2023 Annual Conference & Exposition
Baltimore Convention Center, MD | June 25 - 28, 2023
The Harbor of Engineering Education for 130 Years
ASEE
Paper ID #37058

Revealing the Bulk Mechanical Property Threshold for Thin Metallic Samples to Support a Desktop-Scale Stress-Strain Apparatus

Miss Sofia Ahmed, University of Florida

Sofia Ahmed is an Undergraduate Aerospace Engineering student at the University of Florida. Her research focuses on experimental mechanics and she has other research interests in aerospace structures and materials. She also has academic interests in high powered rocketry through leading in University of Florida's rocket design team.

Dr. Matthew J. Traum,

Dr. Matthew J. Traum is a Senior Lecturer and Associate Instructional Professor in the Department of Mechanical and Aerospace Engineering at the University of Florida. He is an experienced educator, administrator, fund raiser, and researcher. As of 2022 he has co-authored a textbook, a book chapter, 20 peer-reviewed research and pedagogical journal papers, 53 refereed research and pedagogical conference articles, and given 4 invited presentations. As PI or Co-PI, Traum has attracted over $898 K in funding for research and education. Prior to UF, Dr. Traum was founding CEO of Engineer Inc., an education technology social enterprise and leader in STEM instructional lab kits.

Previously, Dr. Traum was an Associate Professor and Director of Engineering Programs at Philadelphia University. He also served on the Milwaukee School of Engineering (MSOE) faculty as well as co-founding the Mechanical and Energy Engineering Department at the University of North Texas – Denton.

Traum received Ph.D. and M.S. degrees in mechanical engineering from MIT, and he holds two B.S. from the UC Irvine in mechanical and aerospace engineering.

Revealing the Bulk Mechanical Property Threshold for Thin Metallic Samples to Support a Desktop-Scale Stress-Strain Apparatus

Abstract
Hands-on learning is vital in the mechanical engineering curriculum. Availability of inexpensive, accessible, and turnkey lab equipment for students' educational use has received growing attention. For Mechanics of Materials education, stress-strain measurement apparatuses are typically large, expensive machines that students have difficulty operating, let alone accessing. Can a smaller, more cost-effective tensile tester be produced? PASCO's AP-8214A was a product that replicated a stress-strain apparatus. However, it failed commercially because the limited force it generated required very thin samples to be used. The literature reveals that metals exhibit mechanical properties different from accepted bulk values below certain thickness thresholds. AP-8214A samples were too thin and gave erroneous results. Determining this threshold thickness is an important parameter in developing tabletop stress-strain testers. This threshold was studied by testing aluminum dog-bone models of differing thicknesses (0.032in, 0.0625in, and 0.125in) on an Instron 5967 Universal Testing Machine. The dog-bones were cut from a waterjet and then speckled, enabling Vic2D software to accurately detect the sample's stretching by visually tracking the displacement of speckles. Variation of resulting measured mechanical properties with sample thickness was then tallied to determine the thickness threshold where bulk material properties emerge.

This paper outlines a process to determine what stress-stain tensile testing sample thicknesses is needed to reveal bulk properties for three common engineering metals. These thicknesses in turn are used to calculate a key benchtop stress-strain tensile tester design parameter: the force it must produce. This study is implemented using waterjet-cut specimens of identical shape but increasing thickness tensile tested to failure on an Instron 5967 Universal Testing Machine.

Keywords
Remote Lab, Online Student, Universal Mechanical Testing Kit, FreeLoader, Stress-Strain

Introduction
Study of material properties is important for engineering courses including Mechanics of Materials, Manufacturing, and Design. Hands-on learning is vital for engineering students to thoroughly understand material properties, their impact on physical behaviors, and practical applications leading to design principles. Mechanics of Materials is often taught as a laboratory course featuring research-scale tensile testers to extract empirical stress-strain curves from material samples upon which the remainder of the course content is built. The global pandemic forced engineering students online, challenging materials laboratory instructors to adapt instructional delivery to remote learners.

There currently exist no ABET-accredited undergraduate mechanical engineering programs taught fully online.[i] Moreover, while many other college disciplines have extensive histories of successful remote and online instruction, the engineering education community has limited experience teaching lab classes online. Affordable, small, and easily mailed experimental educational lab kits have emerged as a key advancement in hands-on undergraduate engineering instruction.[ii],[iii] A small, inexpensive, and safe benchtop stress-strain apparatus would enable remote learners to generate their own empirical stress-strain curves remotely from home. This capability, in-turn, enables mechanics of materials lab courses to be taught remotely and online.

This paper's goal is to measure using a conventional stress-stain tensile tester at what sample thicknesses bulk material properties emerge in samples of Aluminum 3003, a common engineering metal. This empirical result is needed to determine how tensile properties are affected by part thickness and to reveal the point at which results in agreement with tabulated bulk material values can be reproduced with a benchtop stress-strain tensile tester. This information then sets the key benchtop tester design parameter: the force it must produce. Conventional tensile testing machines are available in a range from 0.02 N to 2,000 kN. However, to keep cost low for a mechanics of materials instructional laboratory kit, it is desirable to target the lowest possible force that would be useful in an educational lab setting on a benchtop machine.

Background

Current laboratory-scale stress-strain tensile testing machines are large and expensive, typically requiring institutional capital expenditure to acquire. As such, they are not easily accessible for remote learners, making tensile testing difficult to perform by students taking engineering classes online. To be accessible and useful for engineering student learning, a benchtop replacement for brick-and-mortar tensile testers must be 1) less than $250, 2) able to measure properties consistent with tabulated for bulk materials, and 3) safe to use.

The $250 price point is set to be consistent with what students usually pay for laboratory fees and textbooks in engineering courses. The emergence of Open Educational Resource (OER) engineering textbooks, which are free to use, enable instructors to shift students' cost burden from textbooks to hands-on learning hardware, giving students a superior learning experience at cost equal to or less than the current financial model predicated on expensive copyrighted texts.[iv] In other mechanical engineering disciplines use of OER texts in combination with educational kits have increased course accessibility and reliance, reduced cost, and improved learning outcomes.[v] Excellent OER Mechanics of Materials texts include works by Gramoll[vi] as well as Vable[vii].

Mechanics of Materials Labs for Remote Learners without Tensile Testers

The literature contains examples of mechanics of materials lab instructors developing educational kits that do not include quantitative tensile testing. Douglas and Holdhusen developed lab experiments including maximum stress and stress concentration studies that students performed on their own by adding a weight to a test element until it failed [viii]. These experiments are useful in determining the maximum stresses test samples can withstand. However, they do not provide information about what occurs before failure: elongation in the elastic region followed by plastic deformation. Students commented negatively in post-course surveys about these activities, indicating that weights given to perform stress experiments were inaccurate and additional purchases beyond the kit were required to be successful in the course.

Existing Benchtop Tensile Testers

FreeLoader is an existing open-source desktop-sized universal testing machine designed by Cornell University to apply tensile and compressive loads to test samples.[ix] FreeLoader costs about $4,000 and weighs 22kg, making it cheaper and smaller than many commercial tensile testers but still unwieldy to ship and far too expensive to be a viable lab teaching tool for remote learners.

The AP-8214A, shown in Figure 1, was a benchtop tensile tester previously available from PASCO. It operated via a manually rotated lead screw to actuate a rotary motion sensor that detected strain. A force sensor attached to the platform and sample measured stress.[x] This device was ultimately discontinued by PASCO because it produced inaccurate results arising from samples being too thin to reveal material bulk properties. Mitigating this problem with thin tensile tester material samples is a key issue in this current paper. Also, the AP-8214A could only test a handful of prefabricated sample types provided by PASCO.[xi,xii] Moreover, the AP-8214A cost $1,135 with additional fees required for the software licenses. This price point was too high for AP-8214A to be accessible for students in a remote / online lab class.

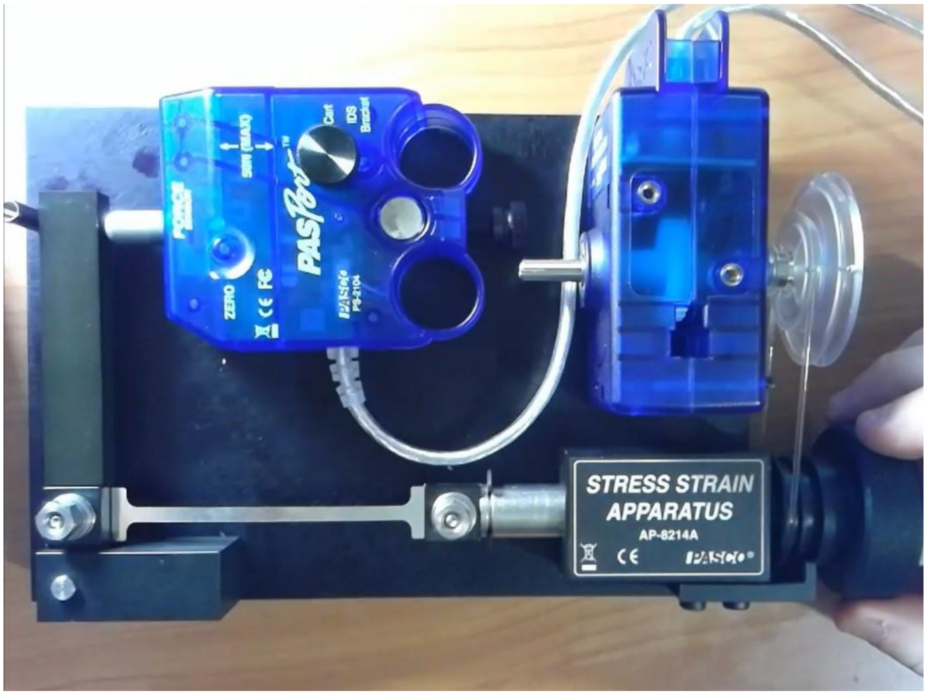

Figure 1: AP-8214A Tensile Tester

Liu and colleagues designed the Universal Mechanical Testing Kit (UMTK) that costs $556. The complementary UMTK curriculum includes elements from solid mechanics, materials science, mechatronics, computer programming, data analysis, industry standards (e.g., ASTM standards), and hands-on fabrication skills. When implemented against traditional teaching and use of a conventual $2000 bench-top tensile tester, direct assessment through quizzes revealed students using the UMTK showed the largest grade improvement in the course and highest satisfaction.[xiii]

Sample Thickness, Grain Size, and Emergence of Bulk Material Properties
Grain size influences mechanical material properties such as hardness, yield strength, tensile strength, fatigue strength, and impact strength[xiv]. Size effects of thin metal sheets were compared to show, in general, that yield strength as well as maximum load both decrease with a decreasing ratio in number of grains to sample thickness. For grain sizes larger than the specimen thickness, yield strength generally increases with the grain size, but high variation is also observed. The effect of this variation on processing these materials is demonstrated in a planar blanking process.[xv]

While changing sample thickness is known to influence material properties, unknowns persist in the underlying theory. Suh and collaborators studied Aluminum 6K21-T4 whereby chemical etching reduced its thickness. No change to microstructure or grain size was noted after etching. Six varying sheet thicknesses were formed: 0.40 mm, 0.72 mm, 1.04 mm, 1.40 mm, and 1.58 mm. As sample thickness decreased, specimen surface area also decreased. Therefore, when the volume fraction of grains having a free surface decrease the effect on the surface is enhanced. Resulting stress-strain curves changed when thickness was reduced, showing mechanical properties were affected by sample thickness in absence of other morphological changes to the samples.[xvi].

In a paper observing effect of specimen thickness and grain size on mechanical properties of 304 and 3016 stainless steel, thicknesses from 18 µm to 360 µm were studied. A critical value was found where stress of a thin specimen equaled the bulk material. It was also observed that metal elongation is affected by the specimen thickness and should be at least 200 µm to yield experimental results equivalent to the bulk material.[xvii] Another paper reviewing the effect of specimen thickness on reactor pressure vessel steel determined the strength is independent of specimen thickness when the thickness is larger than the critical value of about 0.2 mm.[xviii]

A study by Leicht et al highlighting part thickness effect on microstructure and tensile properties showed when part thicknesses is reduced, the surface grain effects increase. Reducing part thickness did not affect the sample microstructure, but it did reduce the tensile properties. Samples with 1 mm thickness had the lowest yield strength; properties improved toward bulk values as sample thickness was increased to 3 mm.[xix].

Standards

In defining what specimens a benchtop tensile tester might accommodate, it is helpful to draw insight from the major standards for the tensile testing metals and metallic materials: ASTM A370 [[xx]], ISO 6892 [[xxi]], and ASTM E8 [[xxii]]. Test samples with width of 12.5 mm (0.5 in) and gauge length of 50 mm (2 in) are the most common specimens, and ASTM A370 (steel) specimen geometries can range between milled round, flat, or as-manufactured. Primary specimen types for ISO 6892-1 (metallic) include sheets, plates, wires, bars, and tubes. In the ASTM E8 Tension Testing of Metallic Materials standard, it is stated that for material with a nominal thickness between 0.13 mm to 5 mm, the sheet type specimen is used. Sheet type specimens are described as metallic materials in the form of a sheet, plate, flat wire, strip, band, hoop, or rectangles. Thicknesses of metal samples tested in the current study were intentionally chosen to be in this range of thicknesses so they adhere to the ASMT definition for sheet metal.

Pedagogical Methods

To carry out tensile test measurements to determine force requirements for the benchtop tensile tester, freshman engineering students from the University of XYZ University Research Scholars Program (URSP) were engaged to conduct the experimental work. The URSP is an invitation-only experience that bridges the gap between classroom and lab experiences by 1) accelerating students into undergraduate research and 2) providing opportunities for leadership, mentorship, and networking.[xxiii]

The Researcher Incubator technique developed originally by Traum & Karackattu was applied to successfully engage URSP students in the research enterprise.[xxiii] The Researcher Incubator posits that if students are 1) taught needed skills, 2) empowered by group work, and 3) vested with serious responsibility they will spontaneously find and/or develop whatever knowledge is required to succeed on the project.[xxii] This technique has proven effective to engage lower division engineering students and even high school students in productive research.

Two URSP freshmen were recruited into the project. These students enrolled in a research-for-credit course in parallel with a classroom-based research methods class. They were mentored by an B.S. student (and past URSP participant) who took the day-to-day lead on managing the project. The URSP freshman, the B.S. student, and their faculty advisor met once per week to discuss project progress and develop forward-looking activities. Figure 2 shows the Gantt chart developed by the team, which evolved throughout their two semesters of interaction. The Gantt chart included both project-related experimental work as well as a section to plan the authorship assignments and progression toward completion of this ASEE Conference paper. Action items were planned in week-long time intervals with milestones coming due the week a deliverable was needed to meet an internal or external deadline. One or more individuals were assigned to take the lead on each task in the Gantt chart, which imparted a sense of urgency and responsibility on each individual research team member essential to the success of the Researcher Incubator approach.

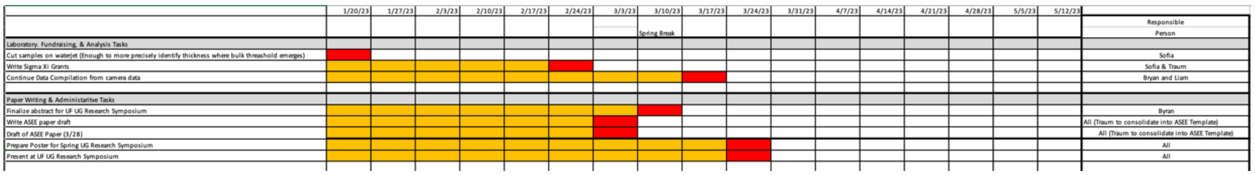

Figure 2: Gantt chart used by the student focused research team to organize project resources.

Methods

To determine the force a benchtop tensile tester must produce to drive samples of reasonable size to failure, the thickness of real samples undergoing stress-strain testing must be experimentally studied. It is known empirically that a sample thickness threshold exists below which bulk material properties are no longer obtained. However, there exist no theoretical underpinnings for this observed phenomenon. Moreover, tensile testing is destructive by nature. One cannot evaluate a sample on an experimental machine and then run the same sample again on a refence machine to provide validation or calibration. Therefore, validation of the proposed benchtop tensile tester must be conducted using bulk properties from known materials as calibration standards. Hence, the force required to exceed the ultimate strength of common engineering material samples (aluminum, brass, steel) that are thick enough to surpass the bulk material property threshold with some safety margin is the central design parameter for any tabletop stress-strain tester.

Dog-bone-shaped specimens of identical material and shape but with three increasing thicknesses (0.032in, 0.0625in, and 0.125in) were fabricated via waterjet. Aluminum 3003 was used in this study. Specimens underwent tensile testing to determine 1) mechanical properties and 2) way mechanical properties change with variable sample thickness. It is predicted that there exists a thickness threshold, possibly related to grain size, where bulk material properties emerge and remain constant as thickness increases further. At this threshold, mechanical properties are no longer dominated by two-dimensional plane stress.

Figure 3: Steel dog bone test samples cut using the water jet.

Waterjet Sample Cutting

The project incorporates a FLOW Mach 2 waterjet machine, shown in Figure 3, for cutting the dog bone samples for tensile testing. For this paper a series of preliminary tests of three Aluminum 3003 sample thicknesses were conducted to become acclimated with the waterjet: 3.2 mm (0.125 inches), 1.6 mm (0.063 inches), and 0.81 mm (0.032 inches). It was found that aluminum stock thinner than 0.81 mm suffered its edges being rolled under due to waterjet cutting. So, dog bone samples thinner than 0.81 mm cannot be directly fabricated via waterjet. To make thinner samples for testing in the future, the thin Aluminum 3003 sheet will be inserted between two sacrificial layers, the sandwich will be cut to the desired dog bone shape, and the sacrificial layers discarded.

Tensile Tester

The Instron 3384 100kN capacity tensile tester is used to elongate the samples to failure in tension. Data for each sample are recorded in Excel as stress strain curves and are later corrected for jaw sliding near the beginning of the run. After all the samples are tested, the stress strain curves are used to generate comparative values as Young's Modulus. The tests performed in this study use Digital Image Correlation (DIC), which is a tensile testing method that measures the full-range strain distribution in tensile tests. This method works by taking images of a speckled test piece during its deformation at a constant rate. The displacement of the speckles is then used to calculate strain. Using DIC methods is more accurate than manual measurement methods and strain gages, it tracks each side, computing the strain for each side as three-dimensional behavior.

Case Study

A classroom example where having a benchtop tensile tester available occurred recently in the ME Capstone senior design course at the University of Florida. A key assignment recurring each semester in this large-enrollment class is the Reverse Engineering Report (RER), an open-ended individual assignment in which students disassemble and analyze a common engineering artifact to discern how it was made and what underlying design decisions led to its final form. [xxx] The Spring 2022 RER artifact was an automatic centerpunch, Figure 4. In trying to understand how the centerpunch springs were selected and sized, students calculated the energy transfer efficiency of the centerpunch in making divots in a scrap piece of aluminum. The volume of a characteristic resulting divot was evaluated using white light interferometry (Figure 4), and the following expression of efficiency, $\boldsymbol{\eta}$, resulted

$$\boldsymbol{\eta} = \frac{\Gamma \Delta V}{\frac{1}{2} k (\Delta x)^2} \qquad (1)$$

where $\boldsymbol{\Gamma}$ is Modulus of Toughness, $\boldsymbol{\Delta V}$ is the volume of the divot measured by interferometry, $\boldsymbol{k}$ is the spring constant of the centerpunch spring, and $\boldsymbol{\Delta x}$ is the centerpunch displacement before triggering.

Figure 4: (left) Automatic centerpunch exploded assembly; (right) centerpunch making divots in scrap aluminum.

All parameters in Equation 1 could be measured or calculated, except Modulus of Toughness, $\boldsymbol{\Gamma}$. This parameter, shown graphically in Figure 6, represents the area under the complete material stress-strain curve. In other words, it quantifies the ability of a material to absorb energy in plastic deformation.

A tensile tester was not available in the Capstone design laboratory. So, students were forced to look up representative $\boldsymbol{\Gamma}$ values. A characteristic value of $\mathbf{51.8} \times \mathbf{10^6}\ \boldsymbol{J/m^3}$ for aluminum was found in the literature, but this value was unreliable as it did not necessarily correspond to the material in which measured divots were forced by the automatic centerpunch. The resulting process energy conversion efficiency, approximately 4%, was deeply unsatisfying to students who continued to question the validity of the Modulus of Toughness value assumed but lacked a method to measure it directly.

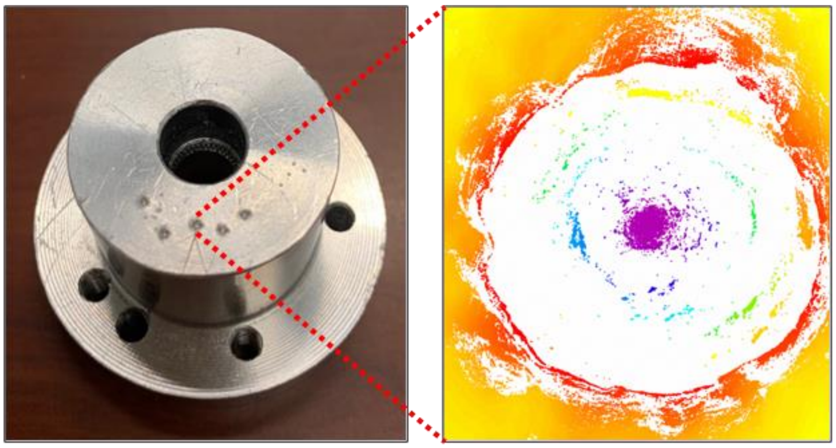

Figure 5: (left) Scrap aluminum part in which representative divots were forced via automatic centerpunch; (right) the divot's volume was evaluated via white light interferometry.

Had an inexpensive desktop tensile tester been available, students could have 1) selected a material to test, 2) created centerpunch divots in that material for volume evaluation by white light interferometry, 3) generated a dog bone material sample via waterjet for testing, 4) tensile tested the material to failure, and 5) analyzed resulting data by taking the area under the curve to extract an experimental Modulus of Toughness for use in the Equation 1 calculation.

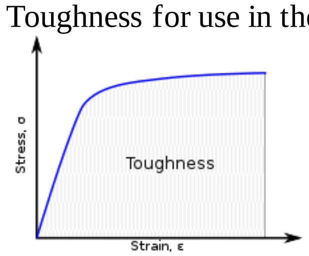

Figure 6: Modulus of Toughness is the total area under a stress-strain curve, representing the energy absorbed by a material in plastic deformation.

Learning Outcomes Enabled by Benchtop Tensile Testers in Non-Materials-Focused Teaching Labs

1. Students will develop a working knowledge of experimental techniques and equipment commonly used in engineering practice.

2. Students will become familiar with the implementation of various statistical data analysis techniques and good experimental planning

3 Student will demonstrate an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions [ABET (6)]

4. Students will identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics [ABET (1)]

Results & Discussion

A total of 18 samples were tested, 6 of each thickness. Strain data collected for each sample through the Instron and DIC software was then processed. 18 unique stress-strain plots were created. For each instance of data collection, common material properties were recorded. Their averages are compared with known, theoretical values in Table 1.

Sample Thickness	**0.032 in**	**0.063 in**	**0.125 in**	**Known Value**
Poisson's Ratio	0.273	0.291	0.310	0.3-0.33
Young's Modulus	65	67	68	68-88 GPa

Table 1: Material Properties for Tested Samples

Conclusion and Future Directions

Studying stress-strain models of a material helps to understand its material properties and how changing a material with change in geometry, thickness, or other treatment can affect those properties. For this specific investigation, it can be said that material properties of Aluminum are well replicated at a thinness threshold of 0.032 in.

This is vital to note because generating stress-strain curves and studying the behavior of common engineering metals, such as Aluminum, is very useful in mechanics and other engineering classes. This contributes to the overall goal of building a benchtop and remote stress-strain apparatus which is more accessible and affordable to students as it identifies the magnitude of samples that could be tested on it.

Once experience is built cutting aluminum samples on the waterjet, two additional common engineering materials will be added for evaluation via tensile testing: 304 stainless steel and 260 brass. For each material there will be at least 12 dog bone copies at each of 5 different thicknesses straddling the bulk property thinness threshold. Ultimately, a total of 72 samples per material will be tested. Twelve samples at each thickness are needed to provide large enough sample populations to perform statistical analysis on the results. This would broaden the materials that could be tested upon a benchtop tensile tester, making its use more valuable.

References

[i] "Listing of Online Engineering Programs Accredited by ABET," [Online]. Available at: https://www.abet.org/accreditation/find-programs/.

[ii] J. Starks, F. R. Hendrickson, F. Hadi, M. J. Traum, "Miniaturized Inexpensive Hands-On Fluid Mechanics Laboratory Kits for Remote On-Line Learning," *Proceedings of the 124th American Society for Engineering Education (ASEE) Conference and Exposition,* Columbus, OH, June 25 - 28, 2017.

[iii] M. J. Traum, F. Hadi, "A Miniaturized Circular Hydraulic Jump for Remote On-Line Fluid Mechanics Instruction," *Journal of Online Engineering Education*, Vol. 10, No. 1, Article 3, June 2019.

[iv] M. J. Traum, S. R. Niemi, P. Collins, M. Q. Jenkins, S. R. Putnam, C. M. Pinkoson, R. Gutierrez, "An Open Educational Resource Engineering Capstone Design Textbook with Case Studies Relevant to Student Experience," *Proceedings of the 2020 Capstone Design Conference*, Dallas, TX, USA, June 1-3, 2020.

[v] D. S. Gaikwad, S. R. Niemi, M. J. Traum, "Hurricane- & Pandemic-Resilient Instructional Engineering Labs Enabled Via Portable Kits," *Proceedings of the American Society for Engineering Education Southeastern Section (ASEE-SE) Conference*, Charleston, SC, USA, March 13-15, 2022.

[vi] K. Gramoll, "Multimedia Engineering Mechanics of Materials," University of Oklahoma Engineering Media Lab, 2019. Available at: http://www.ecourses.ou.edu/cgi-bin/ebook.cgi?doc=&topic=me

[vii] M. Vable, "Introduction to Mechanics of Materials, 2nd Ed.," Expanding Educational Horizons, LLC, 2009. Available at: http://madhuvable.org/wp-content/uploads/2016/04/Entire%20Book%202018.pdf

[viii] Douglas, Jamie and Mark Holdhusen, "Development of Low-Cost, Hands-On Lab Experiments for Online Mechanics of Materials Course," Annual Conference, American Society for Engineering Education, 2013.

[ix] Amend, John R., and Hod Lipson. "FreeLoader: An Open Source Universal Testing Machine for High-Throughput Experimentation." *Volume 6: 35th Mechanisms and Robotics Conference, Parts A and B*, 2011, doi:10.1115/detc2011-48296.

[x] "Stress/Strain Apparatus (without Sensors) • AP-8214A." *PASCO Scientific*, www.pasco.com/products/lab-apparatus/mechanics/centripetal-force-and-rotation/ap-8214.

[xi] M. J. Traum, E. Selvi, A. Hanlon, "Evaluation of DEEP POOL on Student Learning Outcomes Attainment," *Proceedings of the 126th Annual American Society for Engineering Education (ASEE) Conference and Exposition,* Tampa, FL, USA, June 16-19, 2019.

[xii] M. J. Traum, E. Selvi, S. A. Aponte†, C.-D. R. Bayran†, D. J. Diaz Sanchez†, K. J. Lyles†, D. D. Norwood†, J. R. Pruitt†, L. J. Scroggins†, "Developing Engineering Education Products via Project Ownership Oriented Learning in an Undergraduate Mechanics of Materials Course," *Proceedings of the American Society for Engineering Education (ASEE) Southeastern Section Conference*, Daytona Beach, FL, USA, March 4-6, 2018.
[xiii] X. Liu, S. Pajovic, C. Y. L. Kei, Y. Delaviz, S. D. Ramsay, "Use of a Low-Cost, Open-Source Universal Mechanical Testing Machine in an Introductory Materials Science Course," *Proceedings of the 124th American Society for Engineering Education (ASEE) Conference and Exposition*

[xiv] *Freeloader: An Open Source ... - Creative Machines Lab*
://www.creativemachineslab.com/uploads/6/9/3/4/69340277/detc2011_amend.pdf.

[xv] Suh, Chang Hee, et al. "Effects of Thickness and Surface Roughness on Mechanical Properties of Aluminum Sheets." *Journal of Mechanical Science and Technology*, vol. 24, no. 10, 2010, pp. 2091–2098., https://doi.org/10.1007/s12206-010-0707-7.

[xvi] "Grain Size and Its Influence on Materials Properties." *Grain Size And Its Influence On Materials Properties*, IndustrialHeating, 16 Oct. 2018.

http://digital.bnpmedia.com/publication/i=534828&article_id=3214739&view=articleBrowser&ver=html5.

[xvii] Raulea, L.V., et al. "Size Effects in the Processing of Thin Metal Sheets." *Journal of Materials Processing Technology*, Elsevier, 17 July 2001, https://www.sciencedirect.com/science/article/abs/pii/S0924013601007701?via%3Dihub.

[xviii] Iannucci, Lorenzo, et al. "Understanding the Thickness Effect on the Tensile Strength Property of Dyneema®HB26 Laminates." *Materials*, vol. 11, no. 8, 2018, p. 1431., doi:10.3390/ma11081431.

[xix] "The Effect of Specimen Thickness and Grain Size on Mechanical Properties Obtained from the Shear Punch Test: Request PDF." *ResearchGate*, https://www.researchgate.net/publication/259445013_The_Effect_of_Specimen_Thickness_and_Grain_Size_on_Mechanical_Properties_Obtained_from_the_Shear_Punch_Test.

[xx] M. J. Traum, S. R. Niemi, M. W. Griffis, N. A. Thomas, W. G. Sawyer, "Implementing an Effective Large-Enrollment Engineering Capstone Design-and-Build Program," *Proceedings of the 2020 American Society for Engineering Education (ASEE) Southeastern Section Conference*, Auburn, AL, USA, March 8-10, 2020.

[xxi] Wu, X.Q., and I.S. Kim. "Effects of Strain Rate and Temperature on Tensile Behavior of Hydrogen-Charged SA508 CL.3 Pressure Vessel Steel." *Materials Science and Engineering: A*, Elsevier, 13 Dec. 2002, https://www.sciencedirect.com/science/article/pii/S0921509302007372.

[xxii] Leicht, Alexander, et al. "Effect of Part Thickness on the Microstructure and Tensile Properties of 316l Parts Produced by Laser Powder Bed Fusion." *Advances in Industrial and Manufacturing Engineering*, Elsevier, 26 Feb. 2021, https://www.sciencedirect.com/science/article/pii/S2666912921000076.

[xxiii] *Standard Test Methods for Tension Testing of Metallic ...* https://www.galvanizeit.com/uploads/ASTM-E-8-yr-13.pdf.