Multi-scale Characterization and Visualization of Metallic Structures to Improve Solid Mechanics Education

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Multi-Scale Characterization and Visualization of 3D Printed Metallic Structures to Improve Solid Mechanics Education

Abstract

This paper presents the development and preliminary implementation of a multi-scale material and mechanics education module to improve undergraduate solid mechanics education. We experimentally characterize 3D printed and conventional wrought aluminum samples and collect structural images and perform testing at the micro- and macro- scales. At the micro-scale, we focus on the visualization of material's grain structures. At the macro-scale, standard material characterization following ASTM standards is conducted to obtain the macroscopic behavior. Digital image correlation technology is employed to obtain the two-dimensional strain field during the macro-scale testing. An evaluation of student learning of solid mechanics and materials behavior concepts is carried out to establish as baseline before further interventions are introduced. The established multi-scale mechanics and materials testing dataset will be also used in a broad range of undergraduate courses, such as Solid Mechanics, Design of Mechanical Components, and Manufacturing Processes, to inform curricular improvement. The successful implementation of this multi-scale approach for education is likely to enhance students' understanding of abstract solid mechanics theories and establish links between mechanics and materials concepts. More broadly, this approach will assist advanced solid mechanics education in undergraduate engineering education throughout the country.

Introduction

Solid mechanics is a fundamental topic that plays a significant role in engineering education programs, including aerospace, civil, industrial, mechanical, and petroleum engineering disciplines. However, current solid mechanics education mainly focuses on theoretical analysis with limited experimental demonstration. The relationship between material structures at different length scales and their mechanical performance is not commonly introduced in undergraduate solid mechanics courses. Students focus on practicing simplified engineering problems by solving equations without understanding the real reasons for certain material behavior at the macro scale [1-3]. It is necessary to help students connect their learning in materials with mechanics at different scales to improve mechanics education.

Due to the current excitement about additive manufacturing, we focus on additively manufactured metallic materials to provide a solid platform for engineering analysis of length scale effects on materials properties. Our goal is to design and experiment with new approaches to help students understand the relationship between material structure, processing, and properties. In contrast to conventional and subtractive manufacturing methods, additive manufacturing (AM) uses layer-by-layer build-up of parts, and has become popular for fast prototyping and final production [4-10]. Several metallic materials, including structural steel, aluminum, titanium, and copper, can be processed by AM with outstanding properties. Laser beam melting, electron beam melting, laser metal deposition, and ultrasonic welding are the most popular AM methods for metals. Due to the high local temperature during AM (3D printing) of metals, microstructural changes can occur, and therefore, the overall mechanical behavior of such 3D printed materials is highly dependent on the 3D printing process and multi-scale structures [11, 12]. 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 research is to enhance the solid mechanics education by incorporating multi-scale experimental mechanics and visualization using scanning electron microscopy, digital image correlation (DIC), and mechanical testing into existing curricula. A multi-scale mechanical and material experimentation (M^3E) module for property characterization and material visualization is employed to transform undergraduate mechanics education. A schematic of the M^3E module is shown in Figure 1. 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 developed into learning 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^3E 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 multi-scale 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.

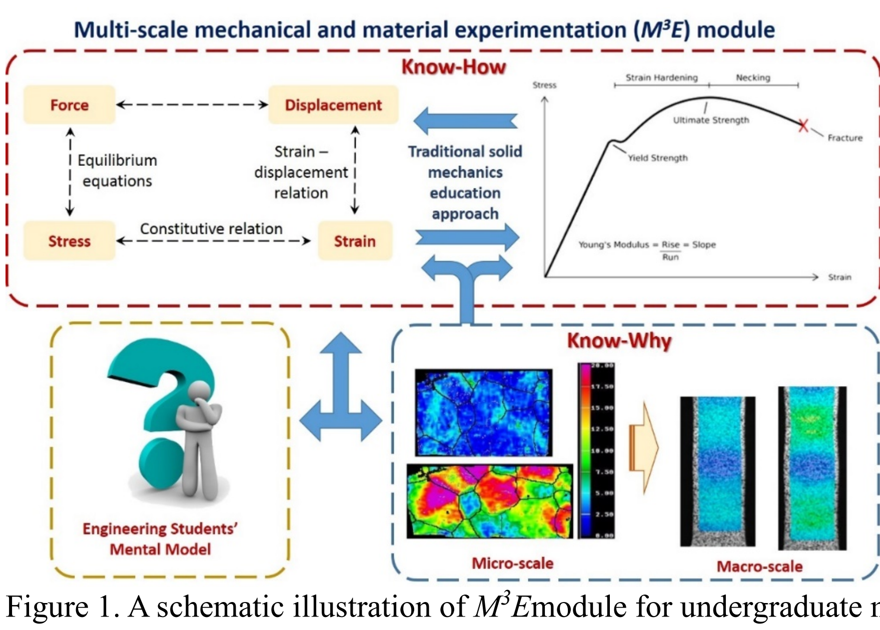

Figure 1. A schematic illustration of M^3Emodule for undergraduate mechanics education.

Multi-scale visualization and mechanical testing

The advancement of experimental mechanics and visualization technology allows the characterization of materials properties and behavior at different length scales from nano to macro. For instance, 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. We first employ the micro-scale imaging of metallic grain structures, size, and shapes by comparing both the 3D printed aluminum and conventionally wrought aluminum samples. Then, 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 database and related modules for the M^3E project. A schematic illustration of the multi-scale experimental testing and imaging procedure is shown in Figure 2.

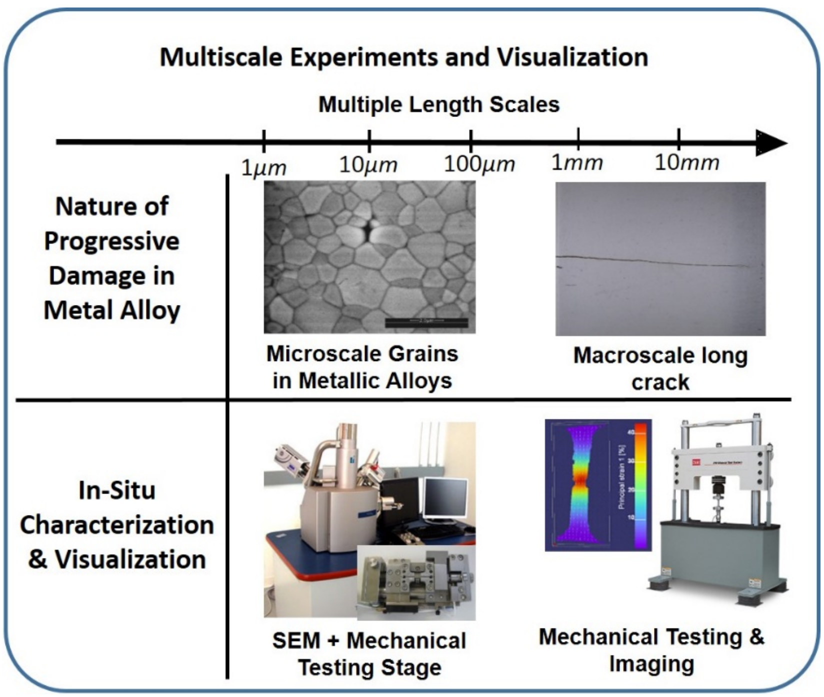

Figure 2. A schematic illustration of the multi-scale experimental testing and imaging procedure.

Micro-scale imaging using EBSD and SEM

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.

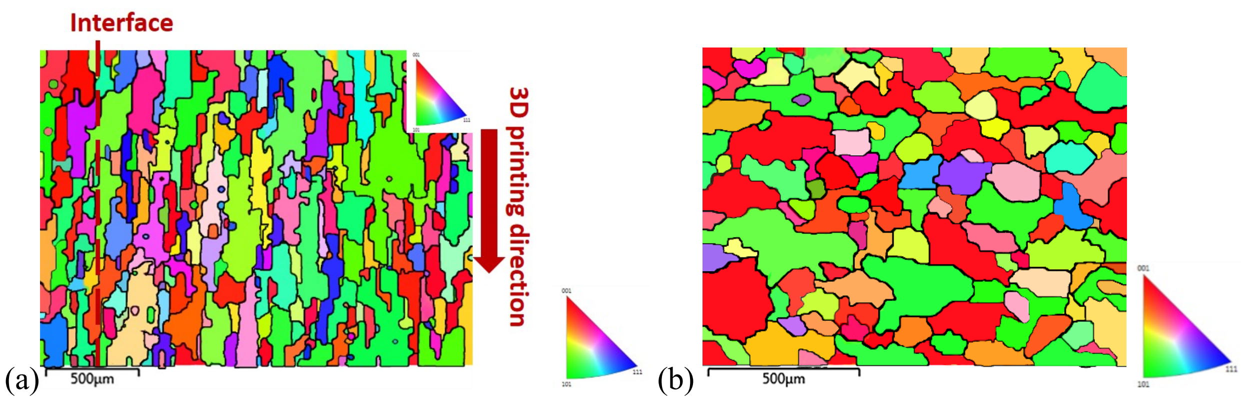

Figure 3. EBSD scanning image of (a) 3D printed aluminum alloy by focused ultrasonic welding (b) conventionally wrought aluminum alloy.

Macro-scale testing and imaging using DIC

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. 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, the strain field was measured using DIC and relative consistent strain field were obtained 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.

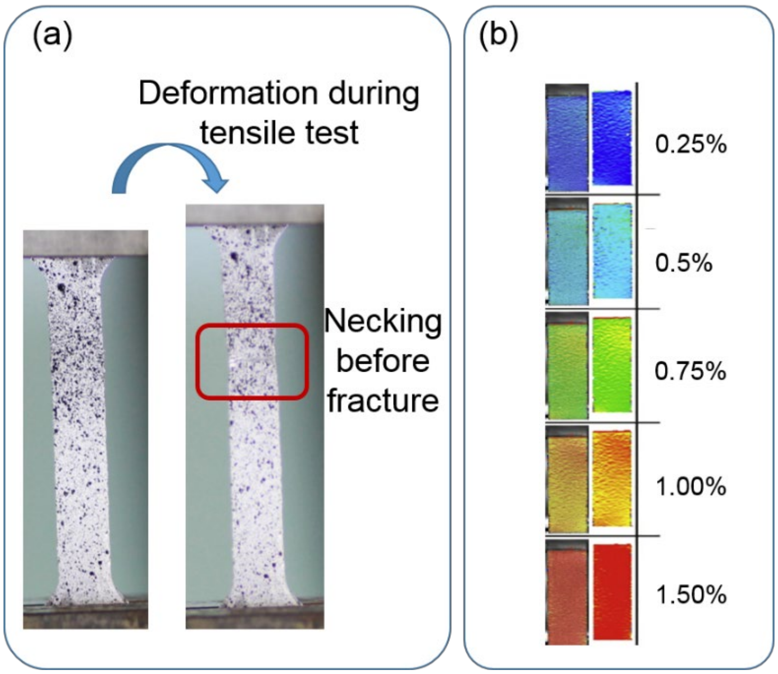

Figure 4. DIC images of the gage area of aluminum sample during tensile tests.

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 *M³E* 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.

Future study using mental model representations

Although conceptual questions can indicate students' understanding of abstract mechanics concepts, more comprehensive analyses and evaluation methods using mental model representations are being developed to analyze learning outcomes. The concept of a "mental representation" is a theoretical construct in cognitive science. It has been shown that "mental models guide and regulate all human perceptions of the physical and social world" [13]. Mental models are representations generated by humans to provide subjectively plausible explanations on a concept and provides the basis for understanding and application of the concept [14]. Consequently, providing learners with appropriate information to help construct appropriate mental representations are crucial during learning of complex concepts.

The developed M^3E module can help students create appropriate mental representations explicitly. The mental model assists students to summarize the complex and abstract solid mechanics concept to a vivid observation, leading to enhanced understanding. Therefore, training students to establish such a mental model using solid mechanics concepts is a reasonable approach, which may benefit students in their entire engineering career. As shown in Figure 6, fundamental concepts in mechanics can be completely separate in students' mind before they have a firm understanding of their meaning. The M^3E 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^3E approach will be evaluated using pre-and post-test comparison of student concept maps. Before being exposed to M^3E, 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^3E. Using different analyses tools and models, the effectiveness of the proposed approach, on learning, can be determined.

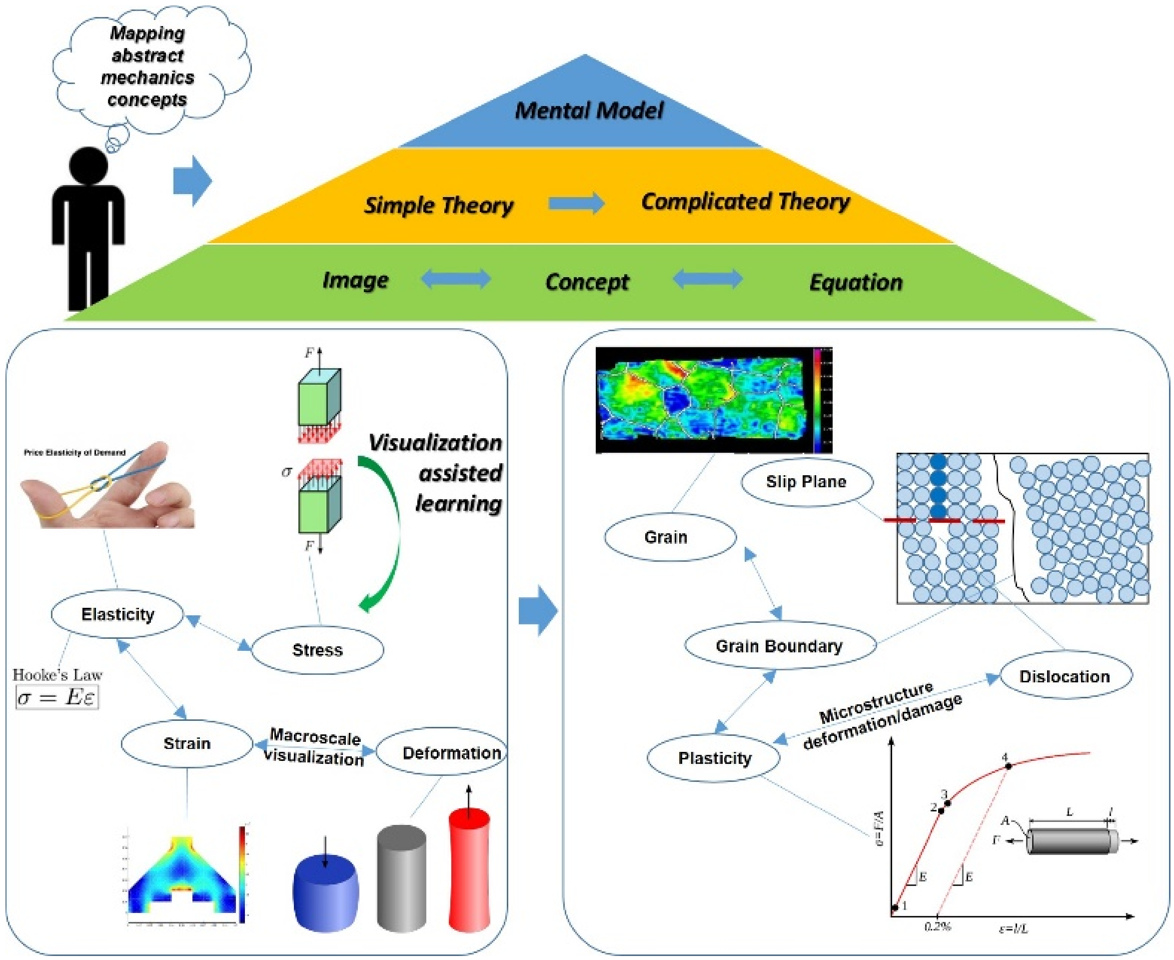

Figure 6. Mental model and mapping of abstract mechanics concepts.

As an alternative to traditional assessment, our research team is employing concept mapping as the main assessment tool. As best described by Trochim [15], 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 Spring and Fall 2018 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 2019 mechanics courses.

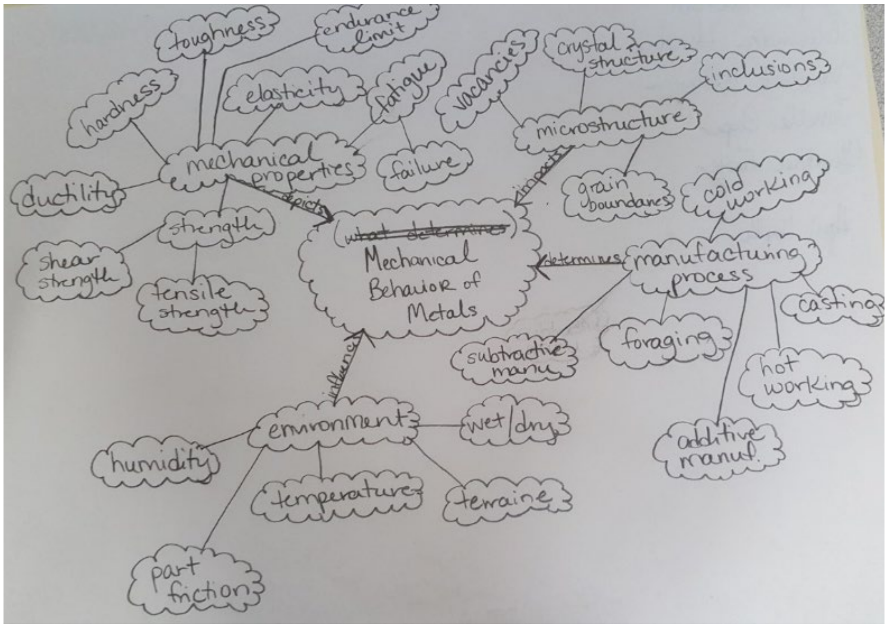

Figure 7. Sample concept map for the mechanical behavior of metals produced by students.

Conclusions

This paper presented the development of M^3E education module to enhance mechanics education for undergraduate engineering students by introducing length-scale effects on microstructures and properties. Multi-scale mechanical testing and visualization experiments were first conducted to create the materials database using both the 3D printed and wrought aluminum samples. At the micro-scale SEM imaging technology using an EBSD detector showed the manufacturing effects on the grain structures. The average grain size, shape, and orientation were significantly changed by the focused ultrasonic welding 3D printing technology. The macro-scale materials properties were tested following ASTM E345 standard. DIC images were taken for the local 2D strain field measurement. To observe and evaluate students' learning patterns, we developed a set of questions to categorize level of learning in mechanics and materials concepts. 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 in the U.S.

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