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Structural Health Monitoring: The Use Of Acoustic Emission To Optimize The Fdm Additive Manufacturing Process

Ethan Phillips

STRUCTURAL HEALTH MONITORING: THE USE OF ACOUSTIC EMISSION TO OPTIMIZE THE FDM ADDITIVE MANUFACTURING PROCESS

A Thesis

by

ETHAN PHILLIPS

Submitted to the Office of Graduate Studies of Prairie View A&M University
in partial fulfillment requirements for the degree of

MASTER OF SCIENCE IN ENGINEERING

December 2023

Major Subject: Mechanical Engineering

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ABSTRACT

Structural Health Monitoring: The Use of Acoustic Emission to Optimize the FDM Additive Manufacturing Process

(December 2023)

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Fused Deposition Modeling (FDM) has gained widespread popularity as an affordable, versatile, and user-friendly additive manufacturing technique. However, ensuring consistent and high-quality prints remains a significant challenge. This study investigated the potential use of Nondestructive Evaluation (NDE) in the form of Acoustic Emission (AE) to optimize the FDM 3D printing process, including filament defects and the selection of print parameters. AE monitoring involves the detection and analysis of acoustic waves generated during the printing post-process, providing valuable insights into the dynamic behavior of a specimen with respect to the selected print parameters and integrity of the system. Specific acoustic patterns associated with different combinations of printing parameters can be identified by capturing and analyzing AE signals.

An experimental setup was established to capture the acoustic emissions generated during tensile testing process to achieve this. Two high-sensitivity piezoelectric sensors were placed on the ASTM D638 specimen under a tensile load to record the acoustic signals in real-time. A combination of 3 levels of 3 printing parameters, 0.10/0.20/0.30 mm layer thickness, 225/200/180 °C nozzle temperature, and 70/50/30 mm/s printing speed were selected during the printing process for experimental analysis. Feature extraction methods were employed to identify distinctive characteristics in the AE signals associated with different combinations. The final results demonstrated the potential of AE monitoring as an effective tool for quality control in FDM 3D printing. The developed classification method achieved a high accuracy rate in determining the best possible combination of parameters, enabling the selection of the most efficient parameter choosing for future prints. The proposed AE monitoring approach offers a nondestructive, real-time, and cost-effective solution to detect and provide valuable information of structural health, enhancing overall quality of the FDM printing process, thereby leading to improved mechanical properties among polymer fabricated objects. Additionally, this research contributes to the advancement of quality control techniques in additive manufacturing, particularly when dealing with the use of NDE methods as manufacturers can determine the most reliable combinations of printing based on their necessities. This research explored the correlation between detected AE patterns and mechanical property characteristics through tensile testing to establish a quantitative relationship.

Index Terms— Acoustic emission (AE), additive manufacturing (AM), ASTM D638, fused deposition modeling (FDM), nondestructive evaluation (NDE), print parameters, quality control.

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GLOSSARY OF ACRONYMS

3D – Three Dimensional

AE – Acoustic Emission

AM – Additive Manufacturing

ASTM – American Society for Testing and Materials

CAD - Computer-Aided Design

FDM – Fused Deposition Modeling

NDE – Non-Destructive Evaluation

NDT – Non-Destructive Testing

PLA – Polylactic Acid

SHM – Structural Health Monitoring

STL – Stereo Lithography

UTM – Universal Testing Machine

UTS – Ultimate Tensile Strength

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1. INTRODUCTION

1.1. Fundamental Concept of Additive Manufacturing

Additive manufacturing (AM), often referred to as 3D printing, is a process of creating three-dimensional objects by adding material layer by layer, rather than subtracting material through traditional machining methods [1]. This technology allows for the creation of complex and customized objects with a wide range of materials, including plastics, metals, ceramics, and even biological materials.

Prototyping, customization, low-volume production, complex geometries, and many other industries, including aerospace, automotive, healthcare, and architecture, are just a few of the many uses for additive manufacturing. One of the first and most popular applications of additive manufacturing is rapid prototyping, which makes it possible to test product designs quickly and affordably [1]. By doing this, it is possible to test geometries more affordably than if costly material were to be used.

Using computer-aided design (CAD) software, a 3D digital model of the item to be produced is usually designed as part of the AM process. The 3D printer follows the blueprint provided by this digital model. After that, the CAD model is divided into thin horizontal layers by means of specialist software called a slicer. The object to be printed is represented by a virtual cross-section in each layer. Several slicers with shared features are linked to specific printers according to the printer's brand or license. This is the area where the user can change a number of parameters, such as support percentages, print process formalities, anisotropic qualities, and print orientation.

This thesis follows the style of IEEE.

Following the slicing process, the model's STL is saved and sent to the printer via Bluetooth, Wi-Fi, flash drives, and other methods that may be available depending on the printer's make and model. After interpreting these sliced layers, the 3D printer uses the modified parameters to start building the object layer by layer. Each layer bonds to the one before it as the printer deposits or solidifies the material in accordance with the design. To do this, different 3D printing technologies employ different techniques, such as sintering powdered material with a laser, curing liquid resin with ultraviolet light, or extruding melted plastic. To attain the required quality and appearance, the object might need to go through extra processes like curing, cleaning, or surface finishing printing.

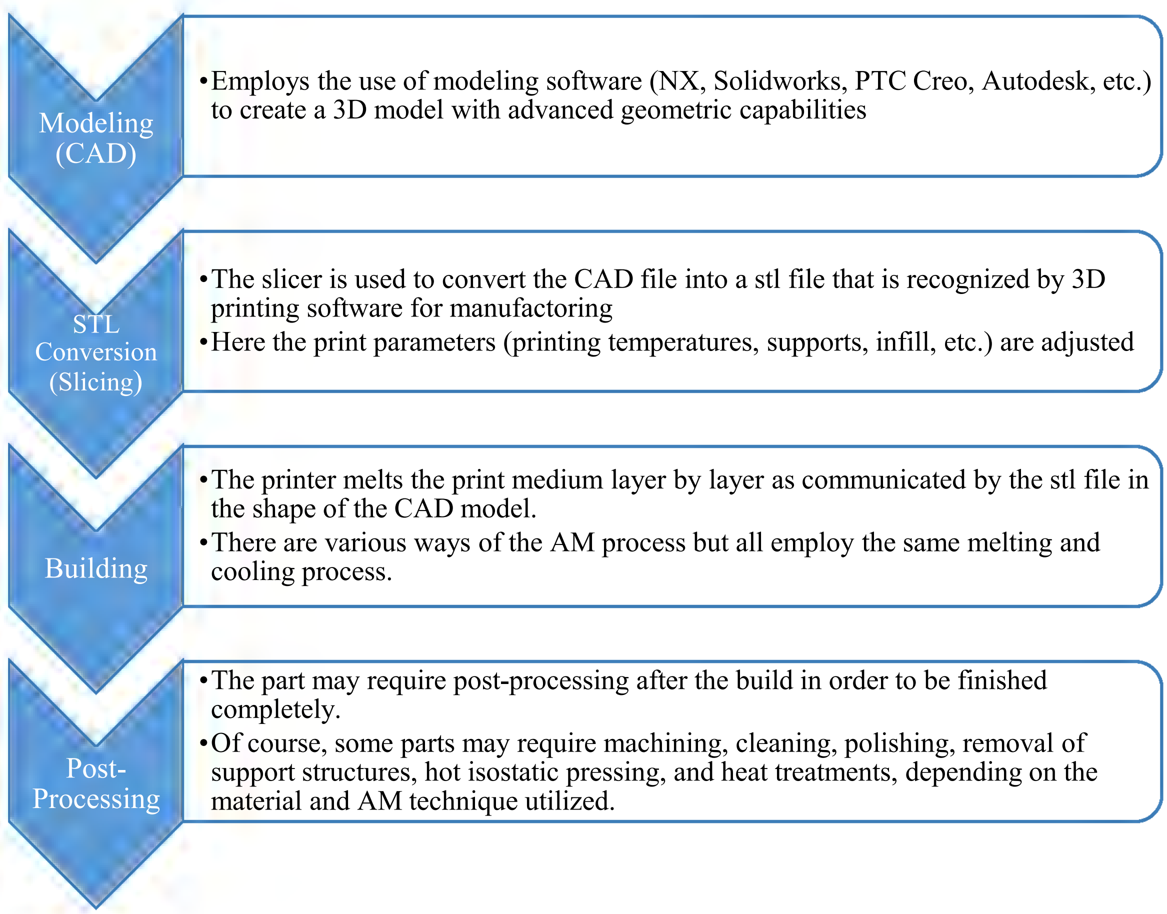


Fig. 1.1 Additive Manufacturing Process Flowchart.

1.2. History

Over the course of several decades, additive manufacturing has experienced significant advancements since its inception. Researchers and engineers started experimenting with different layer-by-layer fabrication techniques in the 1960s and 1970s. One of the first ideas of additive manufacturing is attributed to Japanese researcher Hideo Kodama, who in 1981 suggested a technique for creating solid objects by stacking thin layers of material [2, 1]. The technologies for additive manufacturing progressed during the 1990s and 2000s, and they started to penetrate a number of sectors, such as aerospace, automotive, and healthcare. With the introduction of desktop 3D printers, AM also became more well-liked by customers as the technology became more widely available. The field is still developing as a result of continuous research into new materials, quicker printing methods, and wider use in various industries.

1.3. Techniques

Several processes are included in additive manufacturing, such as binder jetting, material jetting, selective laser sintering, stereolithographic, fused deposition modeling, and directed energy deposition [1]. Additive manufacturing is a flexible and inventive field because these techniques provide a variety of options for creating objects with varying materials, sizes, and levels of complexity.

1.4. Applications

Significant progress in 3D printing has been made in the medical field, with applications ranging from research to practice. Customized orthodontic appliances, prosthetic limbs, medical implants, and even patient-specific medications are being produced via 3D printing. The development of medical supplies and personal protective equipment during the COVID-19 pandemic was made possible in large part by technological advancements [3, 4]. The ability to 3D print living tissues and organs has advanced significantly in the field of biomedical technologies. This may find use in drug testing and regenerative medicine.

Metal 3D printing technologies, such as Direct Metal Laser Sintering , became increasingly used for aerospace and automotive applications [5, 6]. These industries use additive manufacturing for lightweight components, prototyping, and even the production of critical engine parts. Furthermore, Additive manufacturing is playing a crucial role in space exploration. NASA and other space agencies have used 3D printing to produce tools, parts, and even entire rocket engines in space, reducing the need to transport materials from Earth.

Additive manufacturing continued to evolve, with improvements in printer speed, materials, and accuracy. Emerging applications, such as 3D-printed food, construction, and large-scale industrial parts, gained attention. Architecture and construction companies found essential use of the AM process with large-scale 3D printers that can create architectural models, building components, and even entire structures [7, 8]. This has implications for the construction industry, particularly for building rapid prototypes and low-cost housing.

Researchers and businesses have been working on creating a wide range of advanced materials for 3D printing, including metals, composite materials, and high-performance polymers. As a result, material advancement is another area of study. With the help of these materials, additive manufacturing can be used for more applications and has greater potential for sustainability. The use of sustainable 3D printing techniques is growing. This includes developing biodegradable 3D printing materials, cutting energy use, and placing more emphasis on material recycling. The field of additive manufacturing is continually advancing, with ongoing research into new materials, improved printing techniques, and expanded applications. It has the potential to revolutionize how products are designed, manufactured, and distributed in the future.

1.5. Problem with AM

While additive manufacturing (3D printing) offers numerous benefits, it also comes with its share of challenges and limitations. Some of the common problems and challenges associated with additive manufacturing include material limitations and design constraints. Due to the variety of materials that can be used as well as the quality of the finished parts, FDM applications are still very restricted.

The range of materials available for 3D printing is expanding, but not all materials are suitable for all applications. Finding the right material with the desired properties can be challenging. Also designing for 3D printing can be different from traditional manufacturing methods. Certain design considerations, like overhangs and support structures, must be considered [9]. Surface roughness, weak and anisotropic mechanical properties, shrinkage-related geometry deviations and fractures, and others are typical quality problems.

It is crucial to incorporate process monitoring and control on FDM machines to scale up industrial and commercial FDM applications and verify that printed parts meet specifications for its uses. But ensuring consistent quality and accuracy in 3D-printed parts can be challenging, particularly in industrial settings. Fortunately, there is an evaluation method that can be used to monitor mechanical instruments while under operation for quality purposes.

1.6. Fundamental Concept of Nondestructive Evaluation

Nondestructive Evaluation, also known as Nondestructive Testing, or Nondestructive Inspection, is a group of techniques and methods used to assess the integrity, quality, and properties of materials, components, and structures without causing any permanent damage [10]. NDE is crucial in various industries to ensure the safety, reliability, and performance of critical equipment and infrastructure. The primary purpose of NDE is to detect defects, flaws, inconsistencies, and potential weaknesses in materials and structures without altering their functionality or structural integrity. Nondestructive evaluation provides several advantages, including cost savings through preventative maintenance, improved safety by identifying potential failures, and minimizing downtime for critical systems that allows for timely maintenance and repair, reducing the risk of catastrophic failures. NDE is also used in research and development to study material properties, validate new manufacturing processes, and investigate the behavior of materials under different conditions.

1.7. Techniques

There are several NDE methods, each suited to specific materials and applications. Common NDE techniques include ultrasonic, radiographic, magnetic particle, liquid penetrant, thermal imaging, and acoustic emission testing.

Ultrasonic testing employs high-frequency sound waves to inspect internal and surface flaws within materials [11]. It is widely used in various industries, particularly in the evaluation of welds, castings, and composites. Ultrasonic testing relies on the principle of sound wave reflection, with the echoes providing information about the material's condition. It is essential for detecting defects such as cracks, voids, and inclusions.

Radiographic testing involves the use of X-rays or gamma rays to examine the internal structure of objects. It is highly effective for identifying subsurface defects in materials, making it a critical technique in aerospace, manufacturing, and construction [12]. By analyzing the differences in radiation attenuation within the material, radiographic testing can pinpoint flaws, porosity, and inclusions.

Magnetic particle testing is used to inspect ferromagnetic materials. It detects surface and near-surface flaws like cracks and weld defects. Magnetic particle testing involves applying a magnetic field to the material and then dusting it with iron particles. These particles are attracted to areas with magnetic flux leakage, indicating the presence of defects. It is a crucial technique in industries such as automotive and shipbuilding.

Liquid penetrant testing is a versatile NDE technique for finding surface defects like cracks, porosity, and leaks. A liquid penetrant is applied to the material's surface, and it is drawn into any surface openings by capillary action. After applying a developer, the penetrant's presence becomes visible, revealing the location and extent of defects. Liquid penetrant is commonly used in the aerospace, automotive, and oil and gas industries.

Thermal imaging utilizes the detection and analysis of heat patterns to assess the condition of materials, structures, and components. In this method, an infrared camera captures the thermal radiation emitted by an object, producing a visual representation of temperature variations. Variations in temperature can be indicative of defects, anomalies, or structural issues within the material [13, 14]. This technique is particularly valuable for identifying hidden defects, such as delamination, cracks, and voids, in various applications, including aerospace, civil engineering, and manufacturing processes. By analyzing the thermal data, engineers and inspectors can detect irregularities and potential weaknesses in materials or structures. Thermal imaging has become an essential tool in predictive maintenance, quality control, and safety assessment.

1.8. What is Acoustic Emissions

Acoustic emission is a powerful nondestructive evaluation technique that has revolutionized the field of structural health monitoring (SHM). It makes use of the identification and examination of high-frequency stress waves, sometimes referred to as acoustic emissions, produced by mechanical events or modifications in the material or structure that is being studied. AE is essential in many different applications because of its capacity to detect anomalies, defects, and possible failures without causing any harm.

The roots of AE can be traced back to the early 20th century when researchers observed the release of acoustic emissions during the deformation of materials. However, it was not until the mid-20th century that AE started gaining recognition as a viable NDE technique. The introduction of sensitive sensors, amplifiers, and data acquisition systems in the 1950s and 1960s paved the way for AE's application in structural health monitoring. Since then, AE has evolved significantly, both in terms of instrumentation and signal analysis techniques.

The foundation of AE is the theory of elastic wave propagation. Stress causes microstructural alterations in materials, including plastic deformation, dislocation movement, and crack propagation. Acoustic emissions are the result of elastic waves that are released during these events. Depending on the type of event, these emissions come in a wide range of frequencies, from ultrasonic to audible. Through the identification and examination of these emissions, AE offers valuable information about the state of the material or structure being studied.

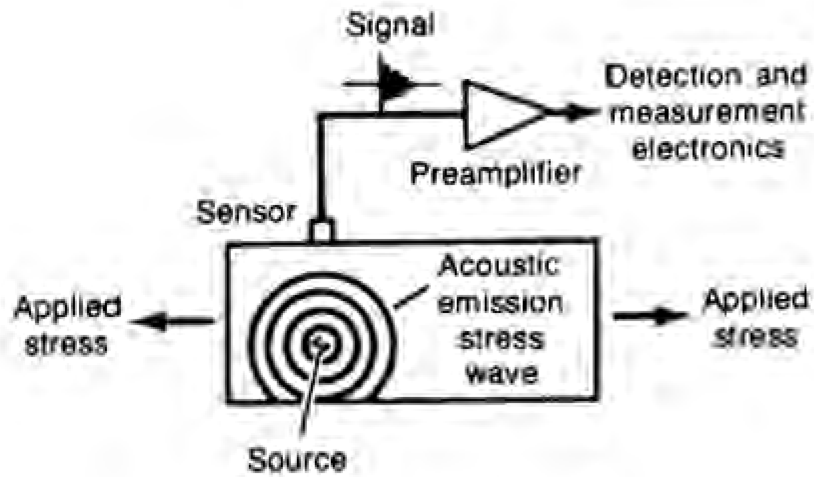


Fig. 1.2 Basic principle of the Acoustic Emission Method [15].

The core of any AE system is its instrumentation. This series of connections includes AE sensors, preamplifiers, the data acquisition system, and its complimentary licensing software. The AE Sensors (transducers) are responsible for detecting acoustic emissions. They are typically piezoelectric or resonant sensors designed to convert mechanical vibrations into electrical signals. They are common in sizes for different applications with certain specific properties. Those properties include heat resistivity, frequency and sound sensitivity, and material. The AE sensors are electrically connected to the preamplifier that takes the signals from AE sensors that are weak and require amplification for accurate detection. Preamplifiers serve this purpose, boosting the signal-to-noise ratio and filtering any unwanted background noises. All parameters concerning the function of the preamplifier are set through the software of the supplier company. This filtered signal then goes into the Data Acquisition System. This system records and digitizes the amplified

AE signals for user interpretation. It captures the time, amplitude, and frequency information, which is essential for subsequent analysis. With this interpreted information and the use Signal Analysis Software, the recorded data is subjected to various signal processing and analysis techniques to identify and characterize AE events. This software can perform tasks such as event location, event counting, and waveform analysis [16].

To extract useful information, a number of analysis techniques are applied to the recorded AE signals. Waveform analysis, frequency, hits, amplitude, and time of arrival are examples of common signal analysis techniques. To ascertain the amount of energy released during an event, amplitude analysis entails measuring the amplitude of AE signals. Larger defects or more significant events may be indicated by higher amplitudes. Time of arrival analysis measures the amount of time it takes an acoustic wave to travel between various sensors, which aids in identifying the source of AE events. Analysis of frequency trends sheds light on the characteristics of the events. Characteristic frequency spectra are produced by a variety of events and can help classify defects. While waveform analysis examines the duration and shape of AE waveforms, it can also provide information about the nature of the event, including information about impact or crack propagation. For the purpose of evaluating the structural integrity and safety of vital infrastructure and components, offering insights into the behavior of materials under stress, and supporting preventive maintenance and safety measures, all techniques extract and relay crucial information for a number of industries, including aerospace, construction, healthcare, and energy. Additionally, AE is a dependable way to generate data for study and advancement.

1.9. Significance of Study

Acoustic emission has effectively transformed the landscape of nondestructive testing and structural health monitoring. Its ability to detect and assess defects in real-time without causing damage has made it indispensable across various industries. AE plays a pivotal role in additive manufacturing process as it acts as a useful source of in-situ and ex-situ quality control and helps to optimize the AM process.

In this work, AE evaluation technique is applied to understand and optimize the AM process. AE signals are generated while a section of material is under tensile load by the creation of elastic waves. In the case of load generation occurrence on a print specimen, the material will generate an elastic wave by the rapid change in the stress state, thus leading it to break. The AE transducer will record the signals and process them for AE hits for interpretation. AE is ideal for this study as its extremely sensitive evaluation equipment can seamlessly capture the desired high frequencies of the material under tensile load.

To do this, Polylactic Acid (PLA) specimens were 3-D printed with a combination of three different parameters, to study the inter-layer bonds [16, 4]. It is usually assumed that the default printing parameters produce the most quality finishes. However, this research aims to investigate the truthfulness of this assumption and determine what combination of printing parameters is the most reliable and efficient.

The remainder of the study will be organized as follows. An overview of the recent studies used to inspire and guidance on the use of the AE equipment for post process monitoring is provided in Section 2. The experimental setup and procedure of the AM process, load generation, and AE acquisition will be discussed in Section 3. The presenting of results and discussions will conclude this paper in the following Section 4 and 5.

2. LITERATURE REVIEW

This project's detailed nature necessitates the accumulation of thoughts and concepts from a variety of previously published articles. This thesis draws on research from mechanical manuals, manufacturing engineering concepts, evaluation methods from diverse backgrounds. Based on previous findings, the use of acoustic emissions to monitor the quality of FDM printers is a vast area of interest. The following section highlights published articles on the use and issues of FDM machines regarding monitoring quality and the incorporation of AE components.

2.1. Use of AM Review: Why focus on AM

In the field of AM manufacturing there has been seemingly a vast horizon of research concerning the usage and improvement. The field of manufacturing has witnessed a significant transformation with the advent of AM and its applications across diverse industries. While subtractive manufacturing has been the traditional method for shaping materials, AM has introduced a revolutionary approach, offering numerous advantages.

Manufacturing has historically relied on subtractive methods, where material is removed from a solid block to create the desired shape. This approach has been effective in producing a wide range of components, from aerospace parts to consumer goods. However, subtractive manufacturing has limitations in terms of design complexity, material waste, and time efficiency.

Additive manufacturing, on the other hand, builds objects layer by layer, allowing for intricate geometries and offering a more sustainable approach to production. It has transformed the manufacturing landscape, with a growing range of applications. AM provides unparalleled design freedom. It enables the creation of complex geometries that would be impractical or impossible to achieve through subtractive methods. One of the other key advantages of additive manufacturing is its material efficiency. It significantly reduces material waste, as only the necessary amount of material is used to build the object, in contrast to subtractive manufacturing, which generates substantial waste through the removal of excess material. AM processes such as powder bed fusion and material extrusion minimize material waste, making it more environmentally friendly and contributes to a more sustainable manufacturing approach [17, 18, 4].

Time efficiency is another area where additive manufacturing shines, particularly in the area of rapid prototyping. One major benefit in the process of developing new products is the expedited design and development process. Faster product development cycles are facilitated by AM's ability to shorten lead times for producing prototypes and final components. The cost-effectiveness of additive manufacturing is also evident in several aspects, from reduced material costs to efficient production to cost of operation as it eliminates the need for expensive molds, dies, and other tooling equipment required in subtractive manufacturing [19, 17, 20].

With advantages over subtractive manufacturing in terms of design freedom, material efficiency, time efficiency, and cost effectiveness, additive manufacturing has become the clear winner. It is especially useful in fields where sustainability, fast prototyping, complex geometries, and material economy are vital. Subtractive manufacturing still has a place in some applications, but additive manufacturing is becoming more and more popular and changing the manufacturing industry due to its versatility and inventiveness. The topic of additive manufacturing was an obvious choice for where to begin the research when deciding how to approach the idea of improvement in the manufacturing field.

2.2. FDM Review: Why FDM

For a number of reasons, fused deposition modeling is one of the most widely used additive manufacturing techniques available today. It appeals to a broad spectrum of users with its blend of affordability, ease of use, and versatility. Due to its comparatively low material and equipment costs, FDM is widely available to a wide range of users. FDM printers are generally more affordable compared to some other 3D printing technologies, making them accessible to a wide range of users [21]. The average cost of a starter FDM 3-D printer kit is around $200 while using inexpensive off the shelf filament. Though it comes with its limitations, it is much more pocket friendly, especially for young people wanting to learn about the industry. Ease of use is another overall factor that would separates FDM from the others. FDM printers are user-friendly and require minimal training for operation. Most of the time, companies who manufacture the printers design the printers with the same operating procedures and slicers as others, resulting in users seamlessly switching brands based on preferences [22]. For example, the CURA slicer application is widely adopted by the AM community as a standard slicing software. FDM is also compatible with a wide range of thermoplastic materials, allowing users to choose materials that suit their specific applications [23].

Though FDM printers are widely used because of its advantages, they still hold their fair share of challenges. Layer adhesion problems are among the most common problems in FDM printing. A lack of cohesiveness between printed layers is a symptom of problems with layer adhesion. FDM prints may exhibit gaps, weak bonds, or delamination between layers rather than forming a seamless object. These problems are concerning because they jeopardize the printed object's overall quality and structural integrity. When using FDM printing, layer adhesion issues can be caused by a number of factors. Inadequate temperature and printing control is likely the most significant. In FDM printing, temperature settings are very important. Insufficient fusion of the layers can lead to weak bonds if the extrusion temperature is too low. On the other hand, excessive temperatures can cause over-extrusion, leading to oozing and poor layer adhesion [22].

High print speeds and excessive extrusion rates can also affect the quality of layer bonding. Faster movements and higher flow rates might not allow the material sufficient time to melt and bond properly. These issues cause weak layer bonds and surface imperfections which compromise the strength and integrity of the printed object. This can be particularly concerning for functional parts that need to withstand stress. Poor layer adhesion may manifest as visible seams or gaps on the surface of the print, affecting its aesthetics. A lot of times the printers might experience print failures where in severe cases leads to wasting time, material, and resources.

Choosing FDM 3-D printing as the area of focus and means to producing adequate research was an easy decision considering the advantages and its popularity. Not only are they cost-effective when purchasing parts and filament, but its ease of use and design permits its high volume of usage cross many industries, which produces many more possibilities as it pertains to researching new ways of improvement.

2.3. NDE Review: Why Acoustic Emissions

Acoustic Emission is indeed a popular and widely used NDE technique due to its versatility, sensitivity, and range of applications. While it may not be the most popular form of NDE overall, it has gained prominence in various industries. Its wide range of benefits leads to its prominent use for evaluation of structural integrity across many industries. AE is highly sensitive to micro cracks, defects, and other structural changes in materials such as filament and can detect and locate damages even at its early stages of stress [24]. This means the research topics that include the production of sounds caused by normal or abnormal operation can be monitored as it provides real-time data on material condition. This is valuable for critical applications where continuous monitoring is essential for improvement purposes [25].

Furthermore, since AE is nonintrusive, it does not require physical human contact with the structure being tested. This is particularly advantageous for inspecting delicate or hard-to-reach areas such as the crevices of a FDM build plate or extruder track. In addition to its functionality, AE provides allows for a wide range of materials, including metals, composites, concrete, and polymers to be monitored and researched, all while being relatively cost effective [26].

One study revealed AE can be more cost-effective than some other inspection methods, especially when used for continuous monitoring [27]. It can reduce the need for costly manual inspections and downtime. Many of the other forms of NDE require consistent maintenance, reboot, and material handling to get the most out of the machine. AE is effortless in operation with its only withdraw the potential of its use is based on the competency of the user [28].

TABLE I

COMPARISON OF NDE METHODS [27]

Method	*Resonant Acoustic*	*Eddy Current*	*Ultrasonic*	*Radiography*	*Magnetic Microwires*
			Defect/Issue		
Cracks	1	1	1	2	1
Material Properties	1	3	3	2	3
Structural Integrity	1	1	1	1	1
Product Lot Variation	2	2	1	1	1
			Defect Location		
Surface (External)	1	1	1	3	1
Surface (Internal	1	3	1	1	1
Bonding/Welding	1	3	2	2	3

			Speed/Cost		
Time Demands	1	2	1	3	2
Inspection Costs	1	2	3	3	2
			Automation Capacity		
Quantitative Results	1	3	2	3	2
Ease of Automation	1	2	3	3	2

1-Excellent; 2-Fair; 3-Poor.

While AE is popular and versatile, it is worth noting that the choice of NDE method depends on specific needs and the nature of the materials and structures being examined. Different NDE methods, including ultrasound, radiography, and magnetic particle testing, also have their own strengths and applications. However, AE's sensitivity, affordability, and ability to provide real-time data make it a valuable tool in the application presented in this paper.

2.4. AE Review: Why Choose This Approach

After an in-depth contemplation of what was to be discovered in the FDM process followed by an extensive researching, a useful article was examined. Researchers at the Georgie Institute of Technology in Atlanta, Georgia also published an article on the study of the AM process based on the failure diagnosis using acoustic emissions. They presented that the numerous obstacles that additive manufacturing now faces with regard to product robustness, quality, and reliability will prevent AM from being used on an industrial scale. To address these issues, they decided that a common AM process defects and correspondingly efficient sensor-based monitoring technique was required. They then used AE signals from both normal and abnormal/failed processes to record and process the investigation of the FDM printing failures. Finally, they concluded with evidence that it is possible to diagnose common process problems, including detection and identification, using the suggested method. The researchers also concluded that this new technique has the potential to be used for various AM processes and could be a non-intrusive diagnostic tool for FDM [20].

The distinction between the presented study above and the remainder of this dissertation will be seen more in-depth in the following section as this thesis aims to study the ex-situ (post process) of the FDM procedure by studying the specimen rather than the 3-D printer itself. A meticulous investigation of this approach was accounted for early on in this research. Originally, the motive was to understand how the 3-D printer reacts audibly to the various changes of print parameters. As seen in Fig. 2.1 and Fig. 2.2, the transducers were placed on top of the build plate and near to the nozzle for monitoring while printing the series of D638 specimen. After experiencing a similar study where AE sensors would monitor a much large metal 3-D printer, the approach was to do the same on small and more available polymer printers. Unfortunately, the approach, like shown in the above study, only allows for data collection in the first layer of the print as the polymer material did not allow for vibrations and clear AE signals to be transmitted through higher layers like metal printers [29]. However, these sources were useful as its presentation of data was registered and mimed in a way, especially concerning the use of charts and points of interest.

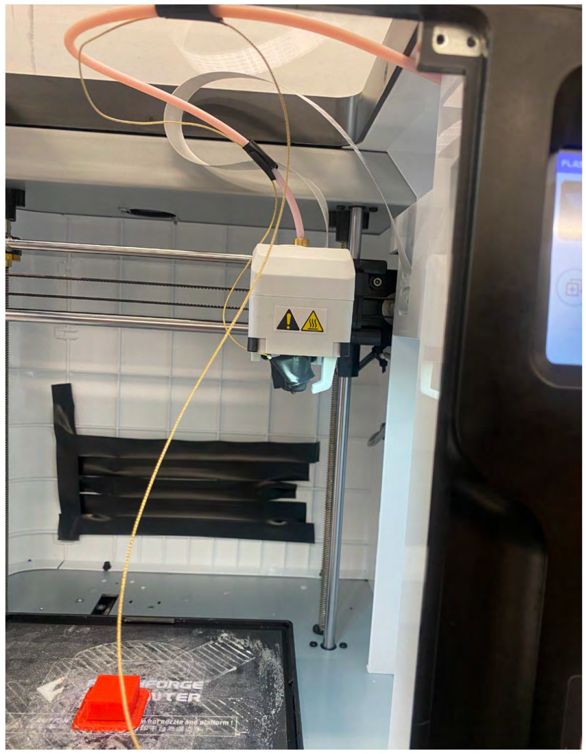


Fig. 2.1 Transducer on Nozzle.

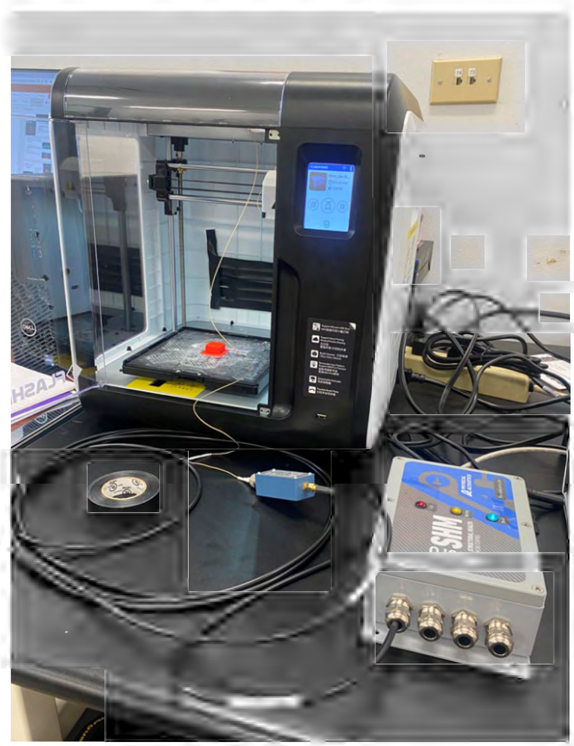


Fig. 2.2 Previous Setup.

The impact of anisotropic printing orientations was one focus presented by researchers of the Universitat Politècnica de Catalunya in Barcelona Spain [30]. They stated that because of the many advantages of this material family, the application of the Material Extrusion process with Thermoplastic Elastomers is currently expanding. These materials are highly flexible and tangible, making them highly valuable in biological applications that necessitate flexible structures with intricate structures. They chose to exam the mechanical characteristics and its anisotropic behavior in printed samples according to three orientations (X, Y, and Z) and relate this to the several kinds of bindings that were created in the samples, including deposited filament, inter-layer bonds, and intra-layer bonds. Sample rigidity was then measured using tensile tests in accordance with ASTM D638, and the failure process trend was investigated using the advanced non-destructive technique of acoustic emission [30]. This study revealed the importance of selecting the correct anisotropic printing orientation as the specimens printed in the orientation of the various axis's displayed different tensile test behaviors and a range of acoustic emissions was produced.

This study focused on the use of NDE through acoustic emission to evaluate the quality and failure of specimens and the use of the tensile testing in compliance with ASTM D638, which will be shown as beneficial to the significance in study. Though this study has its many similarities to this dissertation, this study differs substantially in certain aspects. For starters, the research presented above aims to study how the placement of the specimen's cad design in the X, Y, and Z direction depicts the stress and strain values and the number of hits produced during the tensile test. This accomplished research differs from the research presented in this paper as only the anisotropic printing orientation was varying and the other parameters such as the print speed, layer thickness, and nozzle temperature remained constant for all samples. Nevertheless, this paper turned out to be advantageous as it provided guidance on the approach of the method behind this research regarding placement of the acoustic emission equipment, which will be presented in the next section. To my knowledge, this is the first study analyzing a series of combinations of three printing parameters (layer thickness, printing speed, and nozzle temperature) and incorporating the AE technique to evaluate the damage evolution under ASTM D638 tensile testing criteria.

3. MATERIALS AND METHODS

3.1. Method

The PLA, with hardness 84 used for evaluation was supplied by the Ultimaker Company. PLA is one of the most widely used materials for desktop 3D printing [16]. Because most extrusion-based 3D printers can print with it at low temperatures and without a heated bed, it is the default filament of choice for most of them. It is also characterized by its affordability making it ideal for research as this is the choice filament for many commercial and residential users. This work consists of three mains sections. The first section involves the use of the 3-D printing equipment to print the specimen. The second section covers the standardize use of the Instron 5582 Universal Testing Machine in accordance with the ASTM D638 standards to determine the mechanical properties of the specimen. The third section goes over the use of AE to monitor the specimen and analyze the progression of failure when tensile tested.

3.2. 3-D Printing

The FDM manufacturing process of PLA was accomplished using the Ultimaker S3 3-D printer. The printer was equipped with a composite-ready dual extruder with capabilities of auto bed leveling and use of 190+ materials [31]. The Ultimaker Cura 5.4.0 program was used to slice the 3D CAD models. Here the unique parameters of each specimen was selected along with the orientation. A printing technique was used in the study to form unions between filaments or layers, resulting in two different types of connections. The objective was to analyze the mechanical behavior of these bonds, including their strength and stiffness. Additionally, a comparison was performed by measuring the force needed to test the bonds. Determining whether the unions formed were weaker or stronger than individual filaments was the main goal. To do this, three printing parameters and three levels of each parameter was selected which totaled the number of combinations to 27. In obedience to the ASTM specifications, 5 of each combination must had to be printed to remove any case of rare occurrences during the printing process. In total 135 specimens were printed [32]. The three variations mentioned are displayed in Table 3.1. The printing orientation of the specimen was in the Z direction with the flat face of the specimen facing in the X directions. This configuration was determined by prior research and the use of thermal imaging to collect visual data while being printed. All other printing parameters including, infill density percentage, infill pattern, build pate temperature, and support type remained constant to achieve the level of data reliability needed to determine a conclusion. These parameters can be seen in Table 3.2 and were selected either by research or use of the default setup of the slicer. This manufacturing process was a very tedious task that involved a lot of documentation, material changing, and reprints to accomplish.

TABLE II

COMBINATION OF PARAMETERS

Combination of Parameters		
Layer Thickness (mm)	Nozzle Temperature (°C)	Print Speed (mm/s)
0.10	225	70
0.10	225	50
0.10	225	30
0.10	200	70
0.10	200	50
0.10	200	30
0.10	195	70
0.10	180	50

0.10	180	30
0.20	225	70
0.20	225	50
0.20	225	30
0.20	200	70
0.20	200	50
0.20	200	30
0.20	195	70
0.20	180	50
0.20	180	30
0.30	225	70
0.30	225	50
0.30	225	30
0.30	200	70
0.30	200	50
0.30	200	30
0.30	180	70
0.30	180	50
0.30	180	30

TABLE III

PRINT PARAMETERS THAT REMAINED CONSISTENT

Print Parameters	
Infill Density	40%
Infill Pattern	Triangles (Default)
Build Plate Temperature	60 °C
Support Base Thickness	0.2 mm

3.3. Tensile Tests

Tensile tests were carried out on the specimens using the Instron 5582 Universal Testing Machine that had a 2N-100kN load cell in order to determine their mechanical properties [33]. The design of the specimens and the testing conditions were defined in accordance with ASTM D638 standard [32]. In particular, the printed parts' proportions and form followed the guidelines in the standard type I. To guarantee reproducibility and per ASTM code, five specimens were printed in each orientation. Per ASTM code and for best performance, a 5 mm/min testing speed was selected.

Following the tensile test, the stress and strain data was then organized into an excel sheet for analysis of the average peak stress, duration, and strain amongst the five of each combination. The Matlab application was then employed in affiliation with excel for faster data handling.

3.4. Acoustic Emission Acquisition

The AE technique, which was previously introduced, is a non-destructive testing method for detecting elastic waves. These waves are produced when elastic energy is released as a result of a material's reaction to an external stimulus [15]. During the mechanical test, this technique uses sensors that are placed in touch with the specimen to find the AE events that were produced while the damage increased as seen in Fig. 3.1. Couplant is used as a liquid base to transmit the signal from material to sensor (see Fig. 3.1) [34]. The couplant selected for the research was standard DIY Adhesive deposited with the Rhaegon 60W Hot Glue Gun [35].

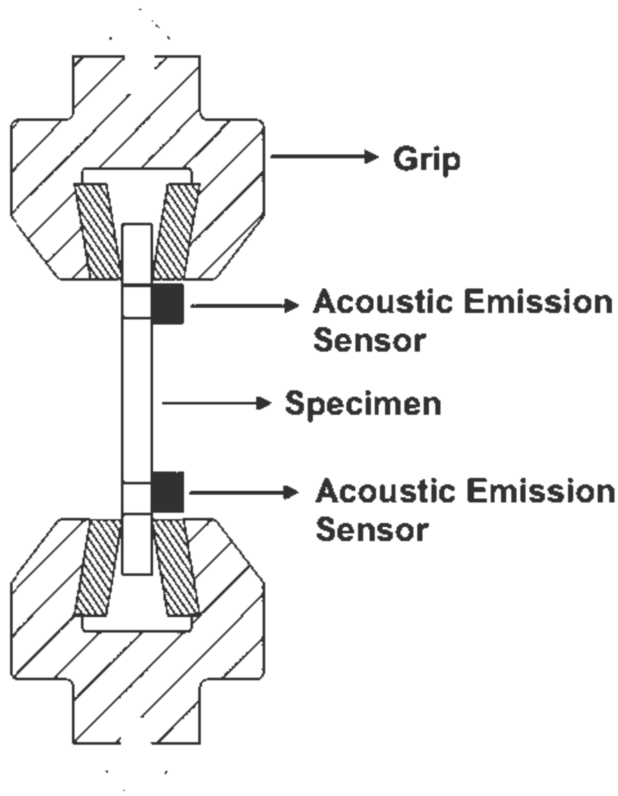


Fig. 3.1 Experimental Use of AE sensors [30].

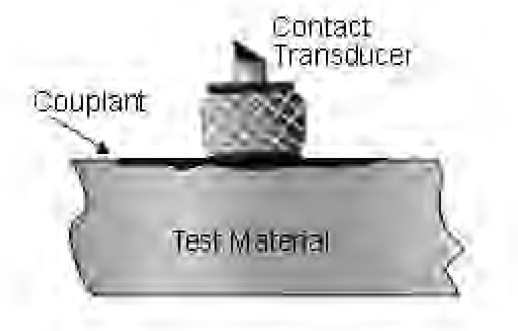


Fig. 3.2 Use of Couplant Diagram [34].

The AE system used to detect and record signals was the Mistras AE Acquisition package containing Micro SHM 4-channel node, 4 In-Line Low Power Wideband Preamplifiers, 8 AE Sensors, and the Mistras licensed AEwin acquisition software [36]. The sensors frequency response was characterized by a minimum of 150 kHz, where the possibility of "shadow" signals from resonating vibrations were limited upon detection. The two AE sensors and preamplifiers were set to 26 dB to ensure that all ambient noises and or noises generated by the Intron machine was not registered, allowing for more accurate data. Each final data set generated by the tensile test consisted of the total number of AE hits, max and average amplitude, and energy which directly correlates with the tensile stress and strain results.

The AE data was then organized into an excel sheet for analysis where an account of the average hit, amplitude, and energy was discovered amongst the five of each combination. The Matlab application was then employed in affiliation with excel for faster data handling.

4. RESULTS

This chapter consists of three main sections. The first section involves the results of the 3-D printing process of the variation of parameters. The second section covers tensile test results while using the Instron 5582 Universal Testing Machine in accordance with the ASTM D638 standards. The third section goes into the results and findings from the use of AE system.

4.1. Printing Process

Three separate parameters were chosen to be researched for determining the quality of parameter selection. The print process was a long and tedious task as print times would vary based on the combination of the parameters as well as several encounters with failed prints. For instance, the prints with the parameters of 0.10 mm layer thickness and 30 mm/s print speed would take four hours each being that 0.10 mm layer thickness means the print requires the completion of more layers to reach the top and 30 mm/s is the slowest of the print speeds. Furthermore, it was discovered that the combination of 180 °C and 70 mm/s print speed often resulted in a failed print due the lack of proper adhesion enough to bare the load of the layers on top of each other Fig. 4.1. As a result, a small adjustment had to be made where the new temperature of 195°C was substituted in for those two fails as seen in Table 3.1. It was revealed that print speed determined the success of the print the most, followed by the nozzle temperature, then layer thickness. This makes sense as the extruded filament would need adequate time to melt and bond to the prior extruded layer. On the contrary, the layer thickness of 0.1 mm rarely failed as the area of the bead of filament that needed to be bonded was smaller, allowing for the possibility of lower temperatures and faster printing.

Fig. 4.1 Defective Specimen.

4.2. Tensile Tests

From the tensile tests, the stress versus strain graphs were calculated. The data from the Instron's operation software was then extracted into raw data files via excel for processing. Matlab's capabilities to extract and organize data from excel sheets was used to generate the graphs shown below in Fig. 4.1, Fig. 4.2, and Fig. 4.3. It should be stated that the lines of the strain versus stress graphs were ordered to start from the moment where the specimen settled in the apparatus, thereby neglecting the portion of the line that experience. The averages of the five specimen per combination was also calculated for analysis. The results from the tensile tests are shown in Table 4.1 where a few patterns can be seen.

TABLE IV

TENSILE TEST RESULTS

Parameter Combination Group	Weight (g)	Stress (MPa)	Force (kN)
0.10_225_70	14.50	51.92	1.89
0.10_225_50	14.20	53.30	1.94
0.10_225_30	14.40	46.15	0.54
0.10_200_70	14.10	46.98	1.71
0.10_200_50	13.80	45.05	1.64
0.10_200_30	13.90	44.51	1.62
0.10_195_70	14.00	45.05	1.64
0.10_180_50	13.90	32.42	1.18
0.10_180_30	14.10	33.52	1.22
0.20_225_70	14.00	49.73	1.81
0.20_225_50	13.90	48.63	1.77
0.20_225_30	14.10	40.38	1.47
0.20_200_70	13.60	43.68	1.59
0.20_200_50	13.60	41.21	1.5
0.20_200_30	14.40	45.33	1.65
0.20_195_70	13.80	44.78	1.63
0.20_180_50	13.30	32.97	1.2
0.20_180_30	13.90	37.91	1.38

0.30_225_70	13.70	40.11	1.46
0.30_225_50	13.80	37.36	1.36
0.30_225_30	14.00	38.19	1.39
0.30_200_70	13.40	36.26	1.32
0.30_200_50	13.20	33.79	1.23
0.30_200_30	13.50	34.34	1.25
0.30_180_70	13.00	29.67	1.08
0.30_180_50	12.20	22.53	0.82
0.30_180_30	14.40	41.48	1.51

The Table presents the peak stress values in MPa with respect to the weight of the specimen in grams, which ultimately shows how strong each specimen turned out to be. The higher stress values were recorded on average by the specimen with the layer thickness of 0.10 mm, followed by the 0.20 mm, and finally 0.30 mm specimen. The Table this shows that amongst the groups with identical layer thicknesses, the print speed and nozzle temperatures also made a visual impact to the stress values. The specimen printed with a temperature of 225 °C on average was able to produce higher stress values than the specimen printed at 200 °C and so on. Finally, the though the slightest differentiation came from the print speed, there is a pattern to be discovered that shows 70 mm/s print speed on average is slightly stronger than the 50 mm/s print speed, followed by the prints of the 30 mm/s speed.

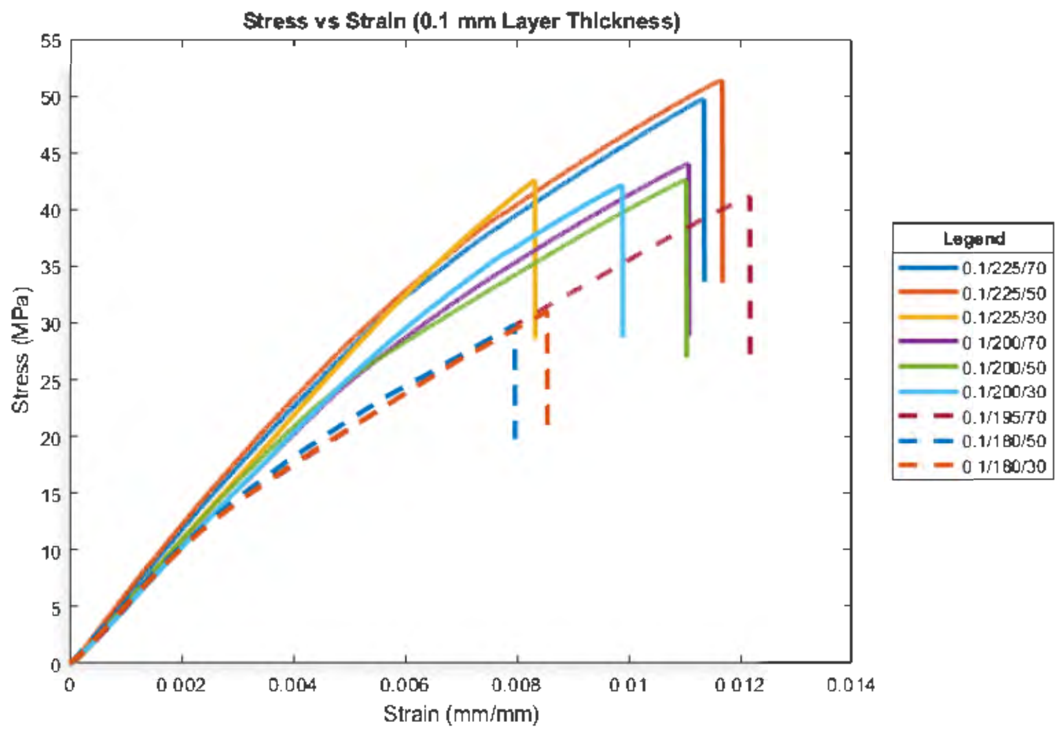


Fig. 4.2 Tensile Test results for 0.10 mm Layer Thickness.

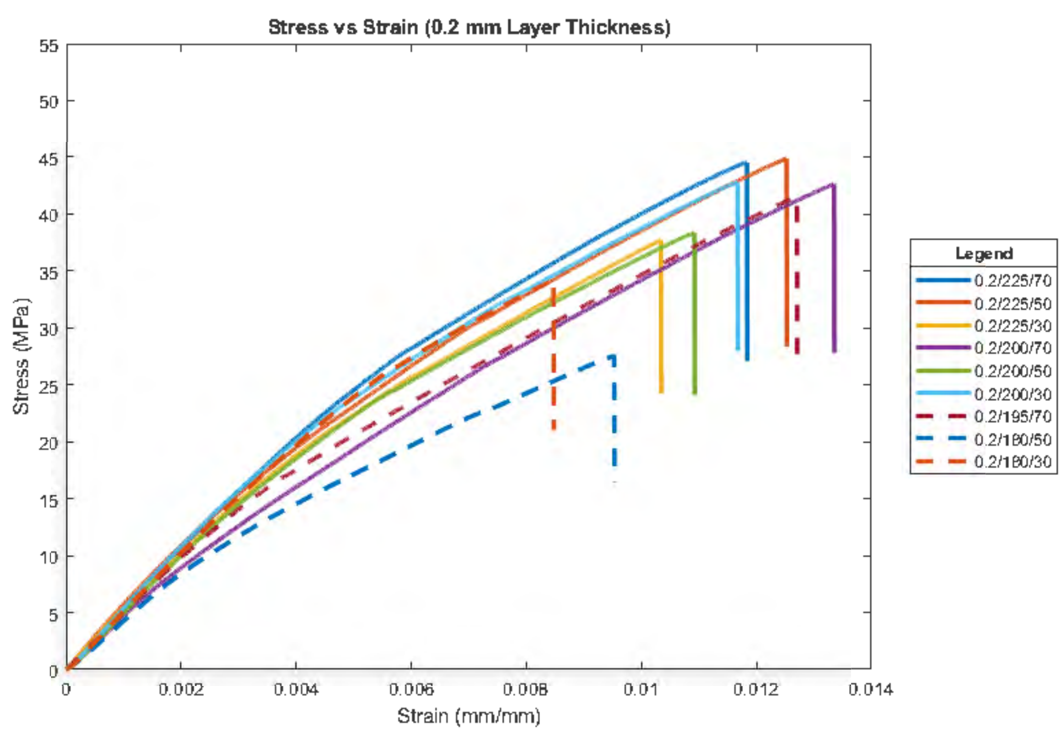


Fig. 4.3 Tensile Test results for 0.20 mm Layer Thickness.

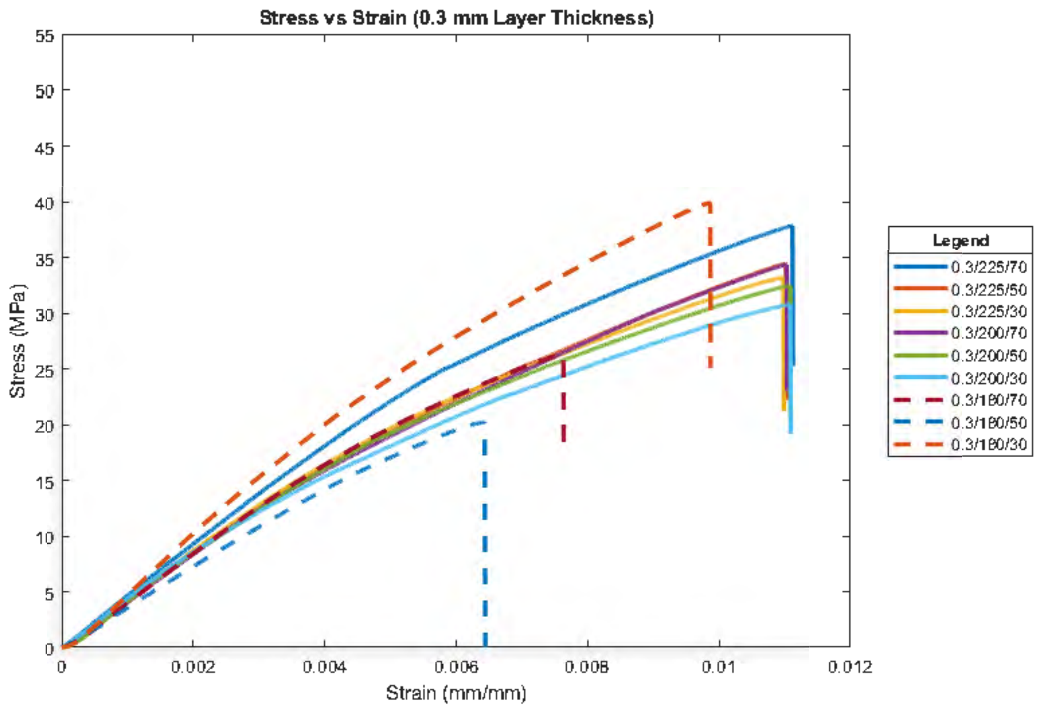


Fig. 4.4 Tensile Test results for 0.30 mm Layer Thickness.

4.3. Acoustic Emission Results

The AE data collected from the uniaxial traction tests were examined. Following the initial examination of the data, signals unrelated to the material breaking due to friction or other noise-producing phenomena were excluded. AE hits was the main focus when acquiring data during the test. The next Table shows the results of the tensile tests.

TABLE V

AE HIT TEST RESULTS

Sorted by Layer Thickness	
Parameter Combination **(Layer Thickness_Nozzle Temperature_Print Speed)**	210
0.1_180_30	210
0.1_180_50	577
0.1_195_70	471
0.1_200_30	906
0.1_200_50	1280
0.1_200_70	1377
0.1_225_30	1239
0.1_225_50	1194
0.1_225_70	440
0.2_180_30	855
0.2_180_50	348
0.2_195_70	531
0.2_200_30	1191
0.2_200_50	913
0.2_200_70	1178
0.2_225_30	579
0.2_225_50	1687

0.2_225_70	1287
0.3_180_30	733
0.3_180_50	937
0.3_180_70	547
0.3_200_30	915
0.3_200_50	652
0.3_200_70	461
0.3_225_30	413
0.3_225_50	670
0.3_225_70	790

Table 4.2 reveals a correlation between AE hits and the print parameters, which can be used to determine the quality of the intra-layer bonds. It can be seen that the specimen printed at 200 °C on average produced the highest number of AE hits amongst the other two variations. The hits for 200 °C were in a range between 900 and 1400 hits while the hits for 180 °C were from 200-800 and the hits for 225 °C ranged from 0-1600. In addition to the nozzle temperature, the layer thickness also produced interesting data where conclusions could be drawn. Amongst three variations of layer thicknesses, those printed with a thickness of 0.3 mm experienced the least amount of hits opposed to the other two. The print speed for the most part again had the least effect on the specimen in regards to the sounds it generated during tensile tests.

The hits graphs generated by the AEwin software was also analyzed and accounted for. Patterns are reveal once a comparison between the tests are presented. The Tables below show the number of hits generated between the two sensors with respect to time as the specimen is pulled apart. An exponential function can be used to describe how time and hits form a relationship in which the number of hits produced increases consistently over time. Moreover, it is evident that the parameters have a significant impact on the hits versus time function characteristics. As show above, it can be seen that the selection of layer thickness upon printing determines the peak amount of AE hits of a specimen under load. The layer thickness of 0.1 mm produces on average the highest peak hit values, followed by 0.20 mm layer thickness and finally 0.3 mm layer thickness. In addition to the peak hits, another discovery regarding the reaction to tensile testing with regards to the print parameters can be visualized. The hits versus time graphs are a product of the cracks and breaks of the filament and intra-layer bonds while it is being pulled apart at a constant speed of 5 mm/min. This means that the lower peak hit values while still maintaining a similar duration before final yield indicates that this combination of print parameters allowed for more elastic properties, there-by producing lets hits. These hit versus time graphs are of direct relations to the tensile test data meaning the high stress producing tests also produced the higher hit amounts.

5. DISCUSSION

By examining the tensile test data and the acoustic emission data collected during the tensile tests, many patterns can be seen that result in the drawing of explanations and conclusions. This section presents the observations gathered and relates what was discovered to answer the questions regarding whether printing parameters determine the quality of the mechanical properties and whether acoustic emissions could be used as a structural health monitoring device while characterizing the intra-layer bonds. The results of the 3-D printing process will be analyzed first followed by the tensile test results. The third section involves analysis of the results from the use of AE system for indication purposes.

5.1. 3-D Printing Results Analysis

The process of printing the variation of specimen resulted in a few combinations failing. As these prints would progress layer-by-layer, the base of the print could not remain stable thus leading to the printer either falling over or moving back and forth while the nozzle was extruding, Fig. 4.2. The reason behind these incidents were thought to be the result of the lack of solid adhesion as the weight of the subsequent layers would be added. This was due to the print speed and nozzle temperature. More specifically, the print speed of 70 mm/s did not allow the proper adhesion of 180°C extruded filament to the bases plate and layers. The temperature of 195°C had to be selected to try to resemble the print quality of the 180°C prints, while allowing for the same print speed. In addition to the failed prints, there were other specimen that produced specimen that contained surface roughness due the similar reasons of layers not being able to bond with the previously extruded layers shown in Fig. 4.1. These faults are the result of the selected combination of printing and the effects were captured during tensile tests.

The orientation of the specimen on the build plate remained consistent for each specimen and allowed for a clear visual of the quality of the prints. Furthermore, the print parameters determined the physical finish of the specimen. The specimen printed in a layer thickness of 0.1mm produced the smoother finishes amongst the other layer thickness. This of course is the results of finer layers producing bonds with smaller spaces between them leading to the adhesion of more bonds through-out the specimen. In addition to the influence of surface quality, the print orientation also had an effect on the reaction to the loading of stress during the tensile tests. Although research suggests that PLA filament has ductile physical properties, the specimen is more brittle than a laid-down printed specimen due to the smaller surface area of each subsequent layer adhering to the preceding layer [30]. It should be noted that orientation of a print heavily determines the reaction to tensile forces. Never the less, the accompanying print parameters were tested and discovered to have just as essential of importance to the mechanical properties.

5.2. Tensile Test Results Analysis

The process of tensile testing the specimen resulted in some interesting findings regarding each reaction to a positive tensile force. Each specimen combination set illustrated, via the strain vs stress graph, unique outcomes that varied in ultimate tensile strength, duration, and slope which is the direct result to their Young's modulus.

The print orientation is one of the key factors affecting a 3D-printed specimen's mechanical properties. Considerations and challenges specific to additive manufacturing arise from the complex layer-by-layer deposition process. A thorough understanding of the interlayer bonds is essential for assessing the printed material's overall mechanical behavior. It is evident that the D638 specimen has properties similar to brittle materials, like some metals, because of the way the print is oriented. This observation is based on the AM principle, which adds layers with the least possible surface area. This layering technique has an impact on the printed material's mechanical characteristics, which include ductility, strength, and deformation behavior.

The D638 specimen, when subjected to tensile testing, showed distinct features in its stress-strain graph that align with the characteristics of brittle materials. Brittle materials typically exhibit minimal yielding and limited plastic deformation before reaching their ultimate tensile strength and eventual failure. This behavior is markedly different from that of ductile materials, which undergo significant plastic deformation and necking before fracture.

In Fig. 4.1, Fig. 4.2, and Fig. 4.3, specific stress-strain graphs for the D638 specimen illustrate this behavior, depicting a limited plastic region and a rapid transition to failure. The stress-strain graph's lack of noticeable yielding and significant plastic deformation is consistent with the traits of brittle materials. This behavior can be linked to the way that layers are bonded together in the FDM process; in other words, the ductility that is observed in conventional manufacturing methods might not be provided by the adhesion between layers.

Comparing the specific stress-strain graph of the D638 specimen with a general strain-stress graph, as shown in Fig. 5.1, further emphasizes the unique mechanical behavior induced by the layer-wise deposition in additive manufacturing. The general strain-stress graph that is commonly linked to conventional manufacturing techniques, like casting or machining, frequently shows an extended plastic deformation region and a more gradual yielding phase. The impact of the additive manufacturing process on the material's mechanical properties is highlighted by this clear contrast.

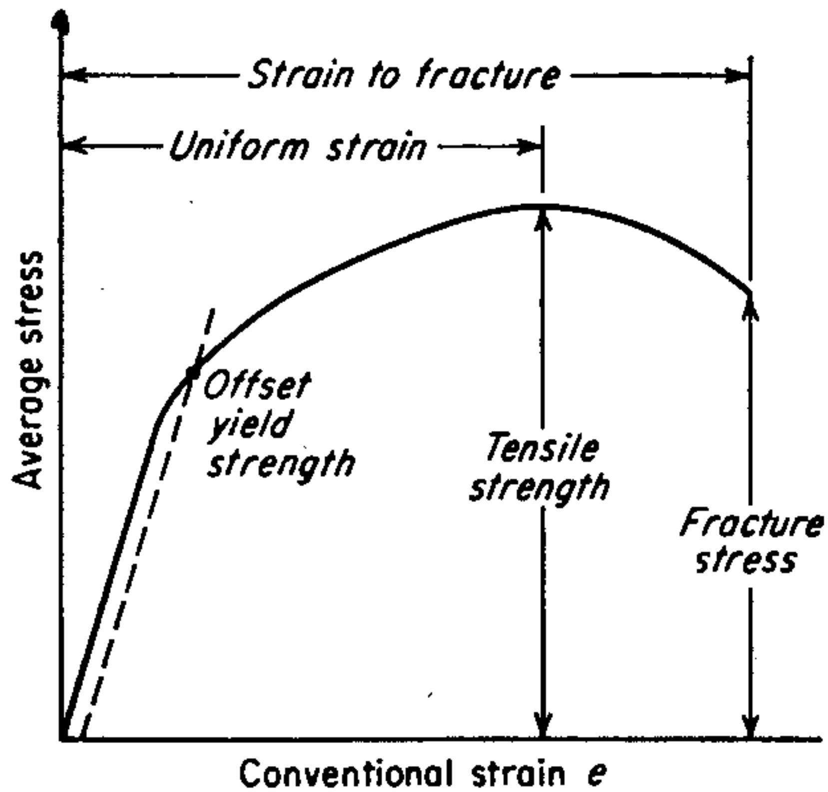


Fig. 5.1 General Strain vs Stress Diagram [37].

The D638 specimen's limited plastic deformation suggests a lower ability to absorb energy before failing, which is a property frequently connected to brittle materials. This has important ramifications for applications where toughness and ductility are essential because brittle materials can break suddenly and catastrophically. It is critical to understand that the mechanical behavior that has been observed is a result of the unique print orientation and layer-wise bonding that are inherent to the FDM process, not a limitation of additive manufacturing in and of itself. Research is currently being conducted to optimize these parameters in order to improve the overall performance of 3D-printed materials. Different additive manufacturing technologies and parameters can result in varying mechanical properties.

Furthermore, after analyzing the graphs for its tensile properties, a few more opportunities for characterization can be discovered. The graphs below show the comparison of Young's Modulus's by layer thicknesses with specified nozzle temperatures and printing speeds. Here several conclusions can be made regarding the Young's Modulus based on the various parameter combinations.

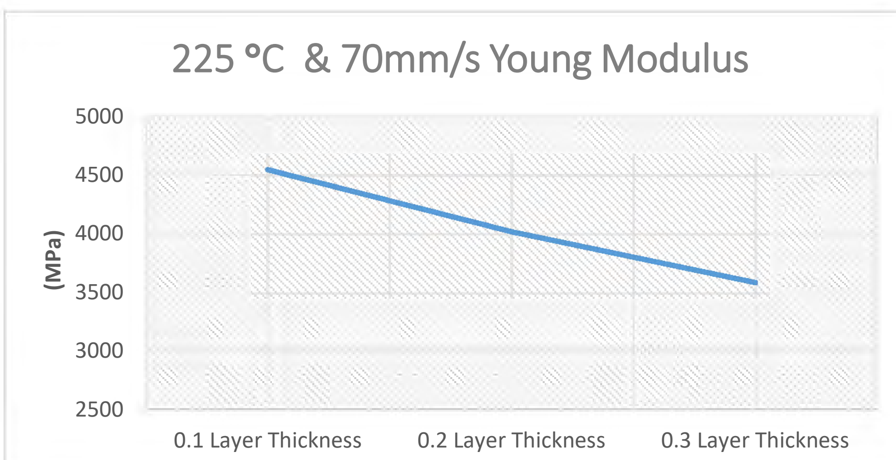


Fig. 5.2 Layer Thickness vs Young's Modulus Graph for 225 °C & 70 mm/s.

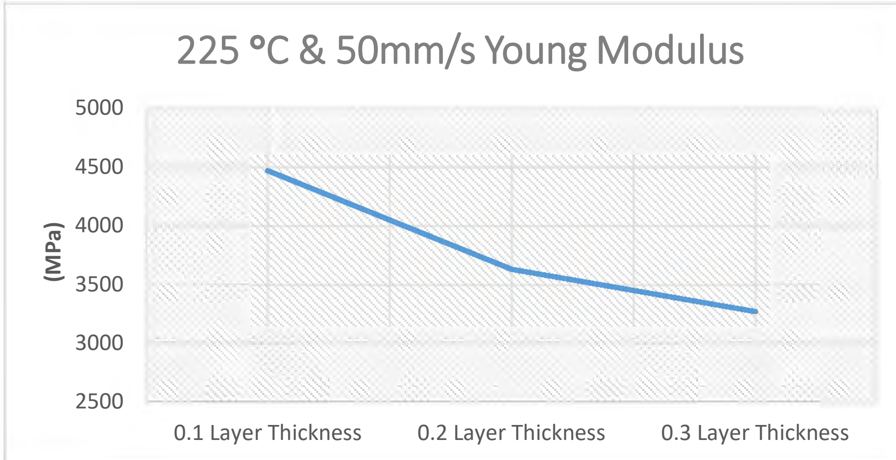


Fig. 5.3 Layer Thickness vs Young's Modulus Graph for 225 °C & 50 mm/s.

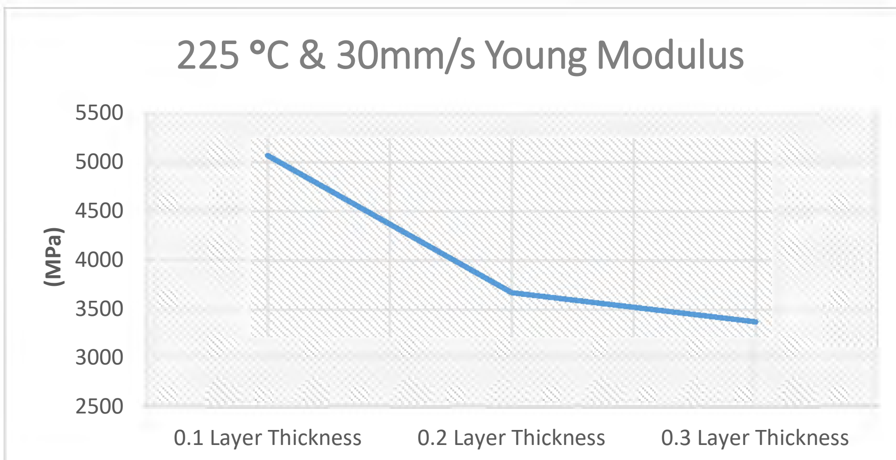


Fig. 5.4 Layer Thickness vs Young's Modulus Graph for 225 °C & 30 mm/s.

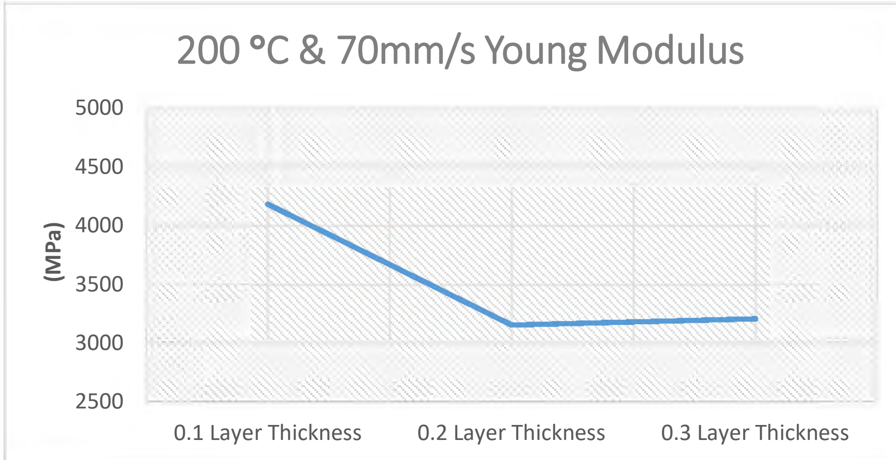


Fig. 5.5 Layer Thickness vs Young's Modulus Graph for 200 °C & 70 mm/s.

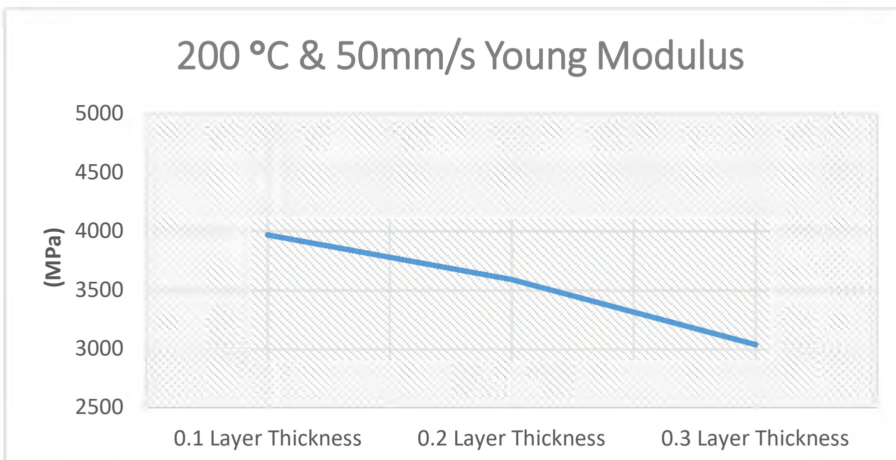


Fig. 5.6 Layer Thickness vs Young's Modulus Graph for 200 °C & 50 mm/s.

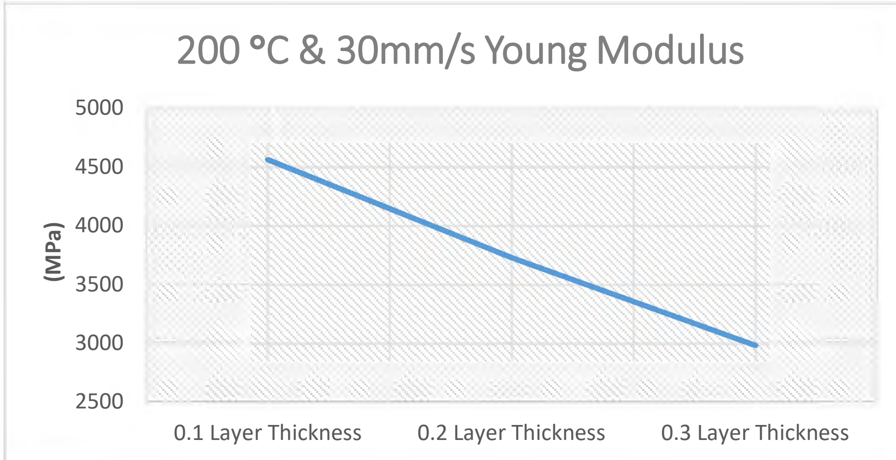


Fig. 5.7 Layer Thickness vs Young's Modulus Graph for 200 °C & 30 mm/s.

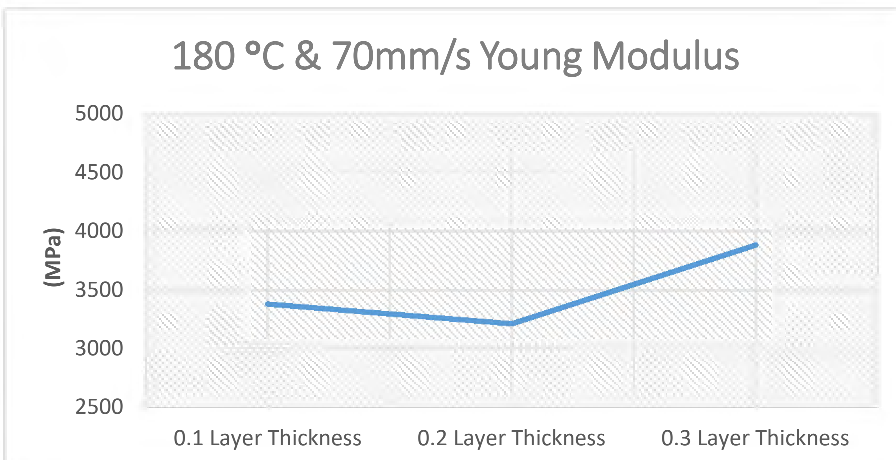


Fig. 5.8 Layer Thickness vs Young's Modulus Graph for 180 °C & 70 mm/s.

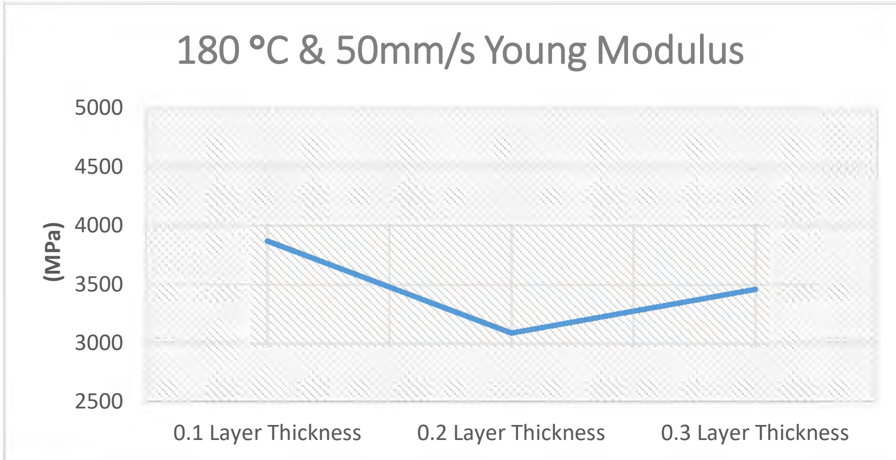


Fig. 5.9 Layer Thickness vs Young's Modulus Graph for 180 °C & 50 mm/s.

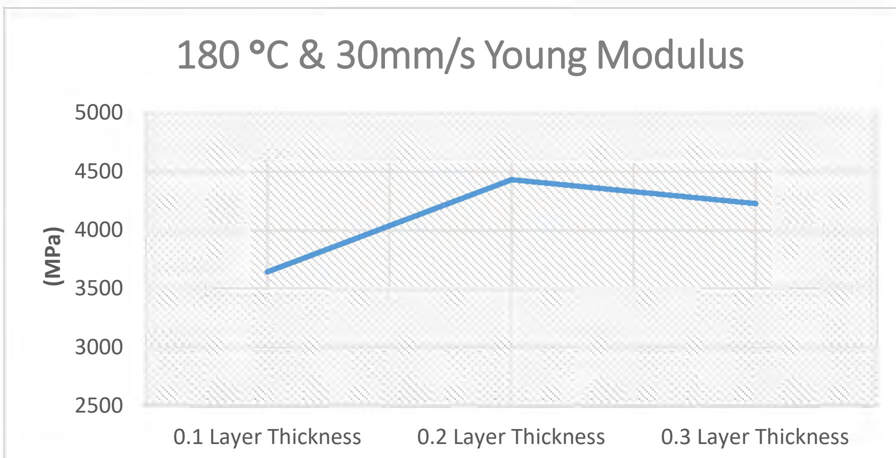


Fig. 5.10 Layer Thickness vs Young's Modulus Graph for 180 °C & 30 mm/s.

Primarily, amongst the first six parameter sets, it can be seen that the Young's modulus, as depicted on D630 stress versus strain graphs, serves as a crucial parameter in evaluating the ductility of specimens, particularly in relation to the thickness of each extruded bead of filament, or layer thickness. The stress versus strain curves provide a visual representation of a material's response to applied forces, and in the context of additive manufacturing, they offer valuable insights into the mechanical behavior of layered structures. A notable observation is that the

Young's modulus, which quantifies the material's stiffness and elastic deformation, is intimately linked to the layer thickness. Thinner layers tend to exhibit higher Young's modulus values, indicating greater stiffness and reduced ability to deform under stress. Conversely, thicker layers often result in lower Young's modulus, suggesting enhanced ductility as the material becomes more amenable to deformation before failure. This relationship underscores the critical role of layer thickness in influencing the mechanical properties of the specimen, with implications for design considerations and material optimization in additive manufacturing processes.

5.3. Acoustic Emissions Acquisition Results Analysis

The acquisition of acoustic signals during tensile testing produced valuable data in both the correlation of the acoustic performance to the mechanical properties, and the aspect of using NDE real time analysis for structural health monitoring and failure prevention. The hits produced during the testing of each parameter combination set was in direct correlation with the values of the ultimate tensile strength (UTS). In particular, it observed that the higher the ultimate tensile strength is, the higher number of hits are collected which can be used to conclude a few things.

AE hits refer to the detectable acoustic signals produced by a material as it undergoes stress or deformation. In the context of D638 specimens, these hits become crucial indicators of the material's response to external forces. The premise lies in the understanding that changes in the internal structure of the material, such as cracking or breaking of bonds, generate acoustic events. Therefore, monitoring and analyzing AE hits during tensile testing can unveil intricate details about the material's behavior.

A compelling finding in recent the investigation is the direct correlation between AE hits and the UTS of D638 specimens. As the UTS represents the maximum stress a material can withstand before failure, the quantity of AE hits seems to increase proportionally with the rising

UTS. This correlation suggests that AE hits serve as an effective real-time indicator of the material's ability to resist tensile forces.

This correlation sheds light on several important factors, one of which is the material's intra-layer bonding quality. During tensile testing, the breaking and cracking of these bonds results in unique acoustic events, or AE hits. A stronger and more durable bonding structure within the material is implied by a higher UTS that results in more AE hits. This finding supports the idea that AE hits are not just random signals but rather are correlated with the strength of the internal bonds within the material. Comprehending the correlation between AE hits and UTS in D638 specimens has noteworthy practical implications. First of all, it offers a real-time, non-destructive way to evaluate the material's structural integrity during testing. As shown in the Tables below, researchers and engineers can also use AE hits as an early warning system to spot possible weaknesses or flaws before catastrophic failure occurs.

TABLE VI

0.1 MM LAYER THICKNESS HITS V TIME GRAPH

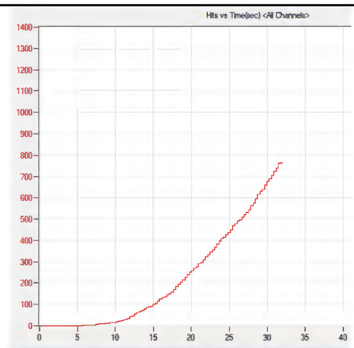
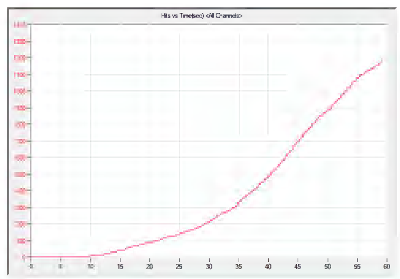
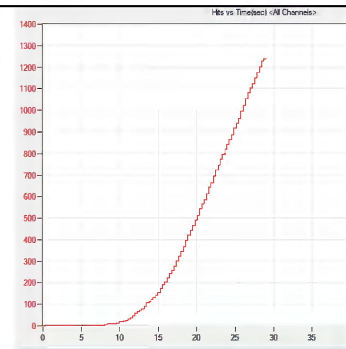
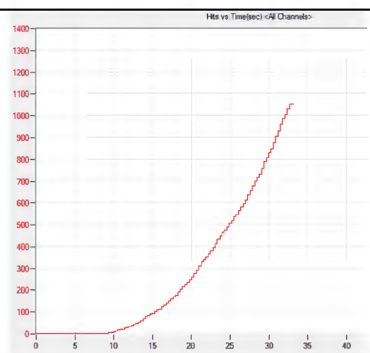
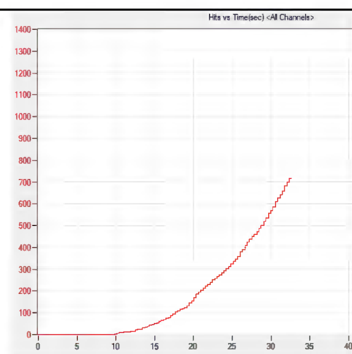
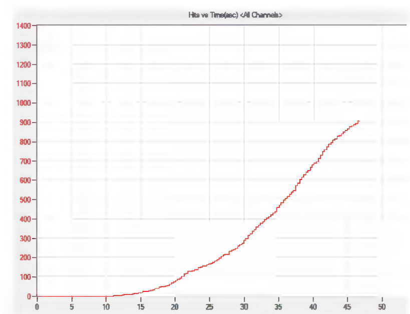
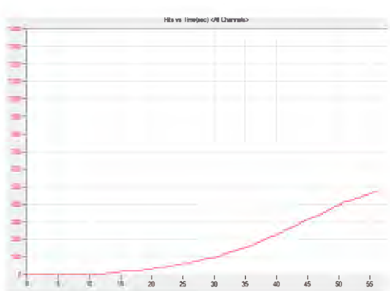
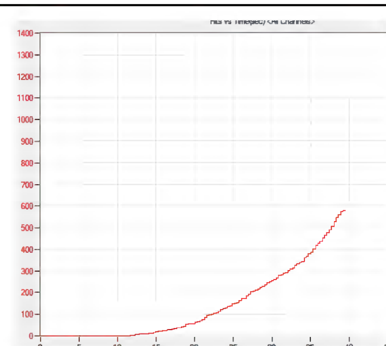
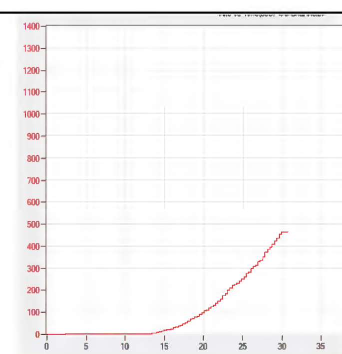
0.1 mm Layer Thickness		
0.1_225_70	0.1_225_50	0.1_225_30
		
0.1_200_70	0.1_200_50	0.1_200_30
		
0.1_195_70	0.1_180_50	0.1_180_30
		

TABLE VII

0.2 MM LAYER THICKNESS HITS V TIME GRAPHS

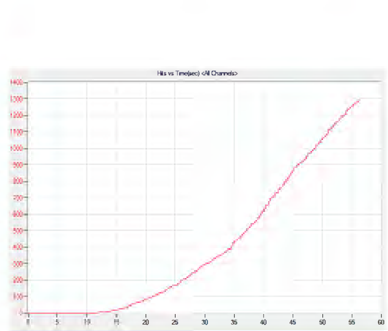
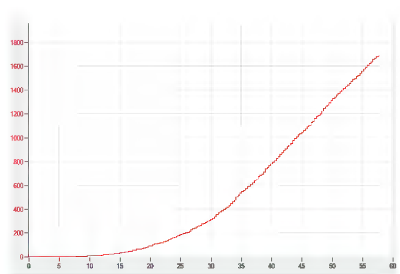
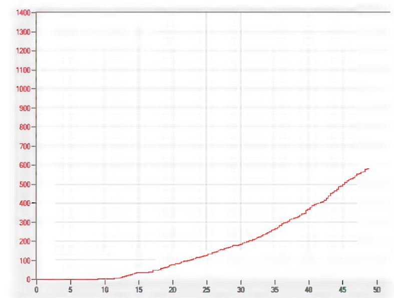
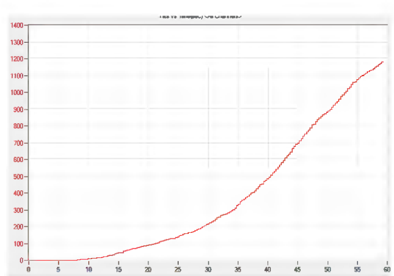
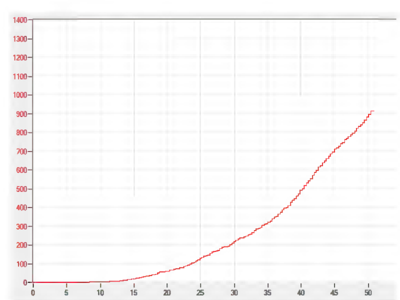
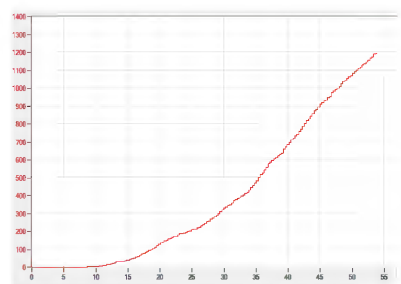
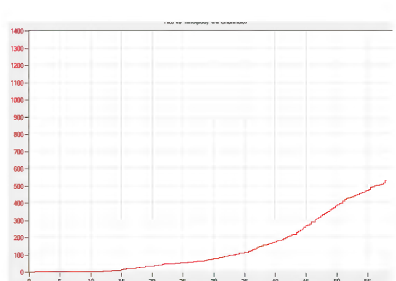
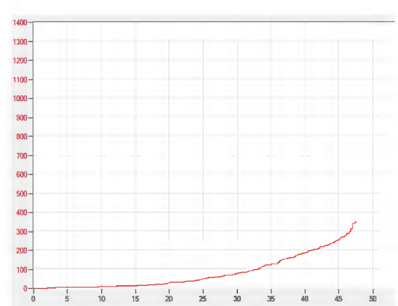
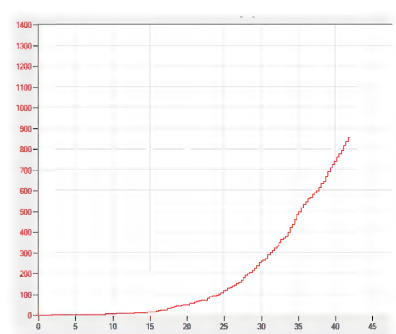
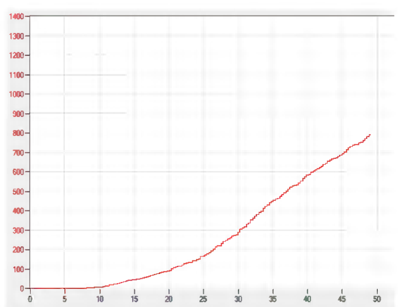
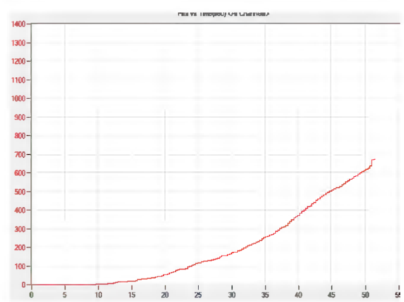
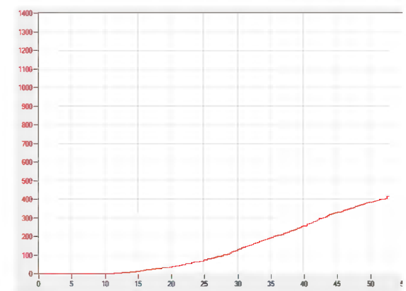
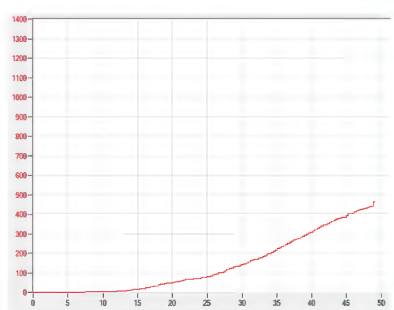
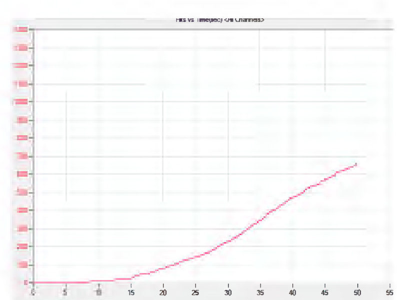
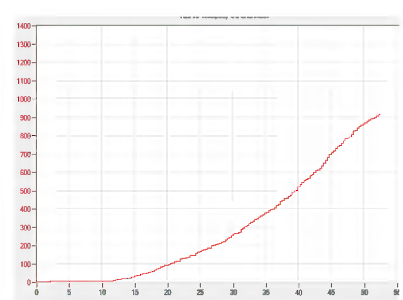
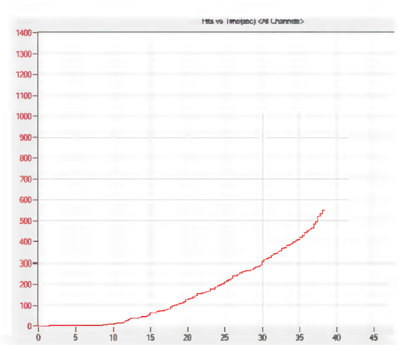
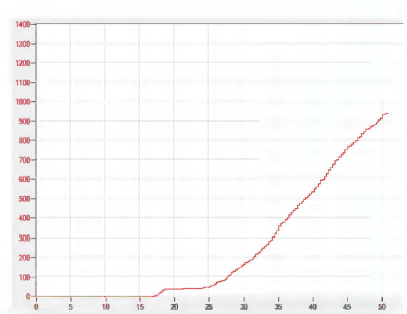
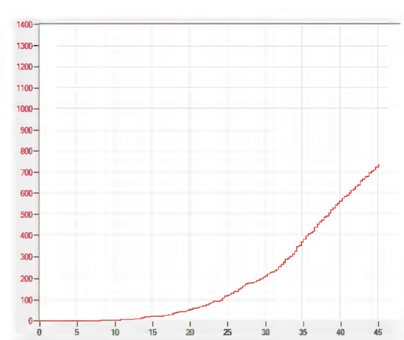
0.2 mm Layer Thickness		
0.2_225_70	0.2_225_50	0.2_225_30
		
0.2_200_70	0.2_200_50	0.2_200_30
		
0.2_195_70	0.2_180_50	0.2_180_30
		

TABLE VIII

0.3 MM LAYER THICKNESS HITS V TIME GRAPHS

0.3 mm Layer Thickness		
0.3_225_70	0.3_225_50	0.3_225_30
		
0.3_200_70	0.3_200_50	0.3_200_30
		
0.3_195_70	0.3_180_50	0.3_180_30
		

An effective indicator for tracking structural health and forecasting probable failure in a material or structure can be the rise in acoustic hits on a hits versus time graph, especially when displaying an exponential growth pattern. This phenomenon is closely related to the AE monitoring method, in which the identification of acoustic signals yields important details regarding the internal alterations taking place in a material. An exponential rise in hits suggests an accelerating rate of these microstructural alterations. The cumulative effect of these occurrences increases as the material gets closer to failure, which causes the number of acoustic hits to increase quickly.

Moreover, a compelling hypothesis emerges concerning the individual slopes observed in the hit versus time graphs, suggesting a potential correlation with the ductility of the specimen group. The steeper slopes appear indicative of brittle specimens, suggesting reduced capacity for deformation before failure, while shallower slopes suggest specimens with bonds more prone to stretching before reaching a breaking point. Based on the graphical representation of acoustic hits over time, this nuanced interpretation provides an additional layer of insight into the material behavior and a useful indicator for differentiating between brittle and more ductile specimens.

The exponential increase in acoustic hits serves as a structural early warning system, exposing microscopic alterations found through AE monitoring prior to noticeable or disastrous macroscopic failures. By enabling proactive actions like maintenance, repair, or component replacement, this timely detection helps avoid unanticipated and dangerous structural failures. Moreover, the relationship that exists between the exponential increase in acoustic hits and the material's increasing stress and strain emphasizes the material's relationship to the material's increasing internal activity when external forces become more intense. This indicates that the material is under greater stress and deformation and may be getting close to its maximum capacity. By examining the rate of increase, the observed exponential trend in acoustic hits allows researchers and engineers to assess the severity of structural degradation in addition to providing a quantitative measure of damage accumulation. Based on the urgency of the situation, this quantitative assessment helps to prioritize actions for maintenance or replacement by improving the precision of understanding how close the material is to its failure point. Furthermore, the exponential rise in acoustic hits is a useful validation tool for structural health models, enabling researchers to compare actual acoustic emission data with expected material behavior under stress to fine-tune and improve predictions.

6. CONCLUSION AND FUTURE WORK

6.1. Conclusion

In conclusion, the relationship found during tensile testing of D638 specimens between acoustic emission hits and ultimate tensile strength provides a nuanced understanding of the choice of additive manufacturing printing parameters. In the context of AM processes, in particular, this correlation is a useful tool for illustrating material behavior under stress. Using acoustic emission hits as indicators offers a straightforward and instantaneous way to evaluate the quality of intra-layer bonds and overall structural integrity. A more thorough understanding of the connections between printing parameters, material qualities, and structural performance is made possible by this capability. Additionally, it greatly enhances the possibility to describe and assess the additive manufacturing process. By employing AE hits as a diagnostic tool, scientists and experts in the field of additive manufacturing can enhance printing parameters, enhance product quality, and improve mechanical properties. In the end, this will improve the reliability and efficiency of additive manufacturing technologies.

6.2. Future Work

As stated before, the focus of this study was the use of acoustic emissions for post-processing (ex-situ) analysis for determining the quality of the combination of print parameters. A future study of the effects these printing parameters have on the print could be had. A recommendation for another form of NDE should be stated as well. There is a possibility that the use of ultrasound or something similar in the auditory nature of acoustic emission would produce affective data that would characterize the FDM process in a different way. Finally, the introducing of a different form of mechanical load should be looked into. Shear and torsion properties are common properties that printed parts might experience in industry, so a study on this would serve to be as beneficial as the one presented.

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Education

- M.S. Engineering, Prairie View A&M University, Prairie View, Texas, 2023
- B.S. Mechanical Engineering, Prairie View A&M University, Prairie View, Texas, 2022

Work Experience

- Company: Bechtel
- Position: Construction Field Engineer (Mechanical), 2023
- Job: Installation of Underground Water and Amine Piping

- Company: CACI
- Position: Mechanical Engineering Associate, 2022
- Job: Simulation Validation

- Company: Leonardo DRS
- Position: Mechanical Engineering Associate, 2021
- Job: Part Remodeling and Documentation

Work Related Experience and Skills

- Skilled in the use of many CAD software (AutoCad, NX, Creo Parametric, etc.)
- Intermediate skill level in programing languages (Python, C++, Yaml)
- Experienced with Acoustic Emission equipment