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Original Article

Non-destructive testing of glass fiber reinforced polypropylene matrix polymeric composites produced by additive manufacturing

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ABSTRACT

Material extrusion-based additive manufacturing (MEX) is an innovative method that has become widely used in the production of polymeric materials. With this method, final products have started to be produced beyond prototype production. However, inherent characteristics of the MEX process can lead to production-related discontinuities that, if undetected, may reduce part performance and cause safety risks or unexpected failures. Non-destructive Testing (NDT) methods, which have been applied in the industry for many years, are crucial in the detection of these discontinuities. To detect discontinuities in thermoplastic composites produced by MEX and to examine the application examples of these methods, samples containing 30 wt% glass fiber with polypropylene matrix were produced in the study. Discontinuities were artificially created in some samples, and the performance of non-destructive testing methods in detecting these discontinuities was measured. 0.1, 0.2, and 0.4 mm layer thicknesses were produced, and the effects of layer thicknesses on ultrasonic sound waves, thermal change rates monitored by thermal camera, and the detection of discontinuities in the sample were examined. In the ultrasonic inspection method, it was found that the increase in layer thickness improves the sound echo transmission and makes it difficult to detect discontinuities in samples with a layer thickness of 0.1 mm. Thermal imaging results revealed that layer thickness did not significantly affect the overall temperature distribution, but the discontinuity detection was more visible in the AL tape region with high thermal conductivity than in the PTFE tape region, and the rate of temperature change was slower in the AL tape region. Discontinuities were detected in NDT controls with ultrasonic inspection and thermal imaging, and it was shown that similar discontinuities can be detected with these techniques.

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INTRODUCTION

Polymeric composites are lightweight, durable, and economical materials widely used in many areas of our daily lives [1, 2]. These materials offer high mechanical performance play an important role various reinforcing elements integrated into the polymer matrix [3]. In sectors such as aerospace and automotive, composites are preferred to increase fuel efficiency by reducing the weight of vehicles and to meet high strength requirements as well as lightness. Polymeric composites, which have a wide range of applications from sports equipment to medical devices, electronic devices to building materials, energy saving and environmental sustainability. These properties have made them an indispensable part of modern engineering and design [4, 5].

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Within polymeric composites, thermoplastics are increasingly emerging as a preferred matrix material. Due to their properties such as thermoformability, recyclability, and high impact resistance, thermoplastics are used in many industries [6, 7]. Their faster processability compared to conventional thermoset matrices reduces production costs and offers an environmentally friendly alternative [8]. Reinforcing thermoplastics such as polypropylene (PP), polyamide (PA), and polyetheretherketone (PEEK) with glass fiber or carbon fiber offers an ideal solution for applications requiring high strength and stiffness. In addition, the reshape ability of thermoplastic matrix composites contributes to the reduction of waste generated during production and sustainable production processes [9].

Thermoplastic composites are produced by a variety of methods and techniques, including injection molding, extrusion, thermoforming, spinning, and rolling. These methods are selected depending on the size and type of reinforcement material in the composite and the design requirements, and the production scale of the composite product [10–13]. In recent years, additive manufacturing methods have attracted attention as an innovative approach to the production of thermoplastic composites [14]. Additive manufacturing allows composite parts with complex geometries to be produced. The advantages of additive manufacturing include minimized material waste, easy implementation of customized designs, and speed in prototype production [15]. Material extrusion-based additive manufacturing (MEX) is the preferred method for thermoplastic composite production. In this method, the use of thermoplastic compounds formed by reinforcing carbon, glass, etc., fibers makes it possible to produce high-performance and lightweight structural parts. This method opens the door to revolutionary applications in the aerospace, automotive, and medical sectors [16, 17].

High-performance thermoplastic matrices such as polyamide (PA), polyetheretherketone (PEEK), polypropylene (PP), and polycarbonate (PC) are generally preferred in the production of thermoplastic composites for engineering applications. These matrix materials are chosen for their properties, such as high temperature resistance, chemical resistance, and mechanical strength. Fibers such as carbon fiber, glass fiber, and Kevlar are widely used as reinforcement materials. These reinforcements increase the strength and stiffness of the composites while at the same time providing a weight advantage. However, in extrusion-based methods, the bonding quality at the matrix-reinforcement interface, homogeneous material distribution, and interlayer adhesion are aspects that need to be improved [18, 19].

Discontinuities such as insufficient extrusion, layer separation, and interfacial bonding problems can occur in thermoplastic composites produced by material extrusion-based additive manufacturing. If these discontinuities are not detected, the mechanical performance of the produced parts is severely reduced, and unexpected failures may occur during use [20]. Failure to recognize such discontinuities can pose safety risks, especially in critical engineering applications. Non-destructive testing (NDT) methods can be used in the manufacturing process to detect discontinuities. For example, methods such as infrared thermography, ultrasonic inspection, and X-ray computed tomography are effective tools for detecting the quality of adhesion between layers and internal discontinuity [21].

Table 1. GF30-PP mechanical properties (XSTRANDTM 3D Printing Filaments, [25])

Properties	Value	Standard
Tensile Modulus (MPa)	6500	ISO 527 (1 mm/min)
Tensile Strength-Yield (MPa)	60	ISO 527 (1 mm/min)
Elongation-Break (%)	1.6	ISO 527 (1 mm/min)
Flexural Modulus (MPa)	4300	ISO 178 (2 mm/min)
Flexural Modulus-Yield (MPa)	83	ISO 178 (2 mm/min)

Ng et al. [22] developed an acceptance criteria model for quality control checks of MEX-manufactured parts using the 2-dimensional (2D) X-ray NDT technique. Preliminary studies have shown that 2D X-ray imaging can detect embedded discontinuities in MEX-manufactured parts. Hernandez-Contreras et al. [23] similarly focused on discontinuity angles to predict the mechanical properties of MEX fabricated parts using NDT. Computer tomography (CT) scanning was used to measure and analyze discontinuities in tensile test specimens produced by MEX in three different directions. The relationship between the mechanical properties of yield strength (σ) and Young's modulus (E) of the specimens and the detected discontinuity structures was analyzed. Butt et al. [24] also performed ultrasonic examination of graphene-reinforced PLA composites produced by MEX at different print speeds and bed temperature values, and correlations between sound transmission times, hardness, and mechanical properties were determined.

The novelty of this study lies in evaluating the detectability of potential discontinuities—such as artificial holes and delamination-like defects between layers—in glass fiber-reinforced thermoplastic composites produced via MEX using NDT methods. The influence of different types of discontinuities and manufacturing parameters on the performance of NDT techniques was experimentally analyzed through comparative assessments. In this regard, the study aims to contribute to quality control practices for additively manufactured composite materials.

MATERIALS AND METHODS

Material

Xstrand GF30-PP filament from Owens Corning was used in the study. PP matrix filament with 30 wt% glass fiber reinforced has 0.94 g/cm^3 density, 167 °C melting point, 120 °C heat deflection temperature [25]. The mechanical properties of the GF30-PP material used are given in Table 1.

Polytetrafluoroethylene (PTFE) film and aluminum tape (Al Tape) were used to create artificial discontinuities in polymeric composite samples produced by MEX. PTFE films are Aldrich brand, product number GF00775122, and the thickness is 10 microns. Aluminum tape is Aluminum Foil Tape 425 product of the 3M brand. AL tape is thick at 0.12 mm.

Table 2. Fixed MEX production parameters

Parameter	Value
Nozzle temperature (°C)	260
Ambient temperature(°C)	30–35
Bed temperature (°C)	80
Bed modification	Paper tape
Print speed (mm/s)	70
Infill degree (°)	0
Infill percent (%)	100

Production

All sample part productions were carried out with the Ultimaker brand model 3 MEX device. A 0.6 mm diameter CC nozzle with hardened sapphire material was used in the production of 30 wt% glass fiber reinforced thermoplastic composite parts. The fixed parameters used for production are given in Table 2. Paper tape was applied to the glass bed plate to increase the adhesion of the first layer, and production was carried out in this way. All parts were fabricated with 3 different layer thicknesses (0.1/0.2/0.4 mm) using these fixed parameters.

During the production, the ambient temperature was recorded with a Fischer Scientific brand 06-664-11 model Traceable Digital Thermometer. The measured minimum and maximum values are given in Table 2.

To test the performance of the non-destructive detection of discontinuities in polymeric composites produced by MEX, parts containing discontinuities were produced. In this context, a rectangular prism measuring 20 x 30 x 10 mm with a 3 mm diameter hole on it, shown in Figure 1 (a), and a plate measuring 20 x 100 x 3.2 mm, shown in Figure 1 (b), were produced in 3 different layer thicknesses. The drawings of the produced samples were designed in the Autodesk Fusion 360 computer-aided design (CAD) program.

Images of rectangular prisms with a 3 mm diameter hole produced at different layer thicknesses are given in Figure 2. The 3 mm diameter hole is positioned to represent an artificial discontinuity. Some of the rectangular prisms do not contain any discontinuity for comparison.

Table 3. Layers where discontinuities are positioned

Layer thickness	Number of layers	Layers where the tape is positioned
0.1	32	16
0.2	16	8
0.4	8	4

PTFE and AL tapes with a width of 20 mm were placed on the plates produced by MEX in different layer thicknesses, as shown in Figure 3 (a), and the dimensions of the plates and the location of the tapes are shown in Figure 3 (b). Images of samples produced with different layer thicknesses and containing PTFE and AL tape discontinuities are given in Figure 3 (c).

The CURA computer-aided manufacturing (CAM) program was used for adjusting production parameters, and the pause command was added to the G-code file created for production in the relevant layers to position artificial discontinuities in the layers. Position of layers where discontinuities are shown in Table 3. Accordingly, for 3.2 mm thick plates, the pause command was applied after producing layer 16 since the parts produced with a layer thickness of 0.1 mm consist of 32 layers, layer 8 since the parts produced with a layer thickness of 0.2 mm consist of 16 layers and finally layer 4 since the parts produced with a layer thickness of 0.4 mm consist of 8 layers.

The production steps are shown in Figure 4. After step 1, PTFE and AL tapes for artificial discontinuity were positioned in these layers that reached exactly midpoints, like step 2, and after production continued. Produced in 3 different layer thicknesses, some parts of the plates are free of discontinuity, and some parts also have layer separation created with PTFE tape and AL tape, as shown in step 3.

Testing

Ultrasonic and thermographic non-destructive testing methods were used to identify discontinuities and to examine the effect of layer thickness on discontinuity detection.

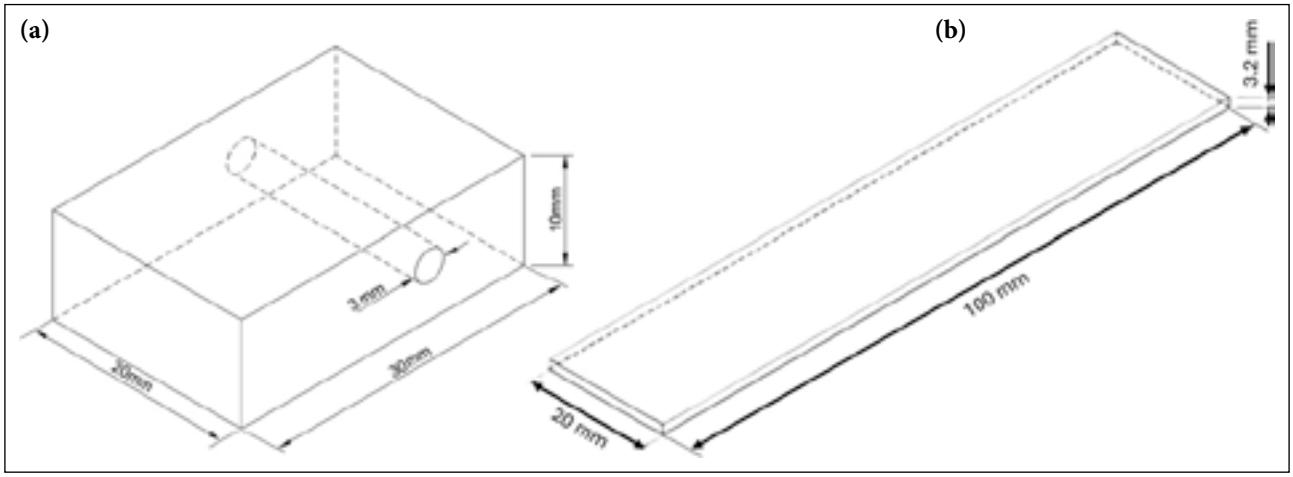

Figure 1. Composite Test Samples produced by MEX.

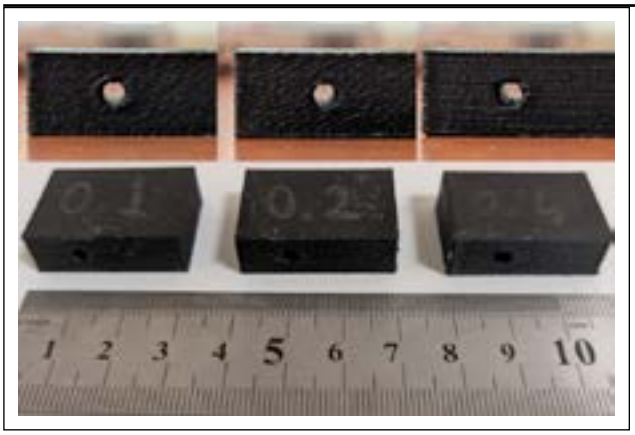

Figure 2. Rectangular prisms with a 3 mm diameter hole produced at different layer thicknesses.

The detection performance of discontinuities in a rectangular prism part with a 3 mm diameter artificial discontinuity produced in different layer thicknesses was performed by ultrasonic inspection. Ultrasonic inspection was performed with a Digital Ultrasonic Flaw Detector from Tru-test. Polymer materials generally have a low acoustic impedance, and high-frequency ultrasonic waves are very damp in these materials. Therefore, Tru-Sonics' BD-412 model with a frequency of 4 MHz and a 12 mm crystal size with a ceramic surface was used in the tests.

Thermal imaging was performed with the UNI-T brand UTi120T thermal imaging camera. The camera resolution is 120*90 pixels, the temperature sensitivity is +/-2 °C, and the frame rate is 25 Hz. The samples were heated to 60 °C in a Nucleon NKD-250 oven before thermal imaging. All thermographic measurements were performed at room temperature, and the ambient temperature was recorded with a Fisher Scientific thermometer. The change from 60 °C to room temperature was monitored and recorded at 30-second intervals. With the images obtained, the thermal temperature changes of the artificial discontinuities created in the specimens were analyzed.

RESULTS AND DISCUSSIONS

Ultrasonic Testing

The images obtained because of ultrasonic testing on rectangular prism samples with a 3 mm diameter hole produced at different layer thicknesses are shared in Figure 5. The graphs on the left in Figure 5 belong to the region with a 3 mm diameter hole created for artificial discontinuity. The graphs on the right in Figure 5 are obtained from the discontinuity-free region. The tests were performed at 10 dB, with a 2 mm delay signal and filtering signals below 30%. The horizontal axis in the graphs shows the distance of the measured echoes to the probe in mm. A 2 mm delay was applied due to interference echoes coming from the area where the probe is in contact with the sample, so the horizontal axis starts at 2 mm. The signals on the vertical axis represent the intensity of the echoes generated by the 10dB sound, reflected from the inner region of the material. In this section, signals below 30% were filtered out for an optimized image of the echoes.

No sound echo was detected in the region where the discontinuity was in each sample, at a depth of 5 mm. With a 0.4 mm layer thickness, the thickness of the rectangular prisms produced in layers was obtained accurately. In the perfect region, the thickness was measured as 10.1 mm, close to the part thickness of 10 mm. In the region containing the discontinuity, the thickness was measured to be 9.8 mm. This is an acceptable tolerance considering the sensitivity of the ultrasonic inspection method and the sound transmission capabilities of polymeric materials [26, 27]. In the echoes from the region containing the discontinuity, It was found that the 3 mm diameter hole region was located at a depth of 5 mm. After the discontinuity, it was observed that the thickness was slightly under-measured due to the loss of echoes. Similarly, the location of the discontinuity in the rectangular prism specimens with 0.2 mm and 0.1 mm layer thickness is seen in the 5 mm depth region. In specimens with a 0.2 mm layer thickness, a thickness of 9.6 mm was

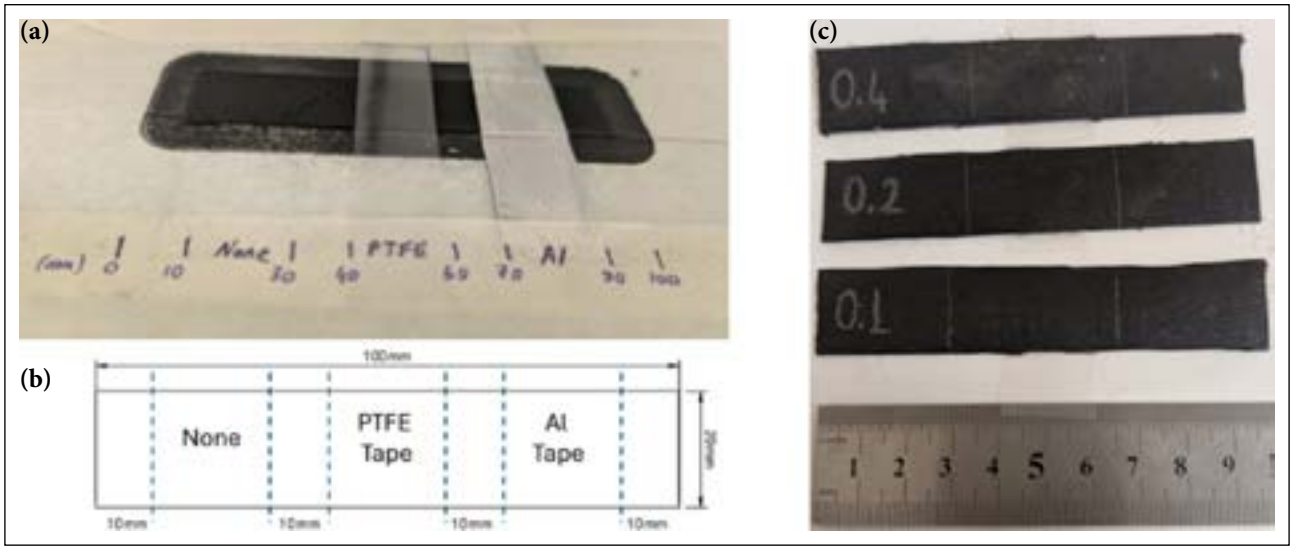

Figure 3. **(a)** The artificial discontinuity location in the plates produced by MEX **(b)** Dimensions of plates and location of tapes **(c)** Production of the plates by MEX.

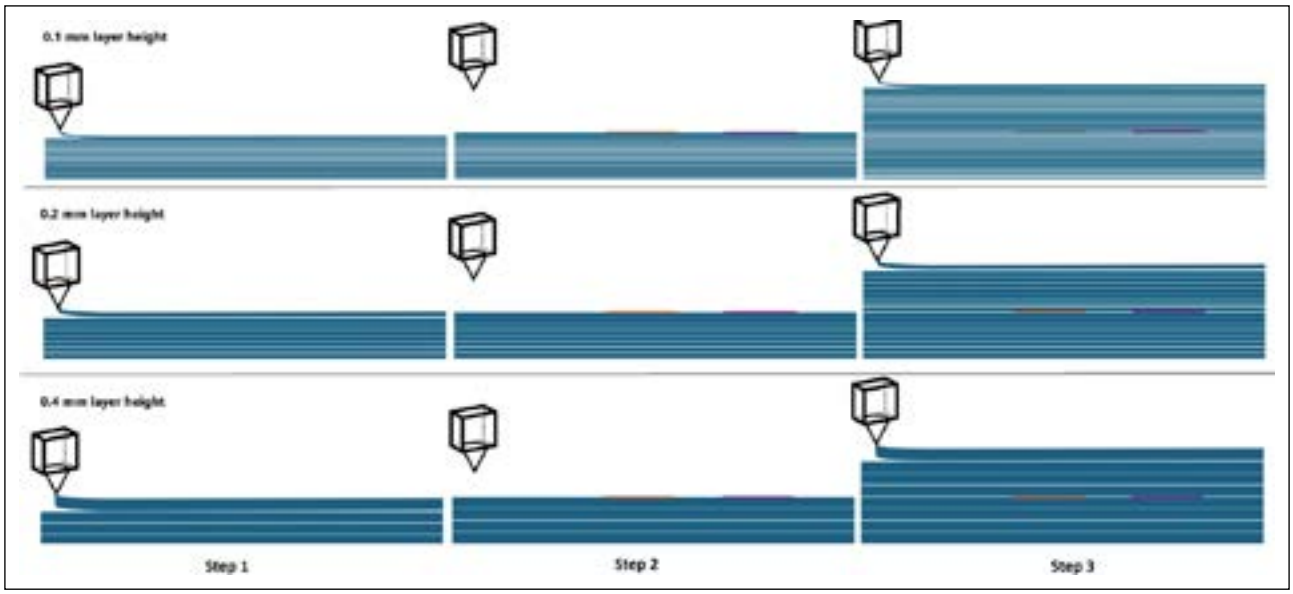

Figure 4. Plates production steps by MEX.

measured in the discontinuity-free zone at the same settings. However, in specimens with a 0.1 mm layer thickness, the thickness in the discontinuity-free zone was measured as 8.5 mm. Butt et al. [24] conducted a study on sound transmission in graphene-reinforced PLA composites produced by MEX with a 0.2 mm layer thickness. In their study, they stated that the production parameters did not significantly affect the sound transmission rate. Similarly, the results show that production parameters affect sound transmission. For example, while the measurements taken from the region without discontinuity in the samples with 0.4 mm and 0.2 mm layer thickness have close values, the number of echoes taken in the samples with 0.1 mm layer thickness decreased, and the thickness value was measured as 8.5 mm. In the region containing a 3 mm hole, the thickness was measured as 8.3 mm; similarly, it was observed that the thickness was slightly lower due to the loss of echo after the discontinuity. The artificial discontinuity was located between the measured thickness values, which allowed it to be detected. However, it would be difficult to detect a deeper discontinuity in samples with a layer thickness of 0.1 mm. This may be due to the layer joints formed by the raw material extruded in layers in MEX production. The junction area of each layer has a negative effect on sound transmission, and the presence of more layers in the samples with a layer thickness of 0.1 mm prevented the echoes traveling along the material from reaching the bottom surface. The specimens with a layer thickness of 0.4 mm had fewer layers and fewer losses at the layer joints, allowing more echoes to be detected for thickness measurements. Samples with 0.2 mm layer thickness showed no significant change, while samples with 0.1 mm layer thickness showed more negative effects. The study conducted by Fayazbakhsh et al. [20] is the first study in which high-resolution images were prepared for parts produced by MEX. In this study, PLA samples containing defects (gaps) were imaged using ultrasonic testing. The study supports the suitability of parts produced by MEX for non-destructive testing. Similarly, the results obtained in the study have shown that discontinuities can be detected in parts produced by MEX using non-destructive testing methods. The results, which were determined for different layer thicknesses by ultrasonic testing, similarly demonstrated the usability of this method in polymeric composites produced by MEX.

Thermal Testing

In Figure 6, time-dependent heat change images of the sample plates produced in different layer thicknesses are shared. The image processing algorithm was run to measure the maximum and minimum temperature values measured in the rectangular region on the screen, and these temperature values were measured in °C. In addition, the temperature value at the point where the PTFE tape was positioned at the center point was also measured. In this way, the temperature values in the AL tape region, in the discontinuity-free region, and in the PTFE tape region were recorded starting from 60 °C until room temperature.

All samples were kept at 60 °C for 24 hours and then imaged at regular intervals until they cooled down at room temperature, respectively. When the temperature changes were examined, no effect was observed due to the layer thickness difference. As seen in Figure 7, all samples tended to cool at similar rates. The data in this graph were created by averaging the maximum temperature values measured on the plate for the relevant minute. The temperature change (ΔT) obtained from the PTFE tape region is 35.8 °C for a 0.4 mm sample, 34.8 °C for a 0.2 mm sample, and 34 °C for a 0.1 mm sample after 7 min. The ΔT obtained in the AL tape region is 34.6 °C for a 0.4 mm sample, 33.9 °C for a 0.2 mm and 33.6 °C for a 0.1 mm sample after 7 min. Changes in layer thickness, although small, affected temperature changes. Increasing layer thickness in both the PTFE and AL tape regions increased ΔT. The presence of more layers in samples with lower layer thicknesses and the interfacial gaps between these layers affected temperature changes.

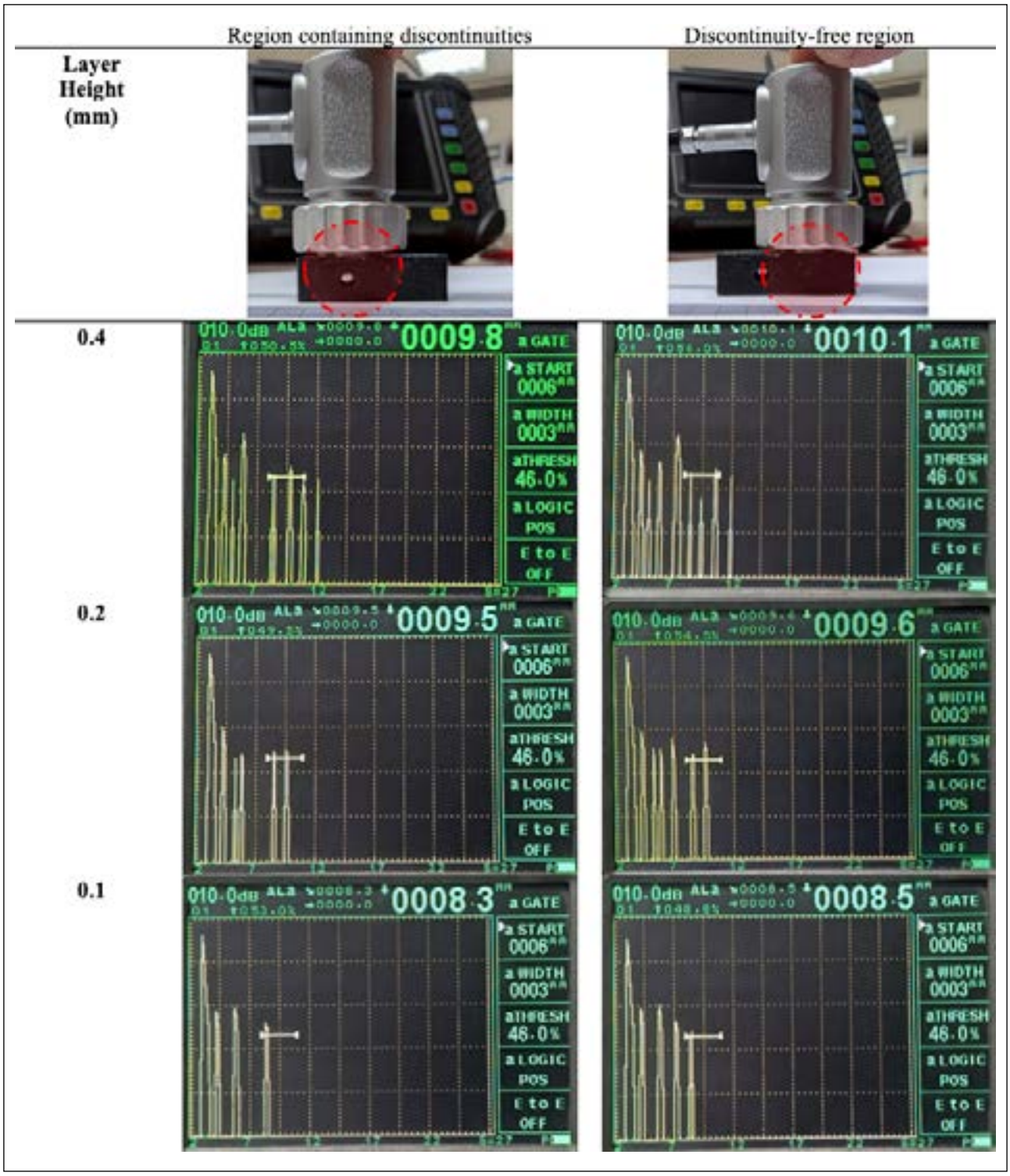

Figure 5. Ultrasonic test results.

When the effect of PTFE and AL tapes on thermal imaging was examined to simulate layer separation, which is one of the important discontinuities encountered in MEX production, it was seen that the highest temperatures were measured in these areas due to the thermal conductivity of AL tape. The temperature values measured in the regions with PTFE tape were not as high as the AL tape values. However, when the temperature values taken from the regions containing PTFE tape corresponding to the midpoint in the measurements are examined, it is seen that the temperature change in these regions also differs compared to the regions without discontinuity. This situation showed that the temperature changes were slower in the regions where thermal conduction was interrupted, where there was layer separation. When the ΔT values were analyzed, a lower temperature change was measured for each layer thickness in AL tape samples. The measured ΔT values varied for both PTFE and AL tape samples depending on the

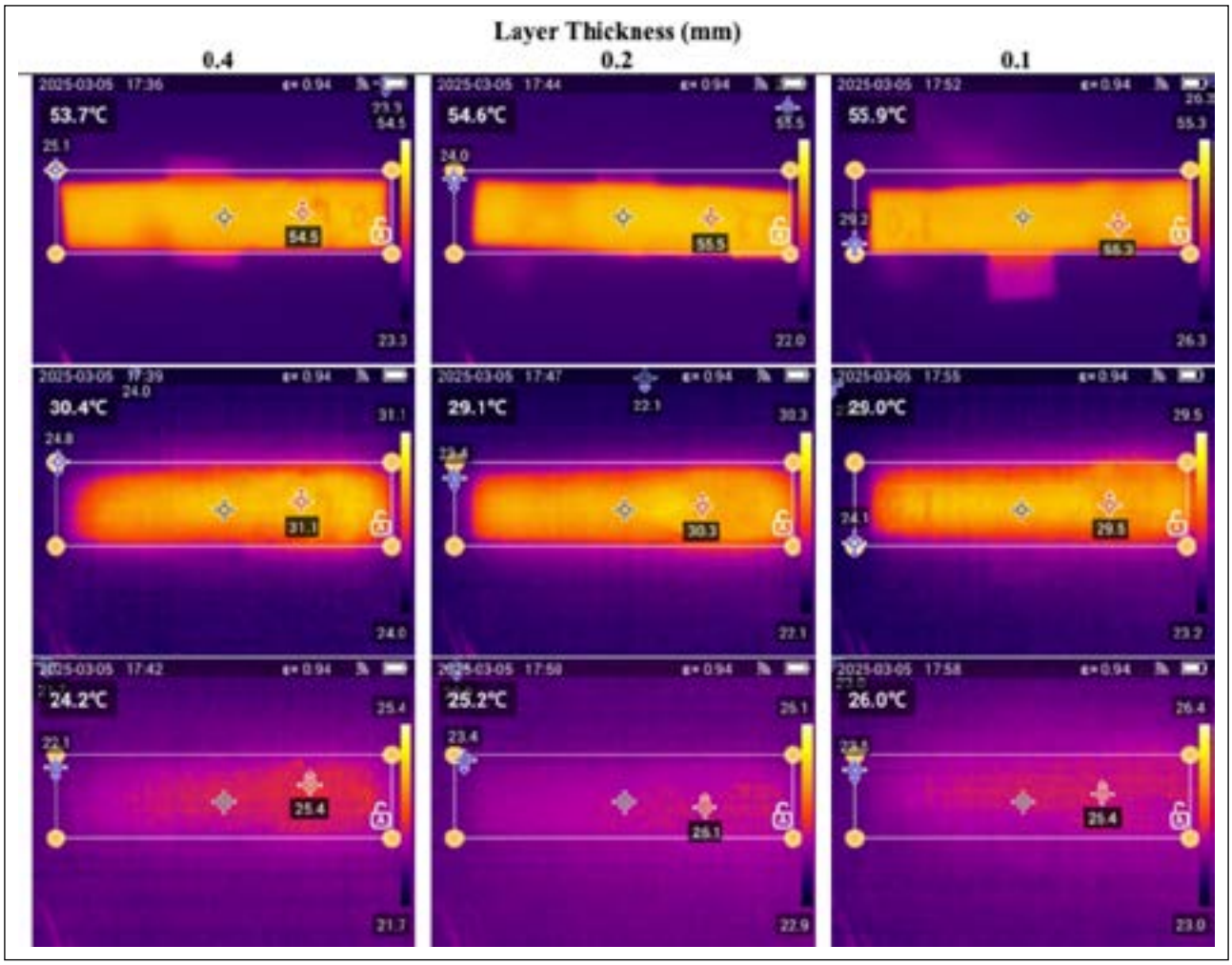

Figure 6. Thermal camera images.

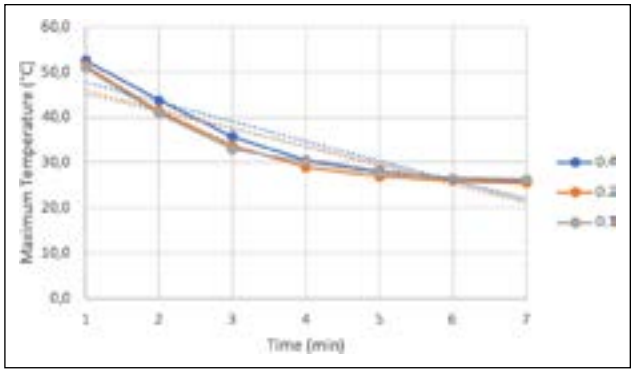

Figure 7. Measured thermal temperature changes.

layer thickness. In both regions, this change is seen as an increasing ΔT with increasing layer thickness. In all samples, slower temperature changes were measured in the regions with AL tape, while a lower temperature gradient was measured in the regions with PTFE tape compared to the regions without discontinuity. This indicates that the thermal conductivity at the points where the layers of the sample plates are in contact is higher than in the regions with layer separation, and that similar discontinuities can be detected by thermal imaging.

CONCLUSION

In this study, the performance of ultrasonic testing and thermal imaging techniques in detecting artificial discontinuities in 30 wt% glass fiber-reinforced polypropylene composites produced by MEX was evaluated for layer thicknesses of 0.1, 0.2, and 0.4 mm.

Ultrasonic detection performance:

- Artificial discontinuities with a 3 mm diameter and 5 mm depth were successfully identified in all samples.
- Measured-to-actual thickness deviations were 1% for 0.4 mm, 5% for 0.2 mm, and 15% for 0.1 mm layer thicknesses.
- Thinner layers (0.1 mm) caused significant signal attenuation and reduced echo clarity, limiting defect detectability.

Thermal imaging performance:

- Layer thickness variation had no major effect on overall temperature distribution.
- The temperature difference (ΔT) in PTFE regions was 35.8 °C (0.4 mm), 34.8 °C (0.2 mm), and 34.0 °C (0.1 mm).
- In Al tape regions, ΔT values were 34.6 °C, 33.9 °C, and 33.6 °C for 0.4, 0.2, and 0.1 mm, respectively.
- Thicker layers showed slightly higher ΔT values, indicating improved thermal conduction stability.

Overall, ultrasonic testing proved more sensitive to internal discontinuities, whereas thermal imaging effectively identified surface and near-surface delaminations. Both methods demonstrated complementary capabilities. The quantitative findings underline that optimal layer thickness and proper NDT technique selection are essential for reliable defect detection and structural integrity assessment in MEX-produced composites.

Data Availability Statement

The author confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

Conflict of Interest

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Statement on the Use of Artificial Intelligence

Artificial intelligence was not used in the preparation of the article.

Ethics

There are no ethical issues with the publication of this manuscript.

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