Development of a Hands-On Surface Roughness Characterization Laboratory for Mechanical Engineering Education

Dr. Arash Afshar, Mercer University

Dr. Arash Afshar is currently an associate professor in the School of Engineering at Mercer University. He earned his M.S in systems and design and Ph.D. in solid mechanics from the State University of New York at Stony Brook. He also received his B.S and M.S in Solid Mechanics from Amirkabir University of Technology in Tehran, Iran. His teaching and research interests are in the area of solid mechanics including composite materials, finite element analysis, mechanical design and machine learning. Prior to joining Mercer University, he taught at Saginaw Valley State University and worked as a design engineer in oil and gas and injection molding industries.

Dr. Dorina Marta Mihut, Mercer University

Dr. Dorina Marta Mihut is a Professor in the Mechanical Engineering Department at Mercer University School of Engineering. She graduated with Ph.D. in Materials Science at University of Nebraska-Lincoln; Ph.D. in Technical Physics at Babes-Bolyai University, Romania; M.S. in Mechanical Engineering, University of Nebraska-Lincoln; and B.S. in Mechanical Engineering at Technical University Cluj-Napoca, Romania. Her teaching and research interests are in the area of materials science and engineering, thin films and coatings depositions using physical vapor deposition systems and related analysis, coatings for wear and corrosion resistance improvement, environmental protection, protection against electromagnetic interference, and antibacterial coatings. Before joining Mercer University, Dr. Dorina Mihut worked as Associate Professor at The University of Texas Pan American, TX, USA, and as Process Engineer at Ion Bond, IHI Group, USA.

Education Ph.D Materials Science, University of Nebraska, Lincoln Ph.D Technical Physics, Babes-Balyai University, Cluj-Napoca, Romania M.S. Mechanical Engineering, University of Nebraska, Lincoln B.S. Mechanical Engineering, Technical University of Cluj – Napoca, Romania

Dr. Stephen Hill, Mercer University

Stephen Hill earned his BS in General Sciences from Morehouse College and his BSME, MSME, and Ph.D. from the Georgia Institute of Technology. He is currently the senior associate dean and an associate professor of mechanical engineering at the Mercer University School of Engineering . He worked for the oilfield services giant Schlumberger for 14 years before returning to teach at Mercer University in the fall of 2013 to pursue his goal of educating the next wave of engineers entering the work force. His experience in the work force was in product development of downhole tools related to the extraction of oil and natural gas from various reservoirs. His current research interests include impact erosion, wear, two-phase flow phenomena, and the scholarship of teaching.

Michael Norenberg, Mercer University

Michael James Norenberg is an undergraduate student earning his bachelor's degree in mechanical engineering at Mercer University.

Caleb Luo-Gardner, Mercer University

Development of a Hands-On Surface Roughness Characterization Laboratory for Mechanical Engineering Education

Abstract

Surface condition plays a critical role in the functional performance, durability, and aesthetics of engineering components. Manufacturing processes such as additive manufacturing, molding, machining, and polishing introduce distinct surface topographies that may further evolve under environmental or abrasive exposure. This paper presents the development and implementation of a comprehensive, hands-on laboratory module focused on surface roughness characterization within an undergraduate mechanical engineering curriculum. Students investigate polymeric and metallic materials produced through multiple manufacturing routes, including 3D printing, injection molding, and metallographic preparation. Surface roughness is quantified using stylus-based profilometry with carefully selected traverse lengths, while surface morphology is examined using optical microscopy. Students analyze how manufacturing method, surface condition, and measurement parameters influence roughness metrics such as *Ra* (average roughness), *Rz* (average peak-to-valley height), and *Rmax* (maximum peak-to-valley height). The laboratory is explicitly designed to support ABET Student Outcome 6 by engaging students in experimental design, data analysis, and engineering judgment. Representative results and assessment outcomes are presented to illustrate both the technical rigor and educational value of the laboratory.

1. Introduction

Surface roughness and texture are fundamental characteristics influencing friction, wear, fatigue, corrosion resistance, sealing performance, and the visual appearance of engineering components [1–3]. In industrial practice, surface quality is closely linked to manufacturing processes and post-processing operations, as surface features are directly inherited from tooling, material flow, and material removal mechanisms [4, 5]. Additively manufactured polymer components often exhibit anisotropic and relatively rough surfaces due to layer-by-layer deposition and filament-based material extrusion, whereas molded components can achieve significantly smoother and more isotropic surface finishes [6–9]. Similarly, metallic components commonly undergo grinding and polishing operations to progressively reduce surface roughness, improve dimensional accuracy, and enhance functional performance in applications requiring controlled surface contact [10]. Understanding how manufacturing processes affect surface condition is therefore essential for mechanical engineers involved in design, manufacturing, and quality assurance.

Despite its importance, surface roughness is often introduced to undergraduate students primarily through theoretical discussion or brief demonstrations, with limited opportunity for hands-on measurement and data-driven analysis [11]. As a result, students may learn definitions of roughness parameters without fully understanding how measurement settings, surface anisotropy, and manufacturing history influence reported values. To address this gap, a dedicated laboratory module was developed to provide students with direct experience in surface roughness measurement, interpretation, and comparison across multiple materials and manufacturing processes. This multi-factor experimental design forces students to exercise engineering judgment rather than follow a procedural recipe, directly supporting ABET Student Outcome 6.

2. Laboratory Design and Educational Objectives

The laboratory was designed for a junior- or senior-level mechanical engineering course. It is conducted over multiple sessions and organized around small student teams, typically consisting of three students per group. Each team is provided with an equivalent set of specimens and access to identical measurement equipment to ensure consistency and reproducibility across groups.

The primary educational objectives of the laboratory are to familiarize students with surface roughness parameters, provide hands-on experience with stylus-based surface roughness measurement equipment, demonstrate the influence of manufacturing process and surface condition on surface quality, illustrate the importance of measurement parameter selection, and develop skills in experimental data analysis, visualization, and technical reporting. Students document procedures, organize data into tables and figures, interpret trends, and discuss sources of variability and uncertainty.

3. Materials and Methods

3.1 Polymer Specimens: Materials and Sample Preparation

Polymeric materials examined in this laboratory included 3D-printed ABS, molded ABS, 3D-printed PETG, and molded PETG. All samples had nominal dimensions of 3.2 mm thickness × 12.5 mm width × 127 mm length**.** The 3D-printed ABS and PETG specimens were fabricated using raster angles of ±45°.

For additively manufactured specimens, profilometry measurements were performed on the final printed layer rather than the build-plate surface, as the printing-induced surface features were more pronounced on this side. Molded polymer samples were measured on the smooth mold face to minimize the influence of mold surface texture on the measured roughness.

3.2 Metallic Specimens: Surface Preparation and Polishing

AISI 4140 steel samples (6.35 mm × 6.35 mm) were embedded in Bakelite mounting pucks and prepared using standard metallographic preparation techniques. Mounting was performed using black Bakelite powder in a LECO PR-25 mounting press under elevated temperature and pressure to ensure secure encapsulation and edge retention. Following mounting, the steel–Bakelite pucks were ground sequentially using silicon carbide abrasive papers with progressively finer grit sizes (120, 240, 320, 400, and 600 grit) on LECO BG-30 and DS-20 grinding systems. Between each grinding step, the samples were rotated by 90° to promote uniform material removal and to ensure complete elimination of scratches from the previous grit.

Final surface finishing was achieved through polishing using diamond paste with particle sizes of 6 µm and 1 µm on a LECO SS-200 polishing system. After each preparation step, the samples were thoroughly cleaned with 99% isopropyl alcohol to remove residual abrasive particles and debris prior to surface roughness measurement. This preparation procedure produced progressively smoother and more uniform metallic surfaces, enabling validation of the polishing process.

3.3 Surface Microscopy

Students performed surface microscopy on both polymeric and metallic samples using a Keyence VHX-X1 series digital microscope to visually examine surface features such as ridges, valleys, and polishing marks. This qualitative observation helps students better relate surface morphology to the roughness parameters measured later using stylus-based profilometry. Figure 1 presents representative digital surface microscopy images of selected samples, illustrating the distinct surface characteristics produced by different manufacturing processes and surface preparation conditions.

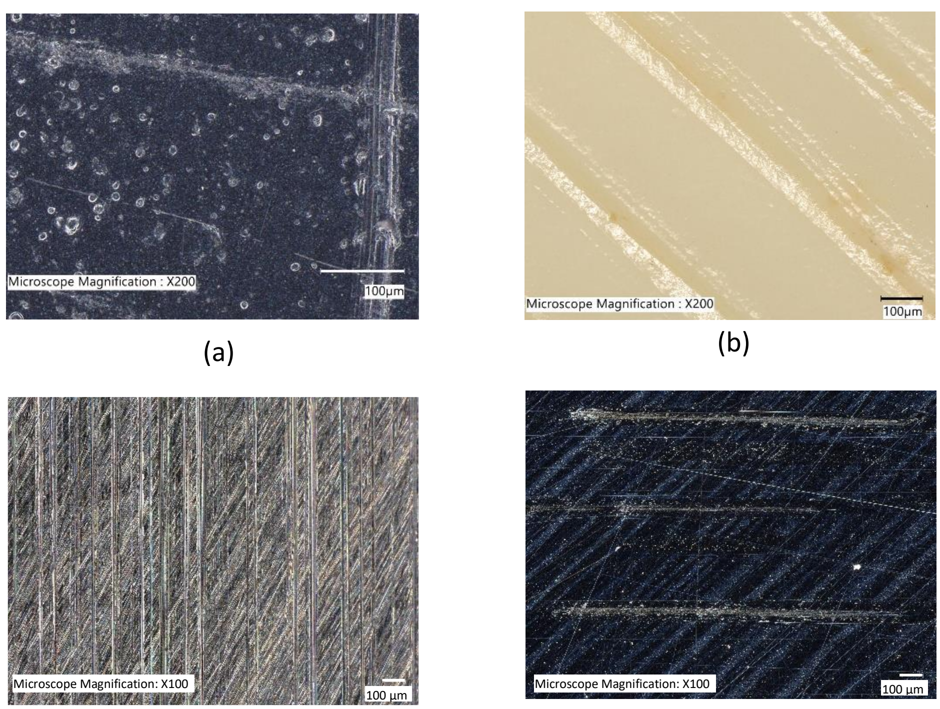

Figure 1. Representative digital surface microscopy images of (a) molded ABS, (b) 3D-printed ABS, and metallic samples after (c) 120-grit grinding and (d) 1 µm diamond polishing.

3.4 Surface Roughness Measurement

Surface roughness measurements were conducted using a Phase II SRG-4600 stylus-based surface roughness tester equipped with a 5 µm diamond stylus (SRG4600-100) and configured in accordance with ANSI surface roughness standards using an RC filter. The experimental setup for the roughness measurements is shown in Figure 2. Traverse lengths followed standard profilometry convention, in which the total traverse length equals the cutoff (sampling) length multiplied by the number of sampling lengths.

Figure 2. Experimental setup for stylus-based surface roughness measurements.

Two traverse lengths were employed. A 0.25 × 5 mm traverse length (total evaluation length of 1.25 mm) was used for metallic samples, where the available scan length was limited, while a 2.5 × 5 mm traverse length (total evaluation length of 12.5 mm) was used for measurements along the specimen length for molded and 3D-printed polymer samples. For each surface condition, three measurements were collected, and the results are reported as the mean ± standard deviation.

4. Laboratory Results and Analysis

Table 1 summarizes the representative surface roughness results for polymeric and metallic specimens produced using different manufacturing processes. Students compared molded, additively manufactured, and polished surfaces and justified observed trends using multiple roughness parameters rather than relying on a single metric.

As an example, *Ra*, defined as the arithmetic average of the absolute height deviations of all measured points along the surface profile from the mean line over the evaluation length, shows that additively manufactured polymer specimens exhibit substantially higher average roughness than molded specimens. Molded PETG surfaces display submicron *Ra* values, while 3D-printed polymers exhibit Ra values on the order of tens of micrometers, reflecting the layer-by-layer deposition process.

To further justify these differences, students examine *Rz* and *Rmax*, which capture peak-to-valley behavior that is not reflected by *Ra* alone. In accordance with ANSI surface roughness standards, *Rz* was calculated as the average peak-to-valley height over five sampling lengths for each profilometry scan, while *Rmax* represents the single largest peak-to-valley distance within the evaluation length. Higher *Rz* and *Rmax* values for 3D-printed specimens indicate pronounced ridges and valleys between adjacent filaments, whereas the much lower values observed for molded samples confirm the absence of large surface asperities.

Table 1. Representative surface roughness data for polymeric and metallic specimens (mean ± standard deviation). *Ra* is the arithmetic average roughness, *Rq* is the root-mean-square roughness, *Rz* is the average peak-to-valley height over five sampling lengths, *Rmax* is the maximum peak-to-valley height within the evaluation length, *Rt* is the total height of the roughness profile, and *RSm* is the mean spacing of surface profile elements.

Material	Type	*Ra* (µm)	*Rq* (µm)	*Rz* (µm)	*Rmax* (µm)	*Rt* (µm)	*RSm* (mm)
ABS	Molded	0.264 ± 0.029	0.365 ± 0.039	1.31 ± 0.10	2.37 ± 0.72	2.37 ± 0.72	0.073 ± 0.031
ABS	3D Printed	5.04 ± 0.26	5.70 ± 0.36	8.64 ± 1.88	20.75 ± 5.29	20.75 ± 5.29	0.347 ± 0.064
PETG	Molded	0.0047 ± 0.0021	0.017 ± 0.0035	0.08 ± 0.00	0.16 ± 0.08	0.16 ± 0.08	0.83 ± 0.72
PETG	3D Printed	18.57 ± 2.13	22.22 ± 1.56	23.04 ± 2.29	90.43 ± 2.46	90.43 ± 2.46	0.453 ± 0.163
AISI 4140 Steel	120 grit	0.661 ± 0.016	0.844 ± 0.032	2.54 ± 0.43	5.84 ± 0.49	5.84 ± 0.49	0.050 ± 0.010
AISI 4140 Steel	240 grit	0.50 ± 0.10	0.70 ± 0.15	3.00 ± 0.50	6.00 ± 1.00	6.00 ± 1.00	0.050 ± 0.015
AISI 4140 Steel	320 grit	0.149 ± 0.026	0.204 ± 0.025	0.99 ± 0.02	1.49 ± 0.05	1.49 ± 0.05	0.023 ± 0.021
AISI 4140 Steel	400 grit	0.20 ± 0.05	0.30 ± 0.06	1.20 ± 0.20	2.50 ± 0.50	2.50 ± 0.50	0.030 ± 0.010
AISI 4140 Steel	600 grit	0.034 ± 0.015	0.063 ± 0.020	0.28 ± 0.07	0.80 ± 0.16	0.80 ± 0.16	0.067 ± 0.015
AISI 4140 Steel	6 µm diamond	0.045 ± 0.005	0.055 ± 0.006	0.18 ± 0.03	0.45 ± 0.05	0.45 ± 0.05	0.020 ± 0.000
AISI 4140 Steel	1 µm diamond	0.071 ± 0.029	0.085 ± 0.024	0.16 ± 0.04	0.21 ± 0.05	0.21 ± 0.05	0.000 ± 0.000

As part of the laboratory requirements, students construct graphs illustrating the evolution of surface roughness parameters during successive metallographic preparation steps, enabling visualization of roughness trends and reinforcing data interpretation skills. An example of such a graph is shown in Figure 3. The plot demonstrates an overall reduction in surface roughness with increasing surface refinement, with *Rmax* exhibiting the greatest sensitivity to coarse grinding, while *Ra* and *Rz* show comparatively smaller changes and tend to stabilize during fine polishing.

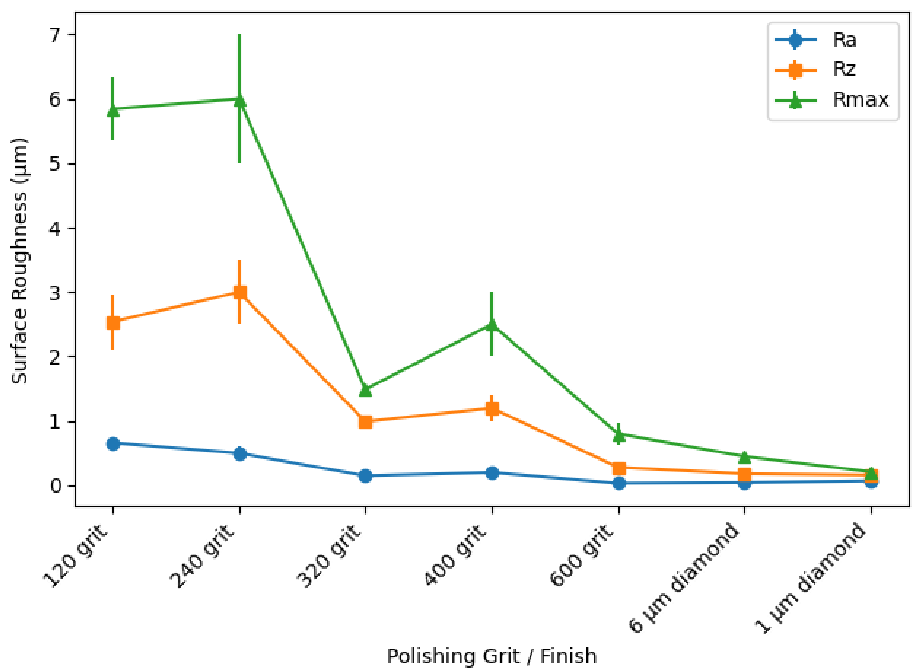

Figure 3. Evolution of surface roughness parameters (*Ra*, *Rz*, and *Rmax*) for AISI 4140 steel as a function of polishing grit and diamond finish. Error bars represent standard deviation from repeated measurements.

5. Assessment and Educational Impact

Student learning was assessed through graded laboratory reports, data interpretation exercises, and targeted discussion questions aligned with ABET Student Outcome 6. Assessment focused on students' ability to correctly select and interpret multiple surface roughness parameters, justify observed trends using quantitative data, and relate measured surface characteristics to manufacturing processes and surface preparation methods.

Analysis of student submissions indicated improved proficiency in distinguishing between average roughness and peak-to-valley metrics, particularly when comparing additively manufactured and molded polymer surfaces as well as metallic samples subjected to progressive grinding and polishing. Students demonstrated the ability to explain why reliance on a single roughness parameter can lead to incomplete conclusions, for example recognizing that two surfaces with similar *Ra* values can exhibit markedly different *Rz* or *Rmax* values due to isolated peaks and valleys. When evaluating polished specimens, students correctly identified systematic reductions in surface roughness with increasing surface refinement. They also demonstrated increased confidence in interpreting measurement variability through the use of repeated scans and reported standard deviations.

Student learning gains related to ABET Student Outcome 6 were evaluated using pre- and post-laboratory concept assessments, as summarized in Table 2. Pre-lab scores reflect students' self-reported conceptual understanding informed by prior coursework and brief independent background research conducted before the laboratory. Post-lab scores reflect self-reported understanding after completion of the laboratory.

Table 2. Self-reported pre- and post-laboratory conceptual understanding of surface roughness concepts using a 0–100% scale

Concept	Pre-lab (%)	Post-lab (%)
Distinguish between different roughness parameters	32	71
Select the most relevant surface roughness parameters	28	50
Recognize anisotropy in 3D-printed surfaces	77	94
Interpret how grinding and polishing affect surface roughness	79	93
Select appropriate scan length	27	72

Based on Table 2, the laboratory produced clear learning gains across all assessed concepts, with notable improvements in students' understanding and application of surface roughness parameters. Post-lab results show increased ability to select, interpret, and differentiate roughness metrics, reflecting the impact of hands-on measurement and data analysis. Students also demonstrated strong gains in recognizing anisotropy in 3D-printed surfaces, interpreting the effects of grinding and polishing, and selecting appropriate scan lengths. While the results are based on self-reported measures, these outcomes indicate that the laboratory effectively strengthened both conceptual understanding and practical data interpretation skills, while also suggesting that additional theoretical background on roughness parameters could further enhance student preparedness.

6. Transferability and instructional value

The laboratory is designed to be low cost and portable, requiring only a basic stylus profilometer, an optical microscope, and standard polymer and metal specimens. A portable stylus profilometer suitable for instructional laboratories (e.g., Phase II SRG-4600) typically costs approximately $1,700–$2,500, while consumable materials such as polymer specimens, abrasive papers, polishing compounds, and cleaning supplies typically cost approximately $15–$30 per laboratory group.

The experiment can be readily implemented in materials, manufacturing, or tribology courses. Instructors can directly adopt the multi-parameter, multi-direction measurement framework to transform a routine surface roughness exercise into a true experimental design experience that emphasizes data interpretation and engineering judgment. The same experimental setup can also support future instructional modules with minimal additional equipment. For example, students could investigate surface roughness evolution after environmental exposure, abrasive wear, or changes in additive manufacturing parameters, enabling expansion of the laboratory while utilizing the same instrumentation.

7. Conclusions

A comprehensive hands-on surface roughness laboratory was developed within an undergraduate mechanical engineering curriculum. By integrating polymeric and metallic materials, multiple manufacturing processes, and careful selection of measurement parameters, the laboratory provides students with a realistic and rigorous introduction to surface engineering concepts. The module strengthens experimental skills, reinforces theoretical understanding, and promotes critical thinking related to surface characterization. Future expansions of the laboratory may incorporate additional experiments that connect surface roughness evolution with real-world service conditions.

8. References

1. Bhushan, B. (2013). *Introduction to tribology* (2nd ed.). John Wiley & Sons.

2. Nadeem, H., Ghazali, N., Nabeel, M., Ahsan, M., & Khurram, A. (2023). Experimental assessment of surface roughness of fused deposition modelling parts and method of improvement. *Journal of Thermoplastic Composite Materials, 37*(3), 1187–1201. https://doi.org/10.1177/08927057231193378

3. Groover, M. P. (2016). *Fundamentals of modern manufacturing: Materials, processes, and systems* (6th ed.). John Wiley & Sons.

4. Kalpakjian, S., & Schmid, S. R. (2008). *Manufacturing processes for engineering materials* (5th ed.). Pearson Education.

5. Leach, R. K. (2013). *Characterisation of areal surface texture*. Springer. https://doi.org/10.1007/978-3-642-36458-7

6. Stout, K. J., & Blunt, L. (2000). *Three-dimensional surface topography* (Ultra Precision Technology Series). Penton Press.

7. Townsend, A., Senin, N., Blunt, L., Leach, R. K., & Taylor, J. S. (2016). Surface texture metrology for metal additive manufacturing: A review. *Precision Engineering, 46*, 34–47. https://doi.org/10.1016/j.precisioneng.2016.06.001

8. Whitehouse, D. J. (2011). *Handbook of surface and nanometrology* (2nd ed.). CRC Press.

9. Afshar, A., Mihut, D., Hill, S., Patrick, A., Rehg, Z., Norenberg, M., Luo-Gardner, C., & White, R. (2025). Mechanical and tribological performance of molded and 3D-printed polymers under environmental degradation. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*. https://doi.org/10.1177/14644207261420320

10. Marinescu, I. D., Hitchiner, M. P., Uhlmann, E., Rowe, W. B., & Inasaki, I. (2016). *Handbook of machining with grinding wheels* (2nd ed.). CRC Press. https://doi.org/10.1201/b19462

11. Prince, M. (2004). Does active learning work? A review of the research. *Journal of Engineering Education, 93*(3), 223–231. https://doi.org/10.1002/j.2168-9830.2004.tb00809.x