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Development of Multiscale Experimentation and Visualization Module for Undergraduate Mechanics Education

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Abstract

Engineering mechanics courses are taught in multiple majors, such as mechanical engineering, civil engineering, and petroleum engineering across U.S. Traditionally, undergraduate mechanics courses are taught in large classes and mainly focus on solving textbook problems. Most students are well-trained to employ equations to solve simplified problems without understanding the nature of materials performance under complex load conditions and environmental effects. In the last two decades, the advancements of material characterization and imaging technologies have enabled the understanding of materials performance across multiple length scales and even time scales. Therefore, the implementation of cutting-edge materials characterization technologies can potentially enhance undergraduate students' understanding of complex solid mechanics concepts and behaviors. This paper presents the development of a multiscale materials and mechanics experimentation (M^3E) module that can be potentially implemented in undergraduate mechanics courses, including Statics, Dynamics, Strength of Materials, and Design of Mechanical (Machine) Components, at two participating Universities. Materials behavior and structures across micro- and macro- scales are included in the developed M^3E module. At the micro-scale, both 3D printed aluminum and cold-rolled aluminum samples were characterized using scanning electron microscope. Microstructures, including grains, grain boundaries, dislocation, precipitates, and micro-voids, were demonstrated to students. At the macro-scale, experiments following ASTM standards were conducted and full strain fields carried by all the samples were analyzed using digital image correlation method. The implementation of the developed module in undergraduate mechanics classes allows students to not only visualize materials behavior under various load conditions, but also understand the reasons behind classical mechanics properties. To assess the effectiveness of the developed M^3E education module, an evaluation question was developed. Students are required to classify key mechanics, materials, and processing concepts at both micro and macroscales. More than 40 fundamental concepts and keywords are included in the tests. The study outcomes and effectiveness of the M^3E education module will be reported in this paper.

Introduction

Engineering educators are increasingly concerned with their students' understanding of fundamental concepts and the underlying sciences behind concepts described in textbooks. Recent research has reported that most students do not truly understand their course content, though high passing rates can be achieved in some universities due to reduced requirements and grading policies [1-3]. Although this concern is still relatively new to engineering faculty, the advancement of cutting-edge technologies can be a potential approach to solve this issue. For example, advanced materials characterization and imaging technologies have allowed researched to observe materials behavior under complex load conditions and harsh environmental across multiple length and time scales. Implementation of certain technologies and development of easy-to-understand education modules have the potential to enhance undergraduate students' understanding of materials, mechanics, and even thermal concepts.

It has been well-recognized that solid mechanics is one of the most critical and fundamental engineering topics in multiple engineering education programs, such as aerospace, civil, industrial, mechanical, and petroleum engineering disciplines. Current solid mechanics education, however, mainly focuses on theoretical analysis with limited experimental demonstration. In most engineering programs, the theoretical analysis is delivered to students via a series of courses, such as Statics, Dynamics, Materials of Mechanics. The experimental demonstrations are only included in one laboratory course related Materials of Mechanics. Therefore, it is difficulty for engineering students to truly understand the relationship between material structures and their mechanical performance. In general, this knowledge is not introduced in any undergraduate solid mechanics courses. Only top students who can be involved in solid mechanics related research may have an opportunity to learn certain knowledge through undergraduate research projects. Most courses only require students to practice simplified engineering problems by solving equations without understanding the real reasons for certain material behavior [4-6].

Additive manufacturing (AM) has been employed in many undergraduate education programs in the last decade. Due to their unique material processing methods, 3D printing processes can result in unique microstructures and mechanical properties. Therefore, it is reasonable to systematically study a specific 3D printed material and demonstrate the impact of microstructures on materials' mechanical properties. In this paper, we focus on the additively manufactured metallic materials, providing a solid platform for engineering analysis of length scale effects on materials properties. The goal of this paper is to develop new educational approaches and modules to assist students to understand the relationship between material structure, processing, and properties. Compared to subtractive manufacturing methods, most AM technologies use layer-by-layer build-up of parts, and has become popular for fast prototyping and final production [7-15]. Numerous metallic materials, such as aluminum, copper, and stainless steel can be 3D printed using laser beam melting, electron beam melting, laser metal deposition, selective laser sintering, and ultrasonic welding. Due to the high processing temperature, 3D printed metals can carry totally different microstructural changes compared to the same materials processed by casting and machining. Thus, the overall mechanical behavior of certain 3D printed metals can be highly dependent on the 3D printing process and multi-scale structures [16, 17]. In this paper, 3D printed aluminum materials using focused ultrasonic welding is studied and experimentally characterized at the micro-scale.

The overall goal of this paper is to report the latest development of the multiscale mechanics education efforts for the enhancement of students' understanding of fundamental concepts. In particular, advanced experimental mechanics tools including scanning electron microscopy, digital image correlation (DIC), and ASTM mechanical testing are integrated within one comprehensive framework. A multi-scale mechanical and material experimentation (M^3E) module for property characterization and material visualization is developed and implemented in a junior level mechanics course at the University of Oklahoma and Tuskegee University. Figure 1 shows the schematic of the developed M^3E module. Informed by various components of our project, a framework for an improved multi-scale solid mechanics education is developed that is complemented with an assessment method to evaluate students' learning outcomes. At the microscale, both 3D printed and wrought aluminum samples are scanned using a scanning electron microscope (SEM) and an electron backscatter diffraction (EBSD) detector. At the macro-scale, standard tensile tests are carried out under ASTM standards and 2D strain field images are obtained using the DIC technology. The created dataset has been included in the developed M^{3}E modules for use in different mechanics and materials processing courses at two institutions. Preliminary in-class module integration has been carried out to enhance students' understanding of the relationship between materials structures and properties. The module is designed for short, in-class delivery (about 20 minutes) and is made available online for further student viewing outside class time, as needed. Therefore, the introduction of the module to existing courses will not be at the expense of standard course materials. Additionally, only appropriate information from the developed M^{3}E module will be used in different mechanics courses. For example, the multi-scale microstructures of metals will be introduced with stress-strain curve to junior engineering students in the Solid Mechanics course. The multiscale crack initiation and propagation in metal alloys will be included with the concept of failure and fracture to senior engineering students in Mechanical Component Design course. A mental model representation approach to evaluation and assessment platform is being developed in this project. The mental model representations provide insights to the learning process of engineering students. Understanding their mental model can lead to development of effective approaches to improve the education process and methods and thereby enhance outcomes.

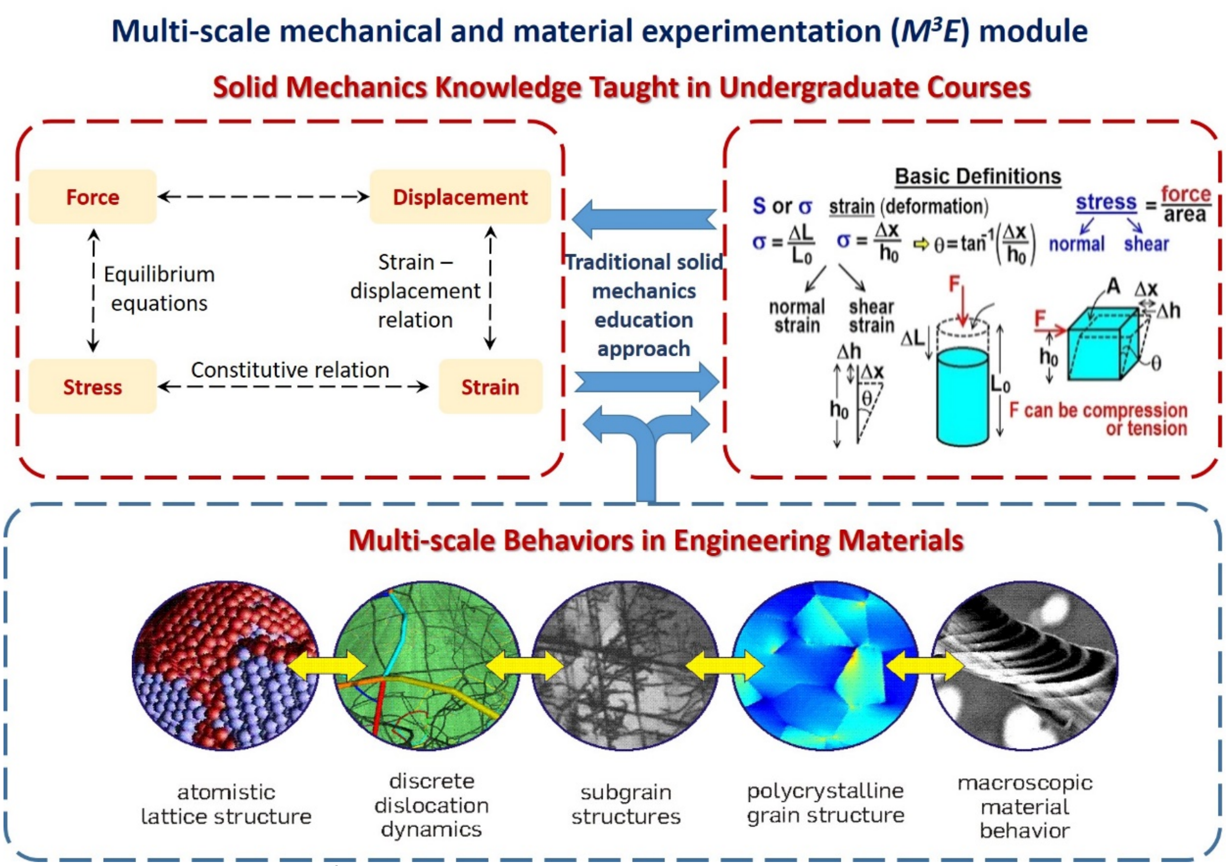


Figure 1. Schematic of M^{3}E module for undergraduate solid mechanics education.

Multiscale visualization and mechanical testing

In the last two decades cutting-edge material testing and imaging technologies have enabled the measurement of mechanical performance and properties across length scales from nano to macro. Bridging those properties from one length scale to another length scale provide fundamental understanding of fracture, impact, and creep mechanisms and the effects of load rates and environments. Significant efforts have been spent to address the length scale effects on materials using both experimental and modeling approaches [18-22]. For example, typical nano-scale and micro-scale mechanical testing methods, such as nano-indentation and atomic force microscopy, allow the measurement of local mechanical properties of materials and visualization of material surface morphology at the micro-scale. At the macro-scale, DIC imaging technology provides a full 2D and 3D strain measurement of specific areas in samples during mechanical testing. Therefore, the calculated stress-strain relationship can be more accurate as the global deformation effects on strain measurement are eliminated. In this paper, we have experimentally characterized the micro-scale imaging of metallic grain structures, size, and shapes by comparing both the 3D printed aluminum and conventionally wrought aluminum samples. In addition, standard ASTM tensile tests using dogbone samples and DIC for strain measurement are conducted. All the obtained experimental data set is used to create the M^{3}E modules. A schematic illustration of the multiscale experimental testing and imaging procedure is shown in Figure 2.

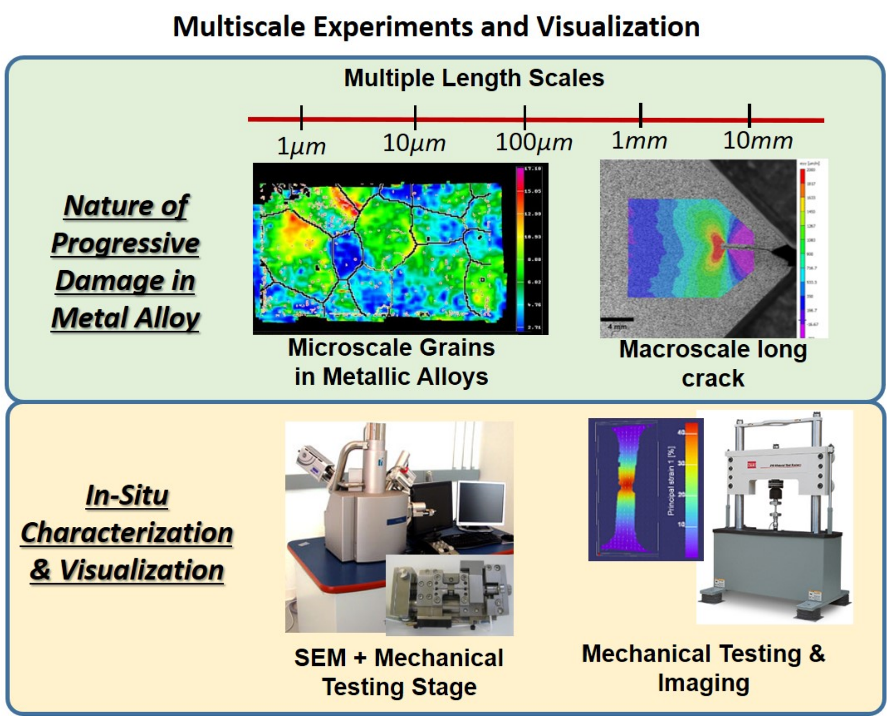
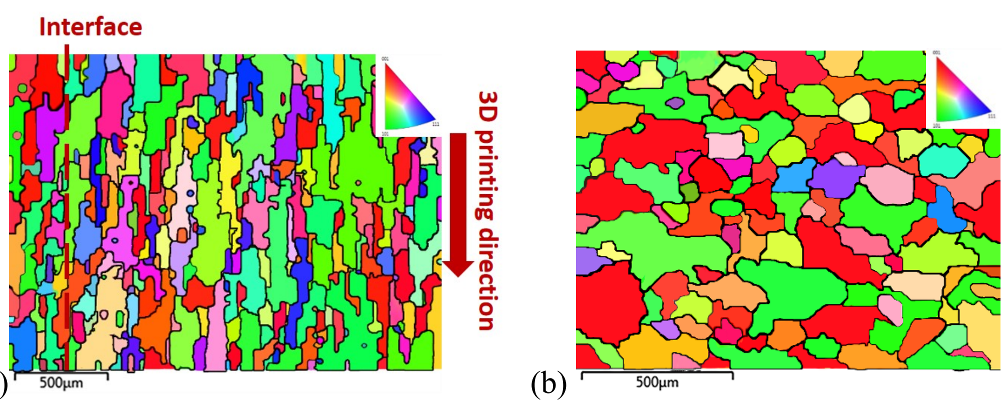


Figure 2. Implemented multiscale experimental testing and imaging procedure.

Micro-scale testing and imaging

To illustrate the effects of length scales on material properties and behavior, we employed micro-scale imaging techniques using SEM and EBSD detector to obtain the grain images at the micro-scale. As shown in Figure 3, both 3D printed and wrought aluminum samples were scanned. For the wrought aluminum samples, the average grain length and width were close to 376 μm. There was not obvious dominate direction because the materials were manufactured with clear isotropic properties. However, the 3D printed aluminum samples using ultrasonic focused welding technology significantly changed their grain microstructures by reducing average grain size and shape. As shown in Figure 3 (a), the grains were pushed longer in the vertical direction, which was the layer direction during 3D printing process. It is noted that large aluminum grains were broken into much smaller sizes. In particular, when the grains were near the interfaces between two layers of aluminum films, the size reduction of aluminum grains was more obvious, as shown in the left section of Figure 3 (a). No obvious voids were generated in the 3D printing process, indicating the effectiveness and successful implementation of the 3D printing technology. The colors in Figure 3 show the grain orientation of each aluminum grain. The definition of each color for grain orientation is shown next to the figure. It is observed that the wrought aluminum mainly stays in the [001] and [101] grain orientation, with minor grain variations. However, the grain orientation of 3D printed aluminum was much more diversified, as the [111] grain orientation also dominated some of the grains. This is due to the significant reduction of grain size and increase of grain numbers in the given scanned area. The ratio of different grain orientation is still equal. All this information is used to demonstrate to undergraduate students the effects of micro-scale structure in metallic materials on their macro-scale mechanical properties and failure mechanisms. For example, the comparison of the grain structure of wrought and 3D printer parts demonstrates the structure-processing relationships in metal processing. Abstract concepts like texture and plastic anisotropy can be better visualized and learned using those materials.



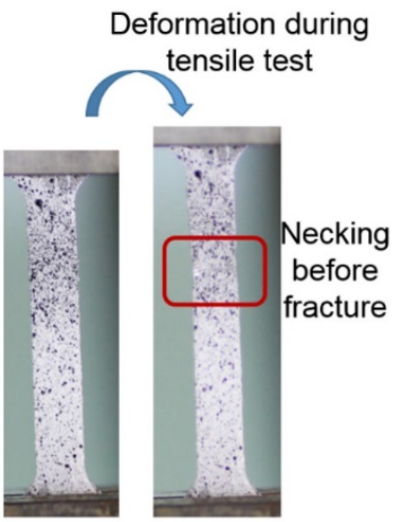
(a) (b)

Figure 3. EBSD scanning image of (a) 3D printed aluminum alloy by focused ultrasonic welding (b) conventionally wrought aluminum alloy.

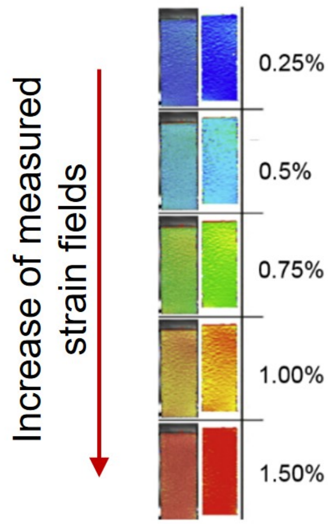
Macro-scale characterization and visualization

Macro-scale mechanical tests are conducted to demonstrate the overall material properties and behavior. The testing results are explained in view of the micro-scale images and structures obtained in the micro-scale imaging study. In this paper, all the tensile tests using aluminum dogbone samples were conducted following ASTM E345 standard. The sample surfaces were painted with white background and black dots for DIC imaging and 2D strain field measurement, as shown in Figure 4 (a). An in-house developed DIC system and open source software based on MATLAB were employed to process the DIC images and testing data. As shown in Figure 4 (b), the strain fields were measured by comparing the painted patterns before and after applying tensile loads. Therefore, relative consistent strain fields were calculated in the gauge area. The captured

2D strain field provided detailed information to explain to students about the critical solid mechanics concepts, such as deformation, strain, Poisson ratio and stress concentration. For example, the location of high stress concentration showed large local deformation with brighter color than the adjacent areas. As the applied load increased, the location with high stress concentration led to necking before fracture. The strain filed images can be integrated with the typical materials stress-strain curve to explain the nature of metallic materials' mechanical properties, providing in-depth explanations of stress and strain, elastic and plastic deformation, necking, and fracture, which are only conceptually explained in current Solid Mechanics textbooks and classes.



(a)



(b)

Figure 4. (a) Aluminum tensile samples with painted DIC patterns; (b) 2D strain fields of the gauge area during tensile tests.

Integration of the micro- and macro-scale experimental testing results can provide additional demonstrations to engineering students, enhancing their understanding of failure theory and fracture mechanics related concepts, such as critical stress intensity factor and materials failure theories, which are currently included in the Design of Mechanical Component course at the University of Oklahoma and the Manufacturing Processes course at Tuskegee University. The initiation of surface cracks in aluminum can be due to the micro-voids embedded in the material during fabrication, such as trapped air during casting. Additionally, the micro-scale crack growth in aluminum can be explained by the sliding of grains under external load. Once the micro-scale cracks grow up to the critical length and density, they would be connected with each other and form the macro-scale cracks, which are often observed by students during the solid mechanics lab. Therefore, providing visualization of materials multi-scale structures and explanation of multi-scale material behavior can broaden students' understanding of materials and mechanics, and assist them to link mechanics concepts to materials behavior they observe in laboratory testing.

Assessment of education outcomes of M^{3}E module

Traditional assessment based on student performance by solving given problems does not provide enough information about how students internalize and organize the knowledge presented to them.

In particular, it is difficult to design a set of testing problems that can efficiently evaluate student understanding of broad solid mechanics concepts and their relationship with manufacturing and design knowledge. However, such insight is necessary for educators to help students achieve deeper learning, particularly when the concepts are abstract as in the case of solid mechanics.

To better evaluate students understanding of solid mechanics concepts, particularly those related to multiple length-scale effects on metals, a set of conceptual questions was designed and implemented in mechanics related courses at the University of Oklahoma and Tuskegee University. While our goal is to develop more comprehensive and effective methods to enhance students' learning outcomes, the motivation for developing the assessment questions is to gain insight into the student outcomes under current methods of instruction, or the baseline (reference point). In the first question, students were given a number of solid mechanics key words (e.g., stress, strain, fatigue texture, gain size, toughness, elastic modulus, annealing) and asked to properly assign them to the proper category (e.g., external loading, macroscale mechanics parameters, microscale material parameters, processing). In the second question, the students were asked to pick one keyword from three or more categories and show their relationship as a chain and build a narrative sentence around it. An example of such a chain can be: *force*→ *stress* → *deformation* → *grain reformation* with a corresponding narrative as: *force generates stress in materials and deformation, leading to grain reformation.* Both questions involve mental processes that are closely related to material's properties and have been previously covered in other undergraduate courses. The designed questions are listed below:

1. Please list the following solid mechanics related keywords in the correct category. Stress, strain, Young's modulus, stiffness, toughness, strength, hardness, grain, grain boundary, grain size, dislocation, grain precipitates, deformation, force, impact, fatigue, tension, compression, shear, moment, torque, crack, fracture, crystal defect, quenching, annealing, hardening, cold working, inclusion, cavity, bending, buckling, pressure, heat treatment, grain reformation, plastic anisotropy, texture, microporosity, and microvoid.

<u>Solutions:</u>

External load	***Macro-scale mechanics parameter***	***Macro-scale material behavior***	***Metallic material microstructure***	***Metal processing***
force pressure impact fatigue tension compression shear moment torque	stress strain Young's modulus stiffness toughness strength hardness	deformation crack fracture bending buckling	grain grain boundary grain size dislocation grain precipitates crystal defect inclusion cavity grain reformation	quenching annealing hardening cold working heat treatment

2. Please pick one keyword from three or more than three categories and show their relationship as a chain. Add a brief explanation of each concept chain (please write as many as you can).
   For example: force➔ stress ➔ deformation ➔ dislocation
   (external force generates internal stress in materials and deformation, leading to grain dislocation)

   Example Solutions:
   cold working → dislocation → stiffness (cold working of metal generates significant amount of dislocation in grains, resulting in enhanced stiffness)
   impact →deformation → strain → fracture / crack (impact load generates a large deformation and high strain in a short time, leading to metal fracture or cracks)
   annealing → grain reformation → stress / stiffness (metal generate new grains after annealing, resulting in reduction of stiffness and removal of residual stress)

Statistical analyses were conducted to evaluate student understanding of fundamental solid mechanics concepts and potential length scale effects. A total of 42 junior mechanical engineering students participated in this study. The students' responses to the first question is shown in Figure 5. Figure 5 (a) shows the average student performances for all keywords in the external load category. For example, on average 95.24% of the students correctly categorized "Force" whereas only 30.95% of the students correctly categorized "Moment". With this data, it can be concluded that students who participated in this test had a better understanding of the concept of Force than Moment. Figure 5 (b) shows the average student performances for all keywords in the macroscale mechanics parameter category. For instance, on average 64.29% of the students correctly categorized "Young's Modulus" whereas only 14.29% of the sample correctly categorized "Plastic Anisotropy". It is reasonable to conclude that students are more familiar with fundamental concepts, such as Young's modulus, than advanced concepts like plastic anisotropy. Figure 5 (c) shows the average student performances for all keywords in the macroscale material behavior category. The results indicate that students had deficient understanding of bending and texture, while the correct response rate of the other keywords was around 65%. Figure 5 (d) shows the student performances for all keywords in the microstructure category. Students' understanding of the microscale structure of metals need to be strengthened, since the correct response rates for most of the keywords were below 60%. A good level student understanding of metal processing is shown in Figure 5 (e) as indicated by the high correct response rate. According to the obtained student data, it is clear that students' knowledge of length-scale effects on materials and structures is lacking. Both macro-scale and micro-scale concepts only obtained about 60% correct answers. The mechanics and load parameters obtained lower than expected correction rates, indicating the necessity to enhance undergraduate solid mechanics education. Considering overall performance by category provides additional evidence with regards to the limited understanding among students on the multi-scale nature of materials and linkages to observed mechanical behavior and properties, Figure 5 (f). The collected student data indicates that although most of the students were able to identify the meaning of each keyword and categorize them properly in the "materials processing" category (77% of students correctly categorized the keywords belonging to "materials processing" category), the macro-scale mechanics parameter results indicate significant misconceptions as reflected by the observation that only 37% of the students correctly categorized the relevant keywords. Although not as pronounced, students also seem to struggle with micro-scale structure concepts with only 50% of the students correctly categorizing the relevant keywords.

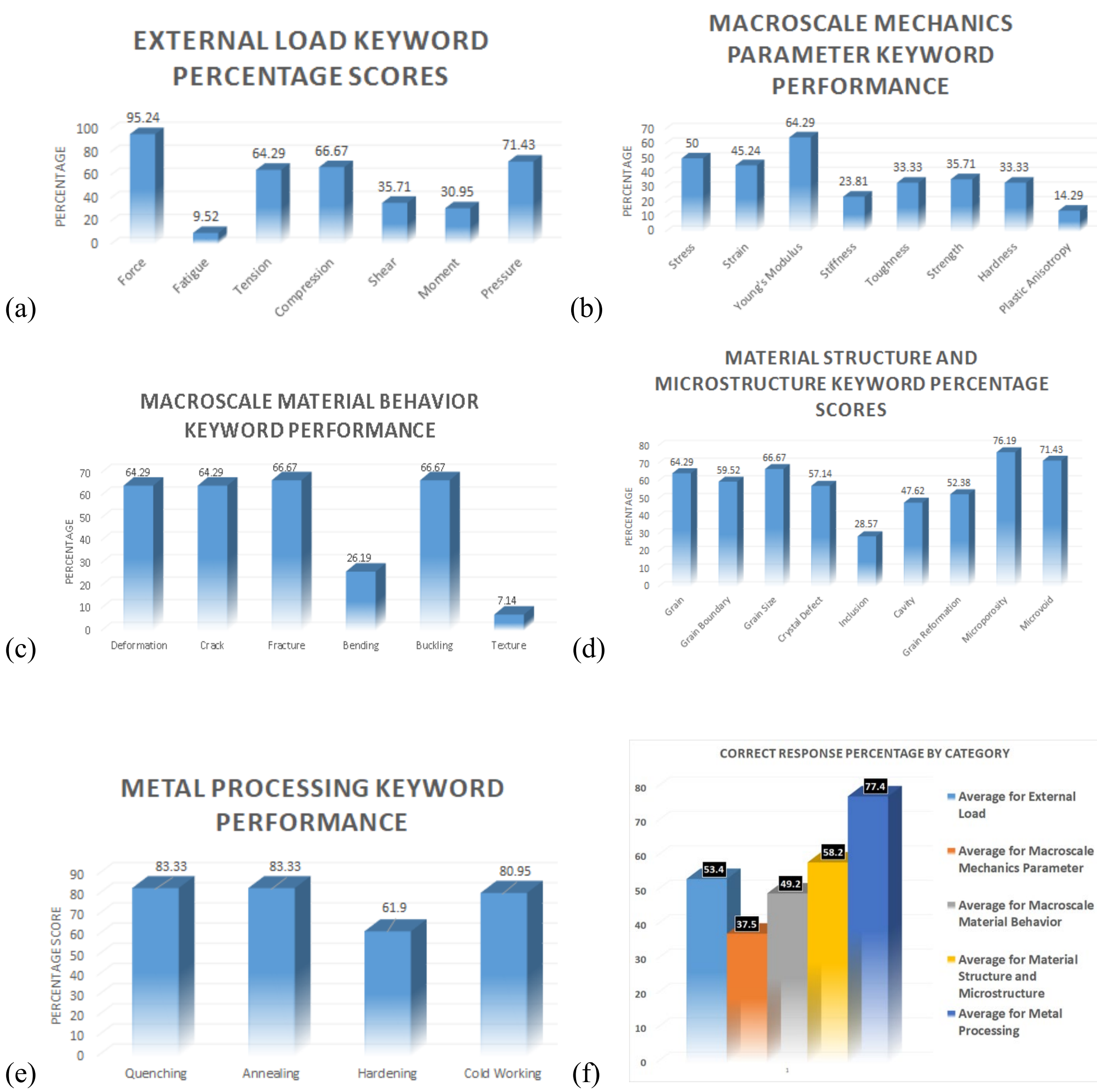


Figure 5. Analyses of student responses to the solid mechanics related keywords questions.

Since the second given question had multiple correct answers, the students' answers showed their in-depth understanding and the connection between mechanics, materials, and processing. All students who participated in the test were able to provide at least one correct answer. Typical correct answers were "force->stress->strain->fatigue", "pressure->stress->buckling->fracture", and "annealing->hardness->strength". This type of answers indicated students have gained some understanding and integrated their knowledge in mechanics and materials. However, no student was able to establish any connection from load/material to microstructures, indicating a lack of instruction and thus learning on the length-scale effects of materials properties. Combining the student responses from the two given questions, we can conclude that there is need to enhance current solid mechanics education to junior and senior undergraduate students in mechanical engineering programs at the University of Oklahoma and Tuskegee University. We plan to test the students with the same questions after the in-class implementation of the developed M^3E module. The student response data will be compared to evaluate the learning outcomes. Additionally, more complicated evaluation methods articulating their mental model will be discussed and carried out in the next section.

Evaluation of students' learning outcomes using mental model representations

Mental model representation method is employed to further evaluate students' learning outcomes besides conceptual questions that can indicate students' understanding of abstract mechanics concepts. In cognitive science, the concept of a "mental representation" has been well-studied to understand human's learning patterns. Recent publications in literature have shown that "mental models guide and regulate all human perceptions of the physical and social world" [23]. In general, mental models are representations to provide subjectively plausible explanations on a concept and provides the basis for understanding and application of the concept [24]. Therefore, providing learners with appropriate information to help construct appropriate mental representations are crucial during learning of complex concepts.

In this paper, the developed M^{3}E module can assist students to create appropriate mental representations explicitly. The analysis of students' mental models can indicate how they summarize the fundamental solid mechanics concepts to vivid observations, representing students' enhanced understanding of these concepts after learning the developed M^{3}E module. Thus, training students to establish such a mental model using solid mechanics concepts is a reasonable approach, which can even contribute to students' engineering career development through their lives. Via appropriate analysis, fundamental concepts in mechanics can be completely separate in students' mind before they have a firm understanding of their meaning, as shown in Figure 6. The M^{3}E approach is expected to help students connect these abstract concepts and develop their mental model to represent a network of such complex concepts. A well-developed concept map, externalization of the mental representation, will show the fundamental understanding of these concepts. Once students have such capability, they can easily adapt it for other engineering applications. The effectiveness of the proposed M^{3}E approach will be evaluated using pre-and post-test comparison of student concept maps. Before being exposed to M^{3}E, students will be asked to connect mechanics concepts, as shown in Figure 6. The results will be compared with post-test, which will be conducted after students use M^{3}E. Using different analyses tools and models, the effectiveness of the proposed approach, on learning, can be determined.

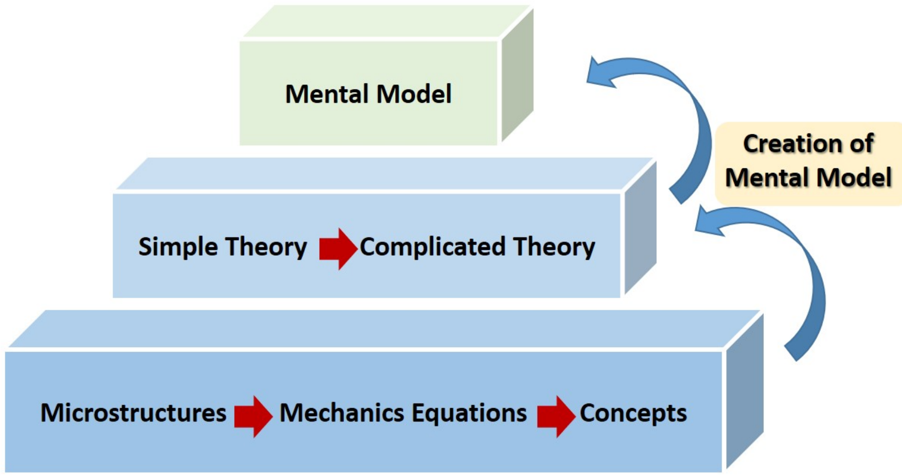


Figure 6. Mental model and mapping of abstract mechanics concepts.

As an alternative to traditional assessment, our research team is employing concept mapping as the main assessment tool. As best described by Trochim [25], a concept map is "a pictorial representation of the [one's] thinking which displays all of the ideas that are related to each other and optionally, shows which ideas are more relevant, important, or appropriate". Our preliminary study carried out in 2018 and 2019 solid mechanics courses at the University of Oklahoma and Tuskegee University have demonstrated that students were able to create concept maps after taking junior and senior mechanics classes, though there were errors in their concept maps. A typical concept map created by a senior student is shown in Figure 7. To efficiently analyze the concept maps, we are currently creating the "expert concept map", and plan to fully implement this approach in our 2020 mechanics courses.

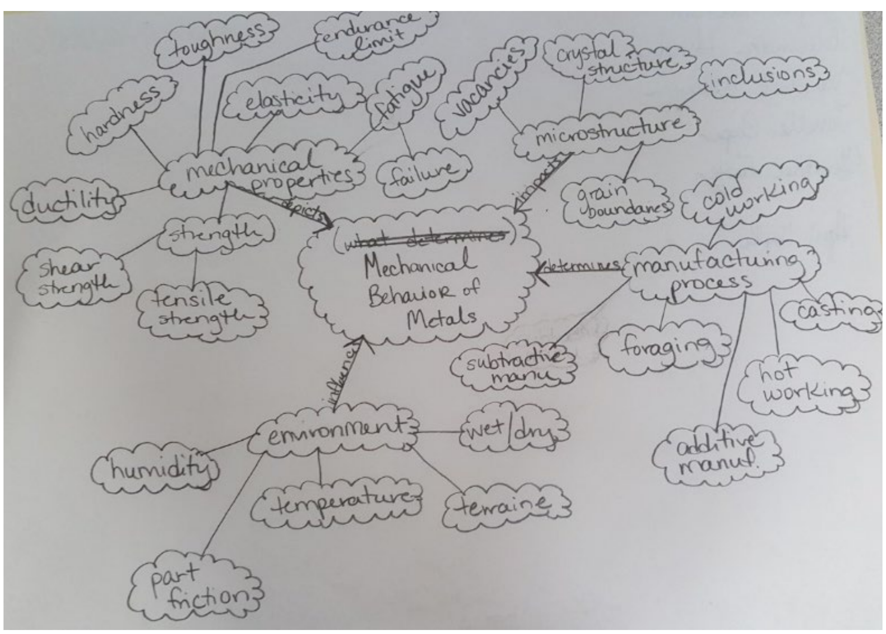


Figure 7. Sample concept map for the mechanical behavior of metals produced by students.

Conclusions

Development of M^3E education module is presented in this paper for the enhancement of solid mechanics education by introducing length-scale effects on microstructures and properties. First, multiscale mechanical testing and visualization were conducted to create the materials database by studying 3D printed and wrought aluminum samples. Both micro-scale and macro-scale experiments were conducted. In particular, SEM images showed the manufacturing effects on the grain structures at the micro-scale. Focused ultrasounds were able to significantly change critical microstructures of the 3D printed aluminum alloys, such as average grain size, grain shape, and crystal orientation. At the macro-scale, fundamental materials properties were characterized following ASTM E345 standard. Both optical images and DIC images were taken during the entire experiments to track crack growth and to measure local 2D strain fields, respectively. All the collected experimental data was used to establish the proposed M^3E education module. A series of learning evaluation problems were created to categorize students learning outcomes after lecturer delivering the developed M^3E module. The compiled data from student responses showed that there is an urgent need to enhance mechanics education and assist students to link abstract mechanics concepts to their experimental mechanics courses. The approach of using concept maps is being investigated to assess and quantify the education outcomes in this project. The developed dataset and assessment approaches are being integrated into a single education module for the enhancement of mechanics education across the U.S.

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