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Implement and Integrate Flipped Metrology Laboratory in Manufacturing Education

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IMPLEMENT AND INTEGRATE FLIPPED METROLOGY LABORATORY IN MANUFACTURING EDUCATION

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Abstract

Traditional manufacturing classes cover engineering materials and manufacturing processes. Upon familiar with basic hand tools like calipers, micrometers, or indicators in laboratory exercises, students would understand metrology as dimension with tolerance and miss other important aspects of metrology such as shape, surface finish, and how the part shape would affect dimensional tolerances. The limited metrology knowledge would later show in capstone projects for undergraduate students and research projects for graduate students when designing and fabricating their engineering components. The issues follow when students joining manufacturing workforce in industry or research institution upon graduation.

With approval from External Advisory Committee and support from industry, the Engineering Technology & Industrial Distribution department at Texas A&M University established a well-equipped metrology laboratory and integrated laboratory exercises with manufacturing curricula. Students in lower-level classes learn theory and have hands-on practice with both contact-type measuring devices and noncontact-type measuring systems before attending other manufacturing laboratory sessions. The upper-level class covers theory of Geometric Dimensioning & Tolerancing (GD&T) and introduces flipped-laboratory practice on this topic. Upon presented several metrology problems, students work in a small group to select suitable instrument, fixture for a problem. A group then takes turn to present the procedure, solution, and measured results to other groups. Preliminary test results show improvement of student understanding of GD&T after flipped-laboratory approach is implemented.

Keywords: Metrology, Flipped-laboratory, Manufacturing, Engineering and Technology Education, Geometric Dimensioning & Tolerancing.

I. Introduction

The traditional "plus/minus" tolerance does not include the function and geometry of a component, leave an opening and ambiguous measuring procedure; therefore, more parts are scrapped and affect product cost and delivery time. Applying Geometric Dimensioning and Tolerancing (GD&T) in design and manufacturing helps to minimize the above issues by improving manufacturing output, productivity, cross-departmental communication, part assembly, part interchangeability while reducing cost and shortening schedule time [1],[2]. Although industry have been implementing GD&T for decades, lack of comprehensive educations in undergraduate engineering/technology curricula make the transition of graduated engineers to industry a difficult period. It was suggested that GD&T should be taught for 60 hours during two quarters or during one whole semester [3]. Literature survey indicates only few institutions in the USA have engaged students with GD&T activities in undergraduate programs while some programs even eliminate technical drawing classes. It is agreed by many educators that teaching GD&T concepts should be complementary with hands-on practices. Waldorf and Georgeou [4] integrated GD&T concepts to eight different courses in mechanical and manufacturing curricula. Such approach, they concluded, has increased student knowledge and efficacy when working on documentation, mechanical design, fixture design, design for assembly, design for manufacture, fabrication, and inspection. Yip-Hoi and Gill [5] also combined the GD&T concepts in model-base definition CAD model in the junior-level course Design for Manufacture with the senior-level course Design of Tooling. Rios [6] implemented both 3D-printed parts and functional gages to illustrate the effects of maximum material condition or least material condition in GD&T; Fuehne [7] simulated industrial environment when maintaining the metrology laboratory at 20 ± 0.5 °C and < 50% humidity. The instructor requested students to build solid models using a CAD software, 3D-print the parts, and then complete with GD&T measurement before writing an inspection report. Hewerdine et al. [8] combined a visual method and hands-on activities to teach GD&T. By printing a defective component for inspection in different ways, the effect of datum selections can be seen when mapping measured data points on to the model. Although 3D-printed components had been used by many educators to teach GD&T concepts, the applying of GD&T to parts fabricated by additively manufacturing route is still being developed [9], [10].

Most traditional GD&T classes are commonly taught by having an instructor illustrating different measuring procedures to student. This paper presents a "flipped laboratory" practice by having students presenting and explaining the measuring procedure to fellow classmates under supervision of an instructor.

II. Approach and Activities

Metrology is implemented to sophomore and junior level courses. Students from the former group learn basic metrology measuring techniques before practicing different manufacturing processes. Students from the latter group learn GD&T in class and practice flipped sessions in their labs. Both groups gain hands-on experiences when using both manual devices and computer-aided metrology systems. The following section describes current laboratory sessions for the junior-level class.

II.1. Measurement with basic tools

The metrology lab is equipped with two large granite blocks that are leveled on respective stands for manual measurement. Each 2-hour lab session typically has 12-15 students. A teaching assistant (TA) first introduces each metrology device (e.g., dial indicator, heigh gage), fixture (e.g., V-block, angle plate), and tool (e.g., indicator) as seen in Figs. 1a-l. The TA illustrates calibration steps and proper usage of each tool. Upon assigned the specific and different tasks, students are divided into smaller teams of 2-3 students to first brainstorm among themselves to come up with suitable measuring procedure given available devices and fixtures; they then proceed with measurement basic GD&T features on provided samples (Figs. 2a-e). Each group is free to choose combination of contact-type metrology device, tool, and fixture for their group. During this stage, the TA only helps to clarify the part requirement and usage of metrology device without showing the solutions.

After 30-45 minutes, each team takes turn presenting to their classmates how they set up and measure a feature, showing the measured data, and concluding if the part is accepted or rejected. The TA then comments on the approach, selection of tooling and fixture, and may suggests alternative ways to constrain datum(s). Common mistakes are observed when teams use the same procedure to measure parallelism and flatness.

The TA then demonstrates the use of laser displacement sensor (Fig. 1-l). He/she compares the measured data using this non-contact technique against the data from a student team using contact-device such as dial indicator. Both advantages and disadvantages for each technique are discussed among all teams. When time permits, students may use the laser system for their objects and compare the new measurement data against their previous data.

a) Height gage

b) Height gage with dial indicator

c) Indicator with flat base

d) Dial indicator with magnetic base

e) T-bubble level

f) Bulls-eye surface level

g) Adjustable leveling plate

h) V-blocks

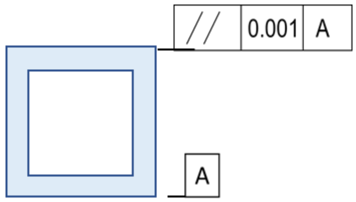
i) Precision angle plate

j) Adjustable V-block

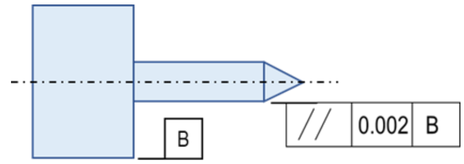
k) Torpedo level

l) Keyence laser displacement sensor

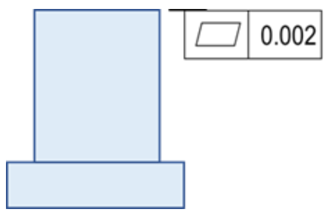
Figure 1. Metrology devices, tools and fixtures.



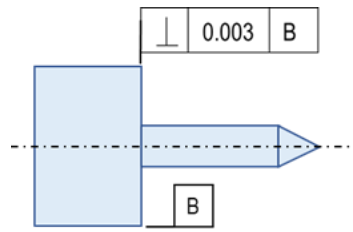
a) Measuring parallelism of surfaces



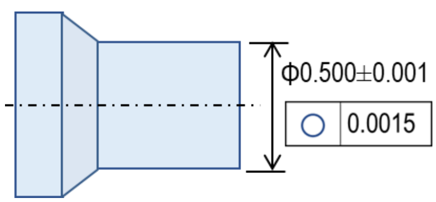
b) Measuring parallelism of lines



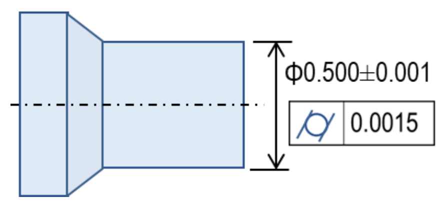
c) Measuring flatness



d) Measuring perpendicularity



e) Measuring roundness



f) Measuring cylindricity

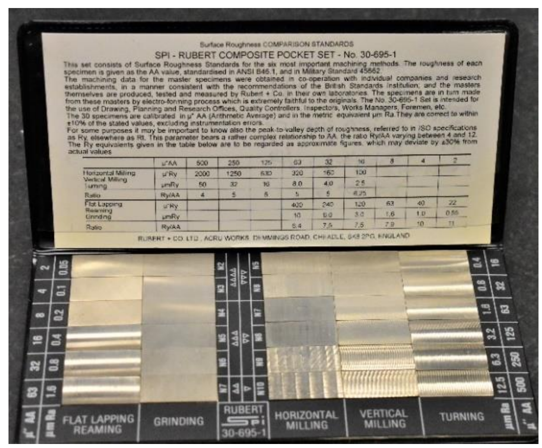
Figure 2. Objects with basic GD&T requirements. Unit: inches

II.2. Surface measurement

Specific surface finish of a components may be critical for proper functionality. Optical components or mating surfaces of moving hip implants are examples of components with strict surface finish control.

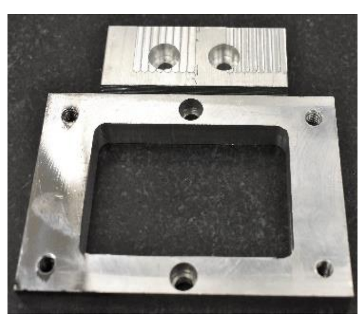
Surface finish measurement and measurement techniques are the objectives of this lab exercise. A TA introduces three measuring tools: a surface comparator set, contact-type profilometer, and non-contact type infinite focus 3D scanner. For each case, the TA show the calibration steps, proper usage of an equipment and how to avoid damages to a dedicate instrument. Approaching angle and contact pressure of a probe are controlled by mounting the profilometer on a height gage (Fig. 3a). Care must be exercise when moving the objective lens toward an object for surface scanning on the optical system (Fig. 3c). Students then work in a small team to estimate /measure the surface finish of different machined slots from a group of samples. The slots on sample #1 (Fig. 3d) were milled at different speeds /feeds using a Ø5mm milling tool, while those on sample #2 (Fig. 3e) were machined with a Ø0.4mm micromilling tool. Three different measurements are made for each slot. Both the line-average *Ra*, surface-average *Sa* measurement and variations of three measurements are reported. Each team then presents the setup, measuring steps, and resulted data to other classmates. Students should realize the limitation of contact-type profilometer when trying to measure surface finish of a small slots, limited data for line scanning, and possibility of damaging a measured sample when using a spring-loaded scanning probe. Such deficiency of the contact-technique is overcome with the non-contact optical technique. An example of scanned microchannel and surface analysis is shown in Fig. 4. The TA would facilitate group discussion to address different criteria including cost, user friendliness, effect of scanning direction when measuring the line-average *Ra*, repeatability, accuracy and limitations of each instrument. If time is permitted, the TA can illustrate advanced topics such as the different surface finish (e.g., *Rz, Rt*), filtering options for waviness…

a) Height gage and adaptor for profilometer

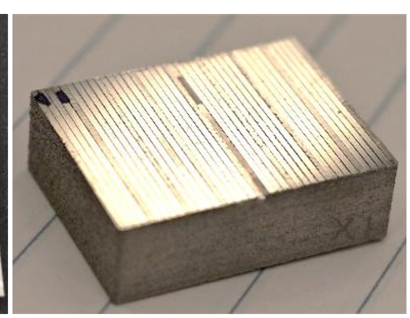


b) Surface comparator

c) Alicona G4 infinite focus 3D optical system

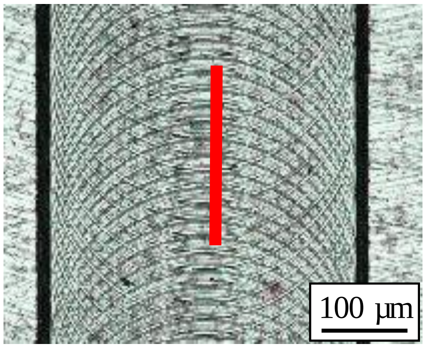


d) Sample #1 with 5mm milled channels for surface measurement

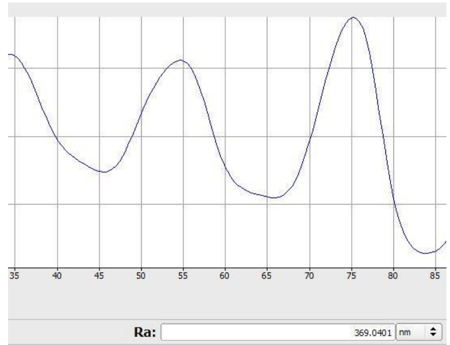


e) Sample #2 with 0.4mm micromilled channels for surface measurement

Figure 3. Surface characterizing devices and testing samples.



a) Line sectioning on micromill slot



b) Sectioned profile and resulted surface finish

Fig.4. Example of scanned and sectional profile of a micromilled channel using the Alicona.

A new white-light interferometer Zygo system is recently added to our metrology lab. Future atomic force microscope will be procured for small surfaces. The students then can experience different non-contact techniques for surface finish assessment.

II.3. Measurement with advanced metrology systems

Some complex engineering components require additional GD&T features and large amount of data that would be difficult to obtain with a basic hand tool such as an indicator. For examples, surface profile of a propeller, sphericity on the spherical end of a hip implant, or position measurement of a hole in odd orientation and including effects of modifiers. Such complicate measurement could be best using a metrology system with built-in computational capability. Profile projector, coordinate measuring system with five or more degrees of freedom, automated runout /roundness tester, and vision system are available for these reasons (Fig. 5a-d). Upon receiving an assignment, a small student team will select a machine and request fixtures for their part and assignment.

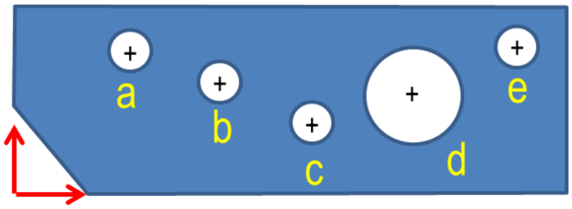
a) Profile projector

b) Coordinate measuring machine

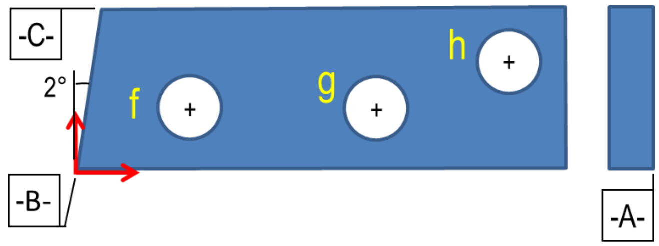
c) Roundness tester

d) Vision system

Fig. 5. Metrology systems for computer-aided inspection.

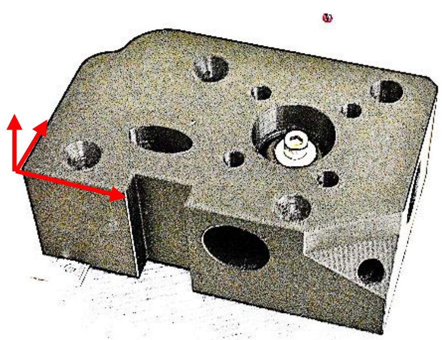


a) 3D-printed sample #3

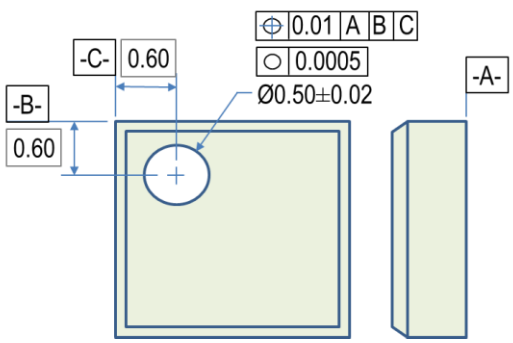


b) 3D-printed sample #4

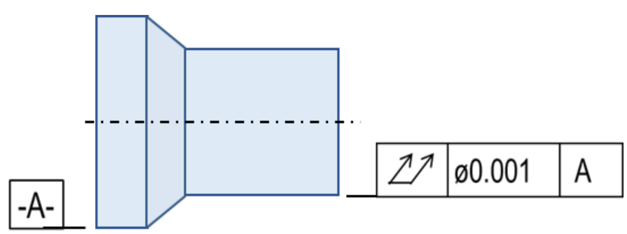
c) Metal sample #5 with different holes (H) and slots (S)



d) 3D-printed sample #6



e) Aluminum sample #7



f) Aluminum sample #8

Fig. 6. Samples for advanced GD&T practice.

Figures 6a-f shows examples for these assignments. The 3D-printed plastic samples #3, #5, and #6 with varying hole positions and hole diameters are for hole center positions and hole size measurement. Combining roundness and position feature is illustrated with the aluminum samples #7. Sample #8 is for measuring one or combination of runout, total runout, roundness, cylindricity, and concentricity. A different team is assigned to study runout measurement (or roundness, cylindricity, concentricity) using sample #8. When using sample #4, students learn the effects of datum order and modifier when center coordinates of a hole are measured following different conditions; students should be able to collect data and see the difference in hole center coordinates when executing different control features (Table 1).

Table 1. Effects of modifier and datum reference

	Sample #4, hole "f, g, or h"	Control feature
(a)	Ø10.00 ± 0.15 mm	⌖ | ø0.20 Ⓜ | A | C | B
(b)	Ø10.00 ± 0.15 mm	⌖ | ø0.20 Ⓜ | A | B | C
(c)	Ø10.00 ± 0.15 mm	⌖ | ø0.20 Ⓛ | A | B | C
(d)	Ø10.00 ± 0.15 mm	⌖ | ø0.20 Ⓢ | A | B | C

The TA only clarifies the objectives and oversees the operation of equipment while letting students free to choose their approach. After completion of an assignment, each student team takes turn presenting their approach and concluding on the measured results. The TA then moderates the discussion and may comment if the student team's approach is not correct and suggest alternative procedure.

Slightly different samples are fabricated for different lab groups. Families of samples #3 and #4 are 3D printed to make samples with different hole positions and diameters. A family of 20 aluminum blocks (sample #7) are machined with slightly different hole positions and hole qualities for this laboratory exercise. The aluminum samples #8 are either machined as a solid part, or mechanically connected for different effects. This way each lab group would work with different samples and collect different measured data for their reports. Due to the complexity of lab assignments, three lab sessions are scheduled so students can rotate and experience with different systems and processes.

II.4. Results

Started in Fall 2021, the flipped lab modules were continuously improved since. Similar quizzes were given in classes to gauge the student comprehension of GD&T concepts and practices. Table 2 lists the average quiz grades from different batches of about 80 students each semester. Virtual lab was implemented during Covid in Spring 2021, and hands-on lab was introduced afterward. The data shows:

- It is difficult to teach the GD&T concept with virtual lab sessions. The Spring 2021 data in Table 2 only shows the average grade of remaining students after about 20% class dropped out.
- Improvement trend of quiz grades when lower dropped out rate, hands-on and flipped lab was introduced after Spring 2021. The dropped out rate for Spring 2023 class is 1.3%. Some data fluctuation is seen due to different TAs, student attitude, and variation of test samples.

Table 2. Quiz grade (50 points maximum)

Quiz	Spring 2021	Fall 2021	Spring 2022	Fall 2022	Spring 2023
GDT-1	26.06	26.67	22.8	25.48	28.11
GDT-2	37.47	36.92	39.23	37.35	42.07

III. Summary

Flipped-laboratory approach is applied to complement learning GD&T to junior-level class. Student team of 2-3 works on an assigned task under uninterrupted supervision of a teaching assistant, the team then presents the procedure and measurement data to their classmates. Hands-on experience with simple and sophisticated metrology systems enhances student knowledge of measuring dimension, form, surface finish, and GD&T requirements. Preliminary results show improvement in test score when the flipped-laboratory approach is implemented.

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