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Nondestructive evaluation method for standardization of fused filament fabrication based additive manufacturing

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ABSTRACT

In the current investigation, an ultrasonic imaging system originally developed for visualization of microstructures in sheet metals, with capabilities of generating plane two-dimensional images at spatial resolutions between 1 and 200 μm, was used to quantitatively evaluate a Fused Filament Fabrication (FFF) processed 3D test part. For the ultrasonic system, a custom software program was written to control all components of the inspection schemes in a continuous scan mode, including the movement of three orthogonal translational stages, as well as display a live ultrasonic image during scanning and provide tools for advanced post-processing of the recorded ultrasonic signals. Prior to collecting ultrasonic data for a selected test specimen, an optical flat reference standard was used to characterize the ultrasonic probes and to quantify the system's mechanical stability, repeatability, and accuracy when measuring the physical dimensions of features. Ultrasonic data collected at different spatial resolutions were used to characterize a part's surface flatness, internal defects, and fusion conditions; and to measure the physical dimensions of intended features. To validate the accuracy of the ultrasonic internal characterization, one side panel of the test specimen was removed for visual confirmation, and additional ultrasonic data was collected and compared to the original data. Finally, a suggestion is made for adopting a process to qualify or certify FFF based additive manufacturing machines in the market by applying a reliable NDE validation method to a standardized part with various features of different shapes and physical dimensions.

1. Introduction

Unlike conventional subtractive manufacturing processes, additive manufacturing (AM) is the process of making three-dimensional objects from a digital model by depositing metallic or nonmetallic material layer by layer to form different shapes. Advancements in AM machines, processing, and materials, have made on-demand manufacturing of customized, complex-shaped parts a reality [1–3]. The use of AM technology is becoming widespread across a variety of industries, including making biomedical devices for health care applications and polymer matrix composites for electronics and aerospace applications [4,5]. Recently, several additive manufacturing review articles have investigated different AM techniques, such as laser-based processes and extrusion processes (e.g., fused filament fabrication), and highlighted the importance of controlling process parameters to improve the quality of the finished parts [6–11].

While there has been great research interest in improving the quality of AM parts, more work is needed to identify specific guidelines for testing, inspecting, and certifying AM parts, which may require additional quality metrics compared to traditional manufacturing methods [12,13]. Researchers have investigated the application of conventional nondestructive evaluation (NDE) methodologies, which may involve, for example, ultrasonics, X-ray micro-computed tomography, or eddy currents, to inspect finished aerospace grade titanium and nickel based alloy AM parts [14]. Development of NDE methods for metallic materials is ongoing, and it is recognized as one of the most important and challenging tasks for improving the quality of AM parts [15].

Most of the NDE investigations involving AM parts have focused on metallic materials, and little work has been done towards establishing standards for polymer-based AM parts. While the manufacturing processes for polymer-based AM parts are different from those commonly used with metals, the post-production NDE inspection of finished parts can involve similar objectives and methods for detecting, locating, and sizing defects within parts. For fused filament fabrication (FFF) based AM processes, build orientation, layer thickness, air gap, raster angle, and raster width are important parameters that must be optimized to ensure the quality of the finished parts [16,17]. Quality considerations

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associated with FFF processes include factors such as dimensional inaccuracy, surface roughness, voids between beads, and unnecessary material in completed parts. To evaluate the quality of a printed FFF part and assess a specific machine's capabilities, a suitable NDE approach is needed.

Although various types of commercial-off-the-shelf (COTS) ultrasonic immersion systems are available in the market, the lowest spatial resolutions and accuracies in motion control for these COTS systems are typically in the range of 50–100 µm, which may be low enough for inspecting large parts in the scale of tens of centimeters or even in meters. The work presented in this paper, however, requires more refined spatial resolutions in order to reveal internal features with dimension of 50–100 µm. To generate such high resolution ultrasonic images motion control accuracies close to a few microns are required. An ultrasonic imaging system originally developed to visualize microscopic features in welded sheet metals was utilized for the current investigation [18].

The inspection system included a three-axis scanner and two highly damped ultrasonic probes operating at 16 MHz to collect data in pulse-echo and through-transmission modes. Depending on the nature of the printed part, this approach could be used to evaluate the actual manufactured part, or it could be periodically applied to printed test specimens to monitor printer capabilities over time. A standardized test specimen with a simple geometrical shape and pre-determined internal features can be printed and evaluated to allow for comparison of manufacturing capabilities across a range of AM machines and materials. The current investigation looks at how an existing NDE technology can be applied to assess the quality of a part created using an extrusion process with thermoplastic polymer filament (ULTEM™ 9085, a polyetherimide PI). Details of the developed method are presented along with the results and findings of the inspections. The ultimate goal of the current investigation is to demonstrate the possibility of adopting a quantitative NDE method to establish a way of standardizing AM processes and machines.

2. Ultrasonic imaging processes and results

2.1. Imaging system

The imaging system used for the present work consists of a three-dimensional scanner, an immersion tank, two highly-damped 20 MHz ultrasonic immersion probes marked as “TX” and “RX” for the transmitting and receiving probes, respectively, a 250 kHz – 20 MHz square wave generator/receiver, and a computer equipped with a data acquisition board capable of digitizing ultrasonic data at a maximum sampling rate of 1 giga samples per second. A schematic system block diagram is shown in Fig. 1. The three-dimensional scanner was assembled with three Aerotech ATS-100 linear translation stages having a total travel distance of 200 mm per axis with a manufacturer-specified position repeatability of 0.7 µm. In the present configuration, both immersion probes were independently attached to three-axis manual stages, which were mounted on an optical table for accurate alignment of the probes. Two miniature manual rotary stages attached to each probe holding fixture were used to adjust probe angles. The test specimen was mounted on the Z-axis of the scanner using a specimen holder equipped with two angle-adjustment rotary stages.

A scanning program developed using Matlab was implemented to control the components of the ultrasonic inspection system and to process the acquired data in real-time. During a scan, a live two-dimensional image, often called C-scan presentation, of the features that scatter or reflect the sound waves is displayed in a gray shade or a color scale for each of the positions where data is recorded. Typically, C-scan images represent relative changes in the signal amplitude or the time-of-flight data. For the current investigation, additional post-inspection signal analysis tools such as adjustable time gate interval, time slicer, and animation of time-sliced instant images were used to evaluate ultrasonic data further in depth. Many of the ultrasonic images reported in this paper were generated after processing with these tools.

2.2. Characteristics of focused probes

2.2.1. Focal distance, focal zone, beam shape, and diameter

Two identical immersion probes were custom made with 20 MHz 9.5 mm diameter 36° Y-cut Lithium Niobate single crystal piezoelectric elements. The acoustic lens in each probe was shaped to have a diameter of 22 mm so that the beam focal distance and diameter in water were approximately 30 mm and 500 µm, respectively. To measure these probe parameters, amplitude distribution profile images were generated by using the imaging system. From the images, focal distance, focal zone, focal diameter, and the beam shape of each probe at the focal point were quantified. It should be noted that detailed descriptions of the new ultrasonic beam visualization technique are beyond the scope of the present paper and hence were omitted.

The beam's side profile C-scan image depicted in Fig. 2 was captured along the beam propagation direction over a distance of 40 mm starting at a 7 mm offset from the probe's front surface. The second C-scan image depicted below the side profile image represents the beam axial profile captured at the focal point position of 28 mm as indicated by the dashed arrow in the figure. From the beam side profile image, the focal-distance and focal-zone were measured to be 28 mm and 12 mm, respectively. The beam axial profile image at the focal point position was used to determine the diameter of the focused beam, which was measured to be about 0.55 mm at −6 dB from the center peak amplitude. The receiving probe's beam characteristics were similarly measured to have a focal distance of 29 mm, focal zone of 13 mm, and a focal diameter of 0.65 mm.

To measure the beam diameter of the transmitting probe more accurately, both horizontal and vertical components of the amplitude distribution data were plotted at the focal point as a function of distance from the beam center as depicted in Fig. 3. The beam diameter at -3 dB from the peak amplitude was measured to be 0.4 mm for both vertical and horizontal components, and at -6 dB it was 0.55 mm and 0.57 mm for the vertical and horizontal components, respectively. When the focal diameter of the receiving probe was measured similarly, the beam shape was circular at the focal point of 29 mm with focal diameters of 0.45 mm and 0.6 mm at -3 dB and-6 dB, respectively.

2.2.2. Damping characteristics and waveforms

Both transmitting and receiving probes were designed not only to have tight focused beams with similar focal distances and focal zones, but also to have a high damping property to minimize the ringing effect. When a probe's damping property is increased, the frequency response of the probe becomes broader while the natural resonance frequency of the piezoelectric element downshifts to a lower frequency. The waveform depicted in Fig. 4 is an oscilloscope screenshot of the ultrasonic signal detected by the receiving probe in water after the transmitting probe was tuned to a maximum output level. The center frequency of the detected signal was measured to be 16 MHz, since 62.5 ns of time elapsed between the two small arrow cursors positioned on the waveform. At this frequency, the wavelength of the ultrasonic signal in the ULTEM™ 9085 filament material is approximately 144 µm based on the measured longitudinal mode sound velocity of 2310 m/s.

2.3. Static and dynamic stabilities of the three-axis scanner

Three linear translation stages were assembled to make a Cartesian coordinated three-axis scanner. The Y and Z axes were used as either the primary or secondary axis depending on the scan configuration desired for the part to be inspected, while the X-axis was used to adjust the location of part with respect to the focal zones of both transmitting and receiving probes.

During the course of preliminary scanning, there were mechanical