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Applications of Ultrasonic Non-Destructive Testing in 3D Printing

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ABSTRACT

To determine the capabilities of ultrasonic non-destructive testing methods in 3D printing, test specimens were designed to evaluate advantages and limitations in using ultrasoundC-scanning to determine 3D printing effectiveness. A Matlab program was written to process the data obtained from the UTwin software and ultrasound tank, as well as produce 3D models of the parts being tested. Thickness, types of features, and various printing methods were evaluated to determine how these characteristics vary in effectiveness of C-scan imaging. Results from the UTwin software C-scans were compared to the Matlab program's imaging and three-dimensional modeling. After determining the capabilities of ultrasonic non-destructive testing methods in 3D printing, applications where the technology could be applied to further the additive manufacturing industry are discussed, and the economic potential of the technology in the industry was identified.

Keywords: Non-Destructive Testing, 3D Printing, C-scan, capabilities, applications

INTRODUCTION

The emergence of 3D printing as a viable, effective method of manufacturing in the past few decades [1] has led to great strides in the technologies and methods used in additive manufacturing process. As excitement increased around this relatively new manufacturing method, the technology and sophistication of these machines also increased rapidly [2]. More organizations are turning to additive manufacturing processes to aid in their current operations, as well as develop new and innovative ways to use the technology. One of these organizations is NASA, which on November 24, 2014 became the first organization to 3D print a part in space at the International Space Station [3]. With additive manufacturing processes opening new doors in the manufacturing industry, some of the focus has now moved from expanding the capabilities of 3D printing, to testing and improving the methods for inspecting 3D printed components. Non-destructive testing methods of completed 3D printed parts is one of these new focus areas as researchers search for effective ways to verify the quality and integrity of 3D printed parts.

Using non-destructive testing (NDT) methods to verify quality and integrity of 3D-printed parts is obviously desirable because checking the part for failures and deficiencies while not altering or damaging the part is essential. Testing during the printing process may also offer material and time savings because as a failure is detected, the printer could be automatically shut down before additional parts are manufactured that don’t pass quality standards. Because of the wide variety of capabilities and applications of additive manufacturing, an NDT method which allows for detection of both surface and interior features of a part is valuable. The ultrasonic non-destructive testing methods used in this study fulfill both of these criteria.

Ultrasonic non-destructive testing methods use sound waves to both measure and detect features or failures on or within a specimen. This is done by using a high frequency pulsating wave signal which is sent and received by a transducer. The waves sent from the transducer diffuse through a couplant, often water or a custom couplant product, and then through a test specimen. The waves then reflect off discontinuities in the material, which can be a surface, flaw, feature, or defect. As the transducer receives the wave signal after reflection, the time difference between the sent and received waves can be correlated to a depth or distance from the transducer at which the reflection took place. Figure 1 provides a simplified graphic of wave reflection within a part and the receiving transducer signal.

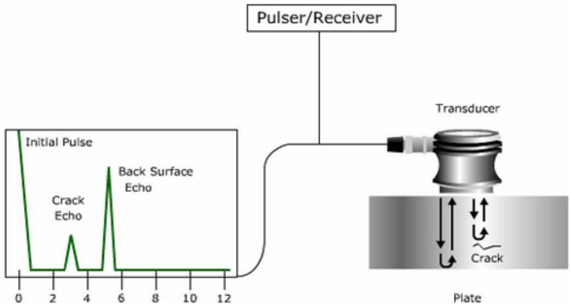

Figure 1: Wave Reflection and Receiver Signal [4]

By using this testing method over a surface, a C-scan image (a 2D image in which colors represent height or depth) can be determined by analyzing the waveform signal, which describes the features of a specimen along a plane of the part or on a surface.

The goal of this study is to test whether ultrasound testing is a viable option for non-destructive inspection of plastic 3D printer parts. Ultrasound techniques are usually very effective methods for non-destructive testing of bulk consistent materials, however, 3D printed parts are not normal bulk materials. Odd surfaces and air gaps exist between layers and may cause significant signal disruptions for ultrasound waves. Test specimens were designed to determine the effectiveness of ultrasonic NDT methods in evaluating different features of the 3D printed parts created. The capabilities of ultrasonic non-destructive testing in 3D printing were then evaluated, as well as a description given of the methods developed to test these capabilities and evaluate the signal data received from the transducer. Finally, the applications of this NDT method in the additive manufacturing industry are discussed.

METHODS

Before an evaluation of the capabilities of ultrasonic NDT methods could be completed, effective test specimens needed were designed to evaluate testing capabilities. When these test specimens were designed, specific characteristics were designed into the specimen to evaluate both the capabilities of ultrasonic NDT as well as any possible limiting factors. The two characteristics focused on during the evaluation process were thickness of the test specimen and internal or backside surface features.

To determine if the thickness of a test specimen related to testing effectiveness, the specimens were designed with varying thicknesses and the same distinct features on the backside surface. By taking a C-scan of the test specimens and comparing the features detected on the backside surface of the specimen, a determination of whether thickness affects ultrasonic NDT capabilities could be justified. A sample test specimen used to determine the effects of thickness on ultrasonic C-scan capabilities is shown in Figure 2. Also considered for evaluation were the effects of feature geometry on a test specimen. The test specimen shown in Figure 2 attempts to vary types of surface features in size and geometry to better understand the capabilities of ultrasonic C-scan capabilities.

Figure 2: Backside Feature of Test Specimen

After the specimen shown in Figure 2 was designed and 3D printed, a specimen devoted to studying the effects of variations in size and geometry was created. Figure 3 displays this specimen, which evaluates the accuracy and precision of the C-scan testing. Surface features were designed as small as 1 mm.

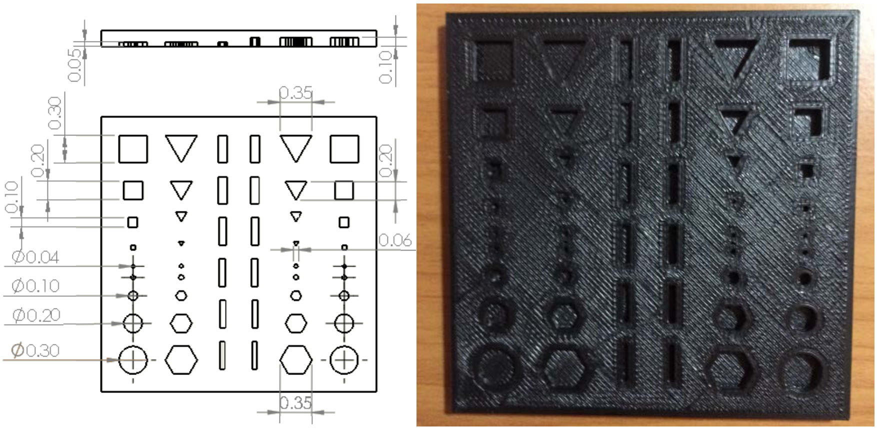

Figure 3: Precision Evaluation Specimen

One of the focuses of the research was the detection of internal features of an object. Using ultrasound C-scan technology, features on the backside surface of a solid object can be detected [4]. However, it is unclear how effective this technology will be when detecting internal features of 3D printed specimens due to the layers of plastic and the different tool paths used to create the layers resulting in disturbances in the ultrasound waves. Furthermore, it was desired to determine if secondary internal features and backside surfaces could be detected along with these types of primary features. The specimen shown in Figure 4 was designed to determine the capabilities of ultrasound NDT in detecting internal features. The boxes shown in dotted lines are located within the specimen; therefore, from the outside, this specimen looks like a rectangular block of plastic.

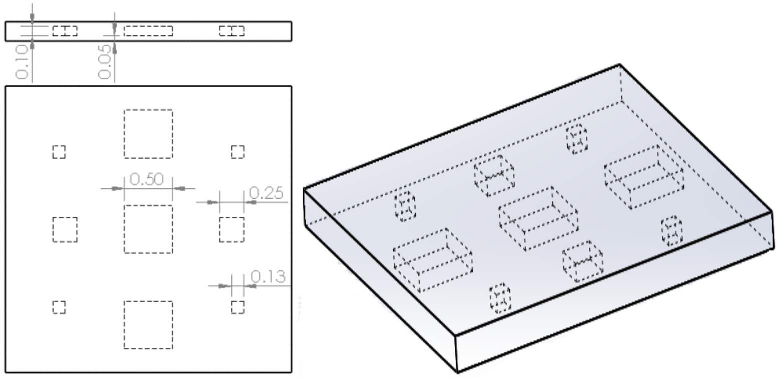

Figure 4: Internal Features Specimen

The three specimens discussed above possess characteristics which aid in the determination of the effectivenss of ultrasound C-scanning. All specimens were printed in Acrylonitrile Butadiene Styrene (ABS) plastic – one of the two most common 3D printing materials. After successful specimens were printed at 100% infill, alternative specimens at varying infills, between 20% and 40%, were tested to determine if infill and hollowness would be a limiting factor in ultrasound NDT of 3D printed specimens.

After the design process and printing of the models was completed, the UTwin software was utilized with the ultrasound tank to evaluate the specimens using a C-scan test. Before running a test, calibration and positioning of both the 10 MHz transducer and specimen to be scanned was completed. The UTwin software's C-scan settings were configured to a resolution of 0.5 mm and a C-scan speed of 10 mm/sec. Figure 5 shows the setup used for scanning a specimen.

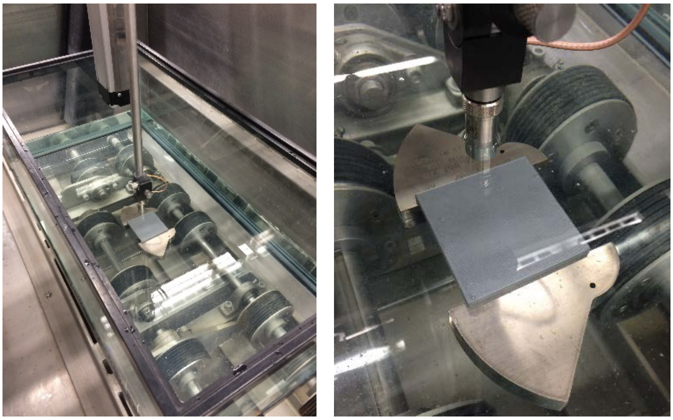

Figure 5: Ultrasound Tank Setup for C-scan (left), Close up of Specimen Setup (right)

When scanning a specimen, a waveform output of the C-scan was produced by the UTwin software. A data file was also generated which contained the waveform depiction of each pixel of the C-scan which was further analyzed in Matlab and used to produce both 2D and 3D representations of the specimens scanned.

RESULTS

The Matlab code was originally written to provide a verification that data logged by a C-scan test could be utilized to produce models, surface images, etc., that went beyond that of the current software used with the equipment. Though the code written did provide this, the most valuable asset it offered related to the time it took to administer a single C-scan test using the UTwin software compared to using the developed Matlab code.

The UTwin software uses “gate” position (“gates” are time period specified to look for signal changes), width, and amplitude to analyze the waveform data received from the transducer. UTwin offers the ability to set up a maximum of four gates which then output four different C-scan results. Although the ability to attempt four different scans at once is valuable, the draw back to the UTwin software is the time it takes for a useful, accurate scan to be obtained. For a high resolution scan of the samples, the average time to scan each sample was 1.5 hours. Furthermore, if a scan is unsuccessful due to gate misplacement, another scan of equal time must be produced to conduct another analysis. In the early stages of the research process, this was identified as a weakness and was then targeted as a secondary goal of the project.

The Matlab program offers three distinct advantages over UTwin. First, only a single ultrasound scan with proper calibration needs to be run with the raw data exported, which allows the data to be analyzed away from the equipment. Because all of the original data is exported, there is never a need to run another scan due to gate placement failure. The Matlab program is able to run a C-scan test on previously exported data and produce a C-scan image in an average of 15.32 seconds, which saves a significant amount of time rather than run another 1.5 hour scan using only the UTwin software.

The two other major advantages of the program dealt with expanding the capabilities of the UTwin software. Writing a custom Matlab program to analyze the data means there are no limitations on the number of gates used to yield a successful C-scan image. The Matlab program could be expanded to as many gates as necessary, providing the ability to determine multiple surfaces during a test and compile those surfaces into a three-dimensional model.

The third advantage of the Matlab program over the UTwin software is the ability to produce three-dimensional models as well as easily analyze specimen thicknesses. Using the program's ability to analyze multiple surfaces, three-dimensional models could easily be compiled by knowing the depth or thickness at which the surface features occurred. The results and capabilities of the program are discussed below.

C-scan Results and Comparisons

To determine if ultrasonic NDT is a viable method of testing 3D printed parts, the specimen shown in Figure 2 was first tested to detect its backside surface features. This test was first run using the UTwin software. The initial test was meant to determine if ultrasonic NDT could be used to pick up backside surface features of a 3D printed part. A portion of the results from UTwin are shown in Figure 6.

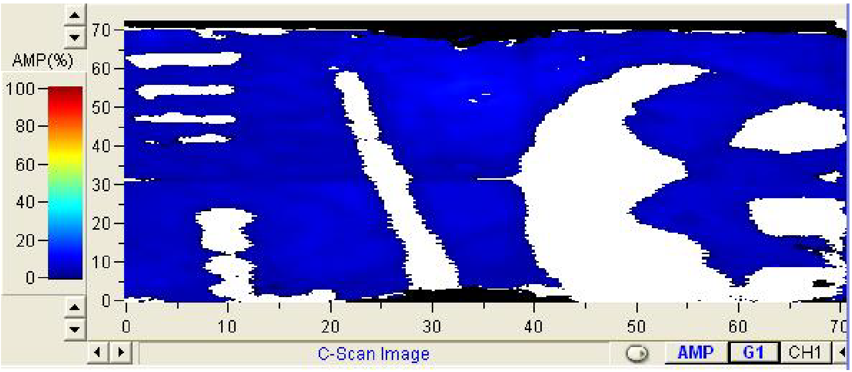

Figure 6: UTwin C-scan Initial Test Results

From Figure 6, it was concluded that the C-scan was able to locate backside surface features designed into the part such as the long diagonal line, the multiple slots, and the randomly shaped round feature. This provided a basis to move forward in developing the Matlab program to further analyze the ultrasound data as well as determine the capability of ultrasonic testing to be used in the additive manufacturing industry.

Next, the Matlab program developed was used to analyze the same data and yielded the 3D model shown in Figure 7 of the specimen pictured in Figure 2 (similar to what is shown in Figure 6 using the UTwin software).

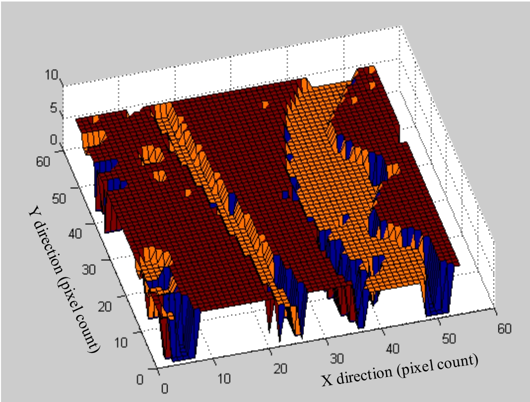

Figure 7: Initial thickness test (in μs) for backside surface geometry detection

The Matlab program was written so each surface depth corresponded to a specific color. The backside (the direction of the specimen facing the direction of the UT sensor) is shown in red, while the surface features designed into the specimen are shown in orange. The blue features of the specimen correspond to data that should be neglected or were not captured by the two gates set during the test. From the average gate position used to detect the backside surface of the specimen, the thickness of the specimen was determined to be 6.7 mm. This compared to the actual specimen thickness of 7 mm, yielding a 4.29% error (thickness determined using nominal wave propagation speeds through non-3D printed ABS plastic sheets [5]).

To evaluate the capabilities of ultrasonic NDT to detect small details on a 3D printed part, the precision evaluation specimen was tested with its features facing up. Although it has been proven that ultrasonic testing is able to pick up these types of features on the top surface of a specimen, 3D printed parts may vary due to the difference in how they are produced. Figure 8 displays the image yielded from the C-scan results produced in the Matlab program.

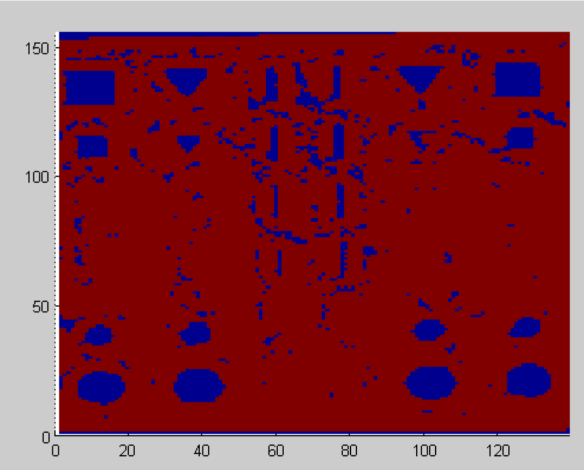

Figure 8: C-scan Image of Precision Evaluation Specimen by pixel

The C-scan was able to detect all of the shape features with a size greater than or equal to 5 mm and parts of features less than 5mm, as shown in Figure 8. The inability of the ultrasound C-scan to pick up the smaller features of the part was unexpected, but is most likely attributed to the uneven, layered surface of the specimen due to the additive layering process of 3D printing. Both depths tested in this specimen yielded similar results, indicating feature depth on the top surface of a part is not a limiting factor in testing capabilities. Noise picked up during testing also caused some error within the imaging of the specimen as shown in Figure 8. These inaccuracies in the imaging due to noise could possibly be filtered out using a function within the Matlab code, and should be considered in future testing.

The internal features specimen (shown in Figure 4) was then tested to evaluate the capabilities of the ultrasound tank in detecting features enclosed within a specimen. Because of the ability to measure the outside features of 3D printed parts rather easily, this feature was identified as one of the more valuable assets of ultrasound NDT. Figure 9 displays the results yielded from the UTwin software when the initial C-scan was run.

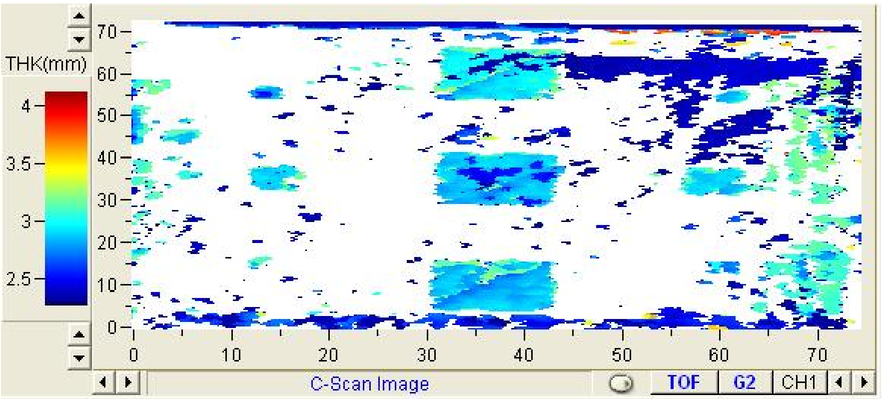

Figure 9: UTwin C-scan Image

From Figure 9, internal features of the specimen were detected (as determined by the UTwin software). The aqua color in the figure definitively represents the feature designed into the specimen. Although this initial scan was successful in finding the hidden features, a relatively large amount of noise also distorted the results. The raw data of Figure 9 were imported into the Matlab program to be further analyzed. Figure 10 displays the C-scan image results from the Matlab program.

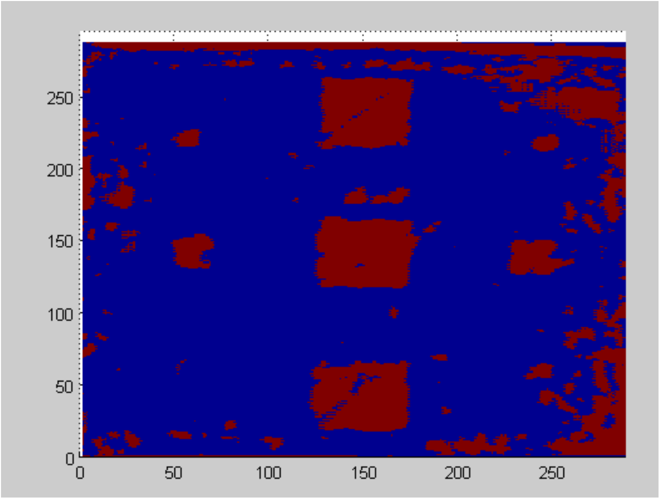

Figure 10: Internal Features Detected by Matlab Program

For this specimen, the image yielded from the Matlab program indicated a thickness of 1.31 mm before the internal features occur. This compares very well to the design thickness of 1.27mm and yields a 3.15% error. This error is again most likely attributed to the difference in the published wave speed through uniform bulk plastic compared to the plastic layers which make up a 3D printed part. The data was further analyzed to detect the secondary surface of the hollow internal features, but these secondary surfaces were not detected. However, from the C-scan results of both the UTwin software and the Matlab program, it was determined that an internal feature as small as 10.9 mm^2 can be detected on a surface located 1.27 mm away from the external surface of a part.

After the specimens printed as solid objects (100% infill) were tested, the initial test specimen was printed with 30% infill to determine if this type of print would pose a problem in producing an effective C-scan image. Figure 11 shows a cross section of a specimen printed with 30% infill.

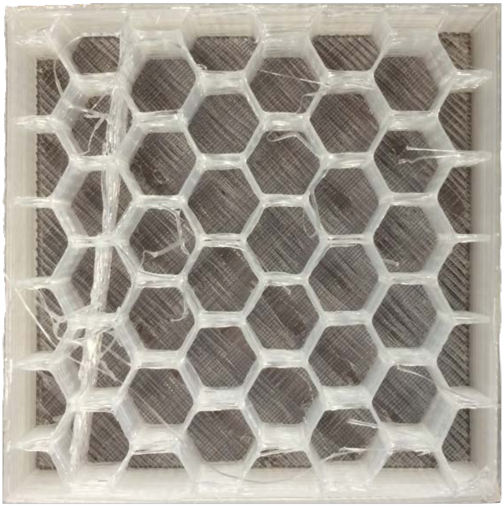

Figure 11: 30% Infill Specimen Cross Section

A C-scan image of the 30% infill specimen produced from the UTwin software is shown in Figure 12. Following the results of the internal features specimen, these results are expected.

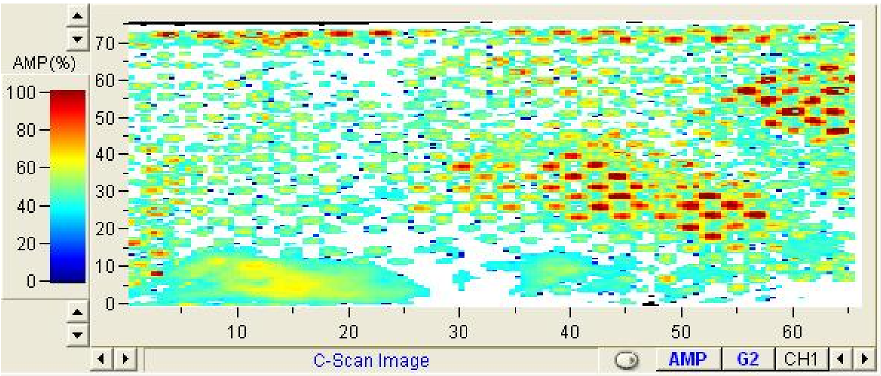

Figure 12: Initial Specimen C-scan Image with 30% Infill

From Figure 12, the honeycomb pattern, which the 3D printers use to fill a specimen partially as support, can be seen very clearly. This type of result was expected due to the air within the honeycomb structures possessing a very low density, which reduces/eliminates the sound wave propagation back to the transducer. Although this type of scan was not successful in detecting the backside surface features of the specimen, it should be considered that the infill was detected by the ultrasound tank fairly effectively. This could be valuable to manufacturers using infill within their 3D printed parts where structural integrity is essential.

DISCUSSION

Through the testing of multiple types of specimens, the capabilities and limitations of ultrasonic NDT methods in the 3D printing industry were determined, and different types of applications of this technology should be considered. The C-scans obtained of the initial test specimen and the internal features specimen identified that ultrasonic testing is able to detect backside surface and internal features of 3D printed parts. This type of application could be very useful to manufacturers who are unable to measure tolerances and part features within an assembly or printed part, but desire to verify the accuracy and success of their print. The major limitation of this testing method is that the testing would need to be completed after the part is manufactured because a high density fluid must be present between the part and transducer.

Two major limitations of ultrasonic NDT of 3D printed specimens were determined from the findings discussed above. Because wave propagation and reflection are related to the density of the material being tested, the reflection of the waves on the second and third layers of a part decreased rapidly, thus posing problems for this type of testing as thickness of a part increases. This, along with the fact that additive manufacturing uses layers to build a part, makes deciphering the waveforms being received by the transducer difficult. This difficulty poses an even greater burden as thickness is increased, and as the layers propagate a greater amount of waves and reduce the return amplitude.

Another limitation determined during the research was the occurrence observed with the infill specimens. Because air is within the specimens when infill is used, wave propagation to layers beyond the air located within the specimen is nearly impossible as air’s density is so small relative to water and the many types of materials tested.

Through the testing of these specimens, two relevant applications for NDT methods were identified. First, through the use of ultrasonic NDT methods after a part is printed, the accuracy, integrity, and quality of the internal features of a part can be tested. Although ultrasonic NDT methods may not be practical in real-time 3D printer monitoring due to the need of a transfer fluid/couplant, a laser or other type of NDT method could be used in conjunction with a program such as Matlab to verify successful progress of a print job by scanning the outside features of an ongoing print. A program would then cross-reference the expected shape and features of the part being printed at the given time or step and determine if the print is proceeding successfully or not. This type of program could save both material and money during large prints, which require a significant amount of time and material.

Although the applications of ultrasonic NDT methods in the 3D printing industry appear limited, the Matlab program developed during this project to better analyze the ultrasound data collected is still a valuable tool that can be used in other material analysis projects completely unrelated to 3D printing. Further testing and analysis should be done to explore more types of applications for the Matlab program and to determine how well the program handles a type of sample/material that is better suited for ultrasonic NDT methods.

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