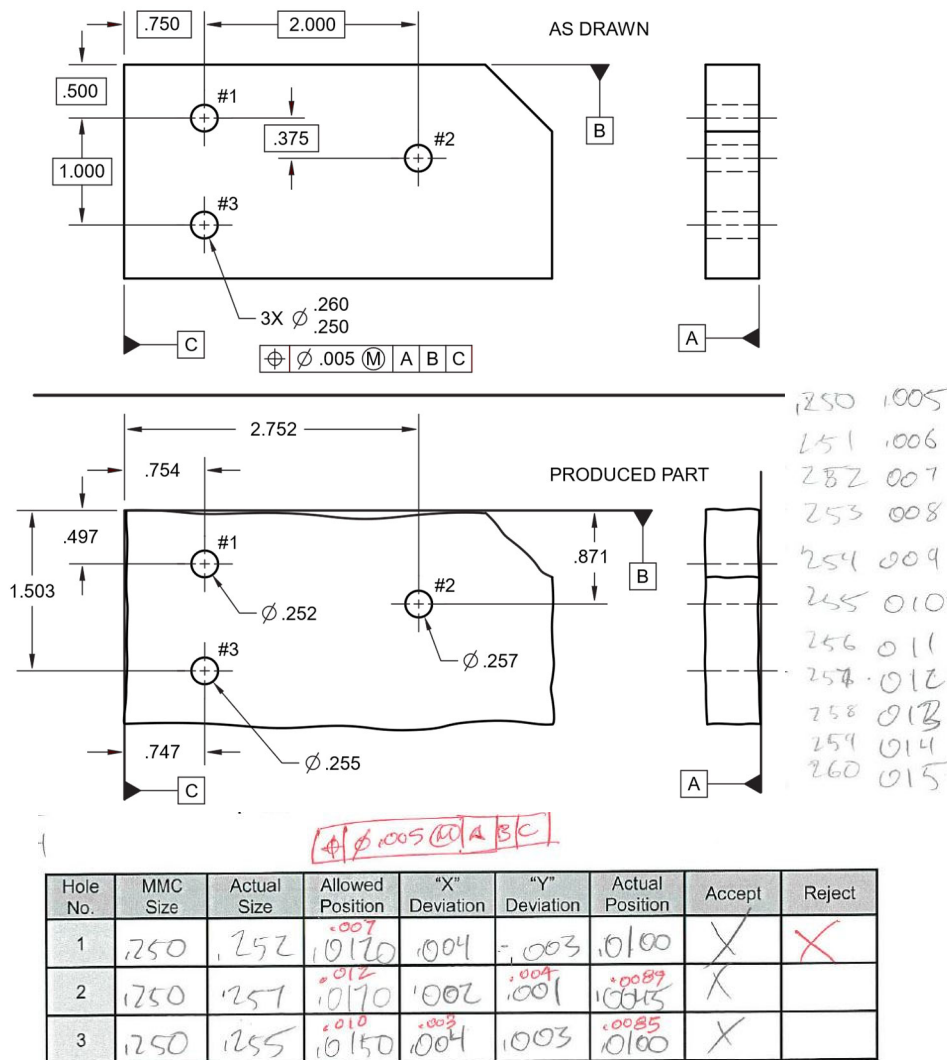


Fig. 12. Example of incorrect allowed position and actual position.

The number of students making the correct decision (accept/reject) also increased but not significantly. In most cases the incorrect decision was the result of miscalculations earlier in the table. In a small number of cases, students calculated everything correctly but just flipped the decision. Fig. 13 displays an example of this scenario. For hole #1, the actual position is larger than the allowed position. This hole should have been rejected. Holes #2 & #3 have actual positions smaller than the allowed positions, so they should have been accepted.

Hole No.	MMC Size	Actual Size	Allowed Position	"X" Deviation	"Y" Deviation	Actual Position	Accept	Reject
1	.250	.252	.007	.004	.003	.0100	(X)	X
2	.250	.257	.012	.002	.004	.0089	X	(X)
3	.250	.255	.010	.003	.003	.0085	X	(X)

Fig. 13. Example of incorrect decision.

Another observation was that the percentage of correct responses for measured variables tended to be lower, in general, in the 2020, 2021, and 2022 semesters than in previous semesters. The Fall 2020 semester was taught in a hybrid format due to the COVID-19 pandemic, and absences during that semester and the Fall 2021 semester were the highest since the course was offered (Fig. 14). Although concentrated efforts have been made over the last three years to provide more resources and one-on-one help with all assessments and assignments, students still seem to be struggling more recently than before the pandemic.

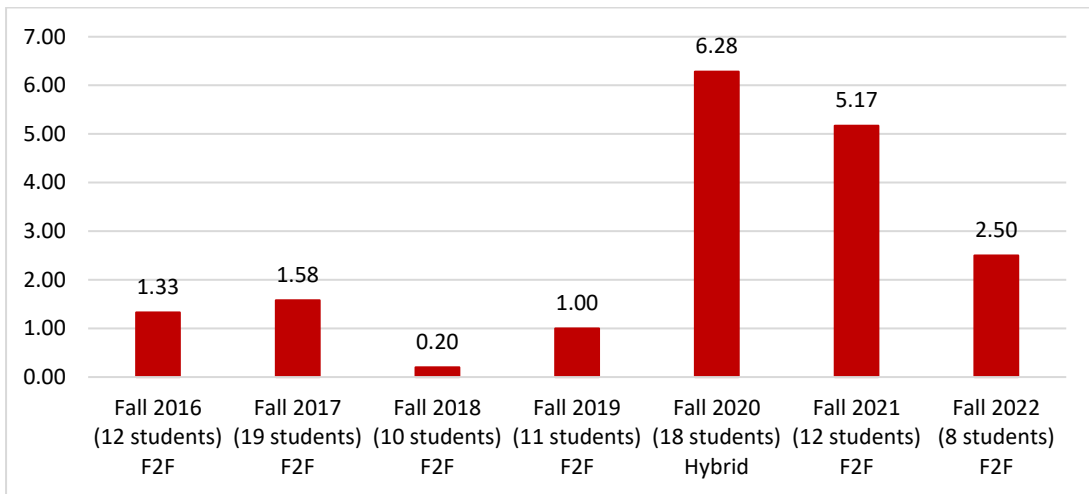


Fig. 14. Average absences per student by semester.

For future semesters, the plan is to introduce more examples of determining MMC as well as doing more in class examples of position verification. The mathematical calculations for these types of assignments are not difficult, but the decision-making concepts appear to give some students difficulty.

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