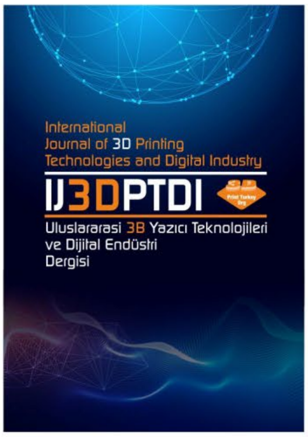

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DETECTION OF ARTIFICIAL DISCONTINUITIES LOCATED IN DIFFERENT LOCATIONS IN PLA SPECIMENS MANUFACTURED WITH MEX AT DIFFERENT LAYER THICKNESSES BY ULTRASONIC INSPECTION

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ABSTRACT

PLA (polylactic acid) is the most commonly used polymer in material extrusion-based additive manufacturing (MEX), which is one of the most innovative methods in the production of polymers. Its biodegradability, availability, and low cost drive its widespread use. Due to the nature of additive manufacturing, some discontinuities tend to occur in the production of polymer materials. Discontinuities such as junction problems between layers, voids, and solidification of extruded polymers occur between the production of layers. Non-destructive testing methods can be used to detect these discontinuities. Ultrasonic testing, a volumetric Non-destructive testing method, is well-suited to detect such discontinuities. This study evaluates how layer thickness influences ultrasonic detection of discontinuities in MEX-produced PLA specimens. 0.1 mm, 0.2 mm, and 0.4 mm layer thicknesses of PLA specimens, each of which has artificial discontinuities (holes) placed at different depths and locations, were analyzed by the ultrasonic inspection technique. In the experimental studies, sound waves were sent to the specimens, and the reflected echoes were evaluated. Results show that layer thickness alters echo amplitude and the positional accuracy of detected discontinuities. In specimens with a layer thickness of 0.1 mm, the detection of discontinuities was clearer, while in specimens with a layer thickness of 0.4 mm, the sound echoes were more scattered, negatively affecting the measurement accuracy. These findings clarify how manufacturing parameters shape Non-destructive testing effectiveness in additive manufacturing and hold practical implications for industry.

Keywords: PLA, Non-Destructive Testing, Additive Manufacturing, Polymers

1. INTRODUCTION

Additive manufacturing (AM) technologies enable fast, cost-effective production of complex geometries [1]. Today, AM technologies, which are at the forefront of industrial production processes with their advantages such as design flexibility, cost-effectiveness, and rapid prototyping, are creating a significant transformation in the manufacturing world [2-3]. One such method, material extrusion-based additive manufacturing (MEX), enables the creation of three-dimensional structures by layering polymer-based materials [4-5].

Polylactic acid (PLA), one of the most commonly used polymers in production with MEX, is preferred due to its biodegradable structure, renewable source, low melting temperature, and good dimensional stability. These properties make PLA both environmentally friendly and suitable for processing. In the production process with MEX, production parameters directly affect the mechanical properties of the parts. The parts produced with MEX exhibit anisotropic properties and lower mechanical properties along the Z-axis. Layer thickness, one of the production parameters, is a critical parameter that directly affects the surface quality, mechanical properties, and internal structural homogeneity of the part. Numerous studies in the literature have examined the impact of these parameters on material performance [6–10]. On the other hand, in the MEX method, discontinuities such as voids, separations, and extrusion layering, which may occur in the internal structure depending on the production process, can negatively affect the reliability of the part [4-5]. Detecting these discontinuities and investigating the effects of production parameters on discontinuity detection are open topics for research [11–18]. Production parameters primarily affect manufacturability in MEX production and can cause discontinuities[19]. Nozzle temperature, printing speed, extrusion speed, and layer thickness affect part quality [20-21]. In their study, Zanjanijam et al. stated that the production quality of PEEK specimens produced with MEX varied depending on nozzle temperature, printing speed, and layer thickness[22]. Triyono et al, examined how nozzle diameter affects porosity in MEX-printed PLA [23]. Sandhu et al investigated the effect of printing parameters on the dimensional stability of PLA specimens in MEX production and determined the process parameters that cause shrinkage [24]. Allum et al. have stated that low extrusion negatively affects the mechanical properties in production with MEX and causes void formation [25]. Gardner et al. have stated that internal stresses generated during interlayer adhesion during production in acrylonitrile butadiene styrene (ABS) specimens cause delamination [26]. Studies have shown that many different discontinuities can occur depending on production parameters and the polymer preferred for production. Detecting these discontinuities is critical for the reliability of products manufactured with MEX and enables the expansion of the application area. The detectability of defects is also one of the issues that needs to be investigated.

Non-destructive testing (NDT) methods are used as effective tools for detecting discontinuities without compromising the structural integrity of materials [18,27]. Among the volumetric inspection methods included in NDT, ultrasonic testing stands out due to its high resolution and ability to detect discontinuities within materials[28].

Fayanzbakhsh et al. detected interlayer voids in PLA specimens produced with MEX using high-frequency phased array ultrasonic testing and investigated their effect on mechanical properties [29]. Butt et al investigated the effect of production parameters on the mechanical properties of graphene-reinforced PLA specimens using ultrasonic sound transmission [30]. To our knowledge, no prior work quantifies how printing parameters or defect location affect ultrasonic detectability in MEX parts.

The layered structure of parts produced using MEX can affect the propagation and reflection of sound waves, thereby limiting detection performance. The effect of layer thicknesses on the propagation of sound waves and the detection of discontinuities is a topic that requires further investigation. In this study, the focus is on detecting artificial discontinuities placed in PLA specimens produced with different layer thicknesses using the MEX method through ultrasonic testing.

2. MATERIALS AND METHODS

2.1. Materials

Ultrafuse Natural PLA filament (BASF) was used. The filament density was 1248 kg/m^3, the melting temperature (T_m) was 151 °C (ISO 11357-3) and the glass transition temperature (T_g) value was 61 °C (ISO 11357-2) [31]. The mechanical properties of the specimens produced in the flat (XY) plane, as specified by the manufacturer of the PLA filament, are presented in Table 1.

Table 1. PLA Filament Mechanical Properties[31]

Properties	Value	Standard
Tensile Strength (MPa)	34.7	ISO 527
Elongation at Break (%)	4.2	ISO 527
Young Modulus (MPa)	2308	ISO 527
Flexural Strength (MPa)	98	ISO 178
Flexural Modulus (MPa)	1860	ISO 178
Flexural Strain at Break (%)	4.8	ISO 178
Impact Strength Charpy - notched (kJ/m^2)	2.5	ISO 179-2

2.2. Production and Design

Hole-containing specimens were printed to assess NDT detection performance in PLA specimens produced with MEX. In this context, 15 × 20 × 80 mm rectangular prisms with 5-mm-diameter holes were produced in three different layer thicknesses, as shown in Figure 1. Figure 2 shows the discontinuity-free region and 5-mm holes in three positions. A 5-mm-diameter was determined to accurately detect discontinuities with the ultrasonic sensor used.

Holes of 3 different depths were created to detect discontinuities at different depths. Three different positionings were made to examine the effect of depth on discontinuity detection. Specimens were modelled in the Autodesk Fusion 360 computer-aided design program (CAD). The CURA computer-aided manufacturing (CAM) software was used for the production parameters.

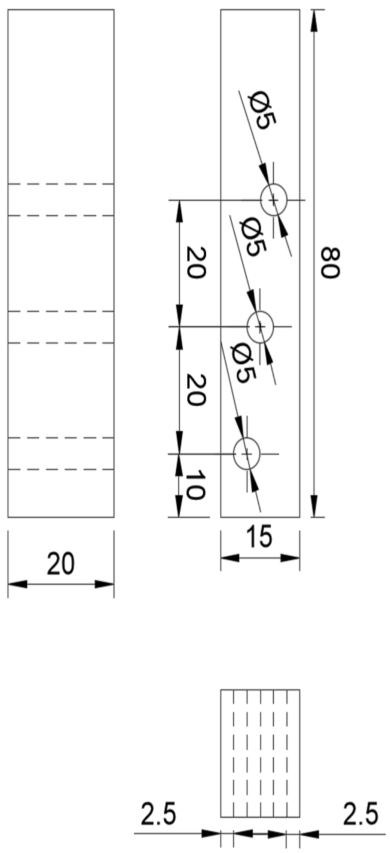

Figure 1. Drawings of PLA Specimens produced with MEX

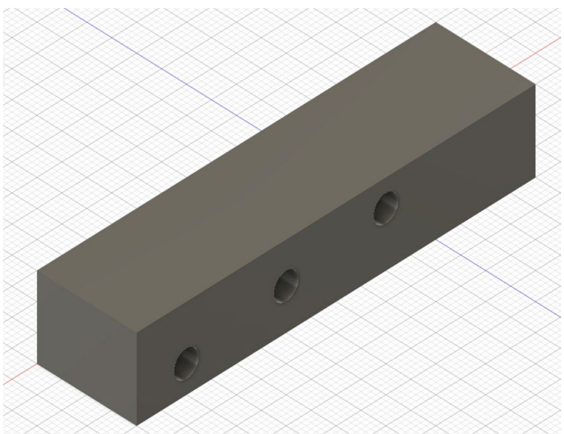

Figure 2. 3D Image of Specimens

The specimens were produced using an Ultimaker Model 3 MEX device with a 0.4 mm diameter Ultimaker Printcore AA nozzle. The fixed parameters used for production are given in Table 2. All specimens were printed with fixed settings except for layer thickness (0.1, 0.2, 0.4 mm).

Table 2. Fixed MEX Production Parameters

Parameters	Value
Nozzle Temperature (°C)	210
Bed Temperature(°C)	60
Bed Material	Glass
Print Speed (mm/s)	60
Infill Degree (°)	0
Infill Percent (%)	100

Each layer was produced parallel to the long side of the specimens in the direction shown in Figure 3 (a) (infill degree). Images of rectangular prisms produced in different layer thicknesses and with a 5-mm-diameter hole are shown in Figure 3 (b). The 5-mm-diameter hole is positioned to represent an artificial discontinuity—the specimens were produced in three different layer thicknesses.

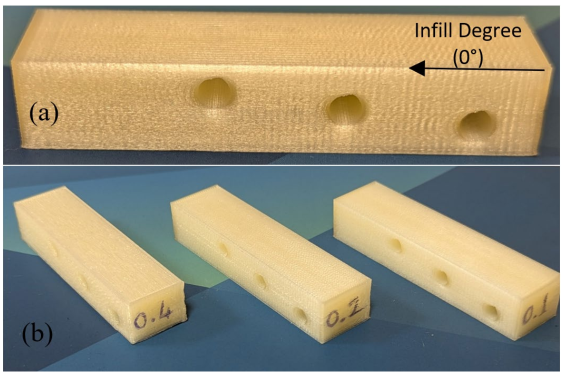

Figure 3. Rectangular Prism Specimens Produced

2.3. Testing

Ultrasonic testing, an NDT technique, was used to determine discontinuities and examine the effect of layer thickness on discontinuity detection.

The detection performance of discontinuities in rectangular prism pieces with 5-mm-diameter artificial holes produced at different layer thicknesses and located in different areas was carried out using ultrasonic testing. The Tru-test brand Digital Ultrasonic Flaw Detector device was used for ultrasonic testing. Because polymers have low acoustic impedance, a low-frequency probe was selected. Therefore, the BD-412 model from Tru-Sonics with a 4 MHz frequency and 12 mm crystal size ceramic-coated vertical probe was used in the tests. Figure 4 illustrates the device and probe.

Figure 4. Ultrasonic testing device and probe used

3. RESULTS AND DISCUSSION

PLA specimens designed in the shape of a rectangular prism measuring 15 × 20 × 80 mm and containing three circular holes with a diameter of 5 mm placed in different positions to represent artificial discontinuities were produced using additive manufacturing with three different layer thicknesses of 0.1 mm, 0.2 mm and 0.4 mm and tested using an ultrasonic inspection method. In addition to the three holes in different positions, one near the bottom surface, one at mid-height, and one near the top surface, each specimen with a different layer thickness also included an area without any internal discontinuities as a reference for ultrasonic inspection.

Figure 5 presents ultrasonic signals from specimens printed at three-layer thicknesses, each with three 5-mm holes. The horizontal axis shows the depth (mm) at which the reflected sound echo signals were received. The vertical axis shows the intensity of the sound signal. The rightmost graphs correspond to the discontinuity-free region. The images of the signals obtained from the holes near the surface, middle, and bottom regions are shared from left to right. The tests were performed at 11 dB, with an 8 mm delayed signal, and signals below 29% filtered out.

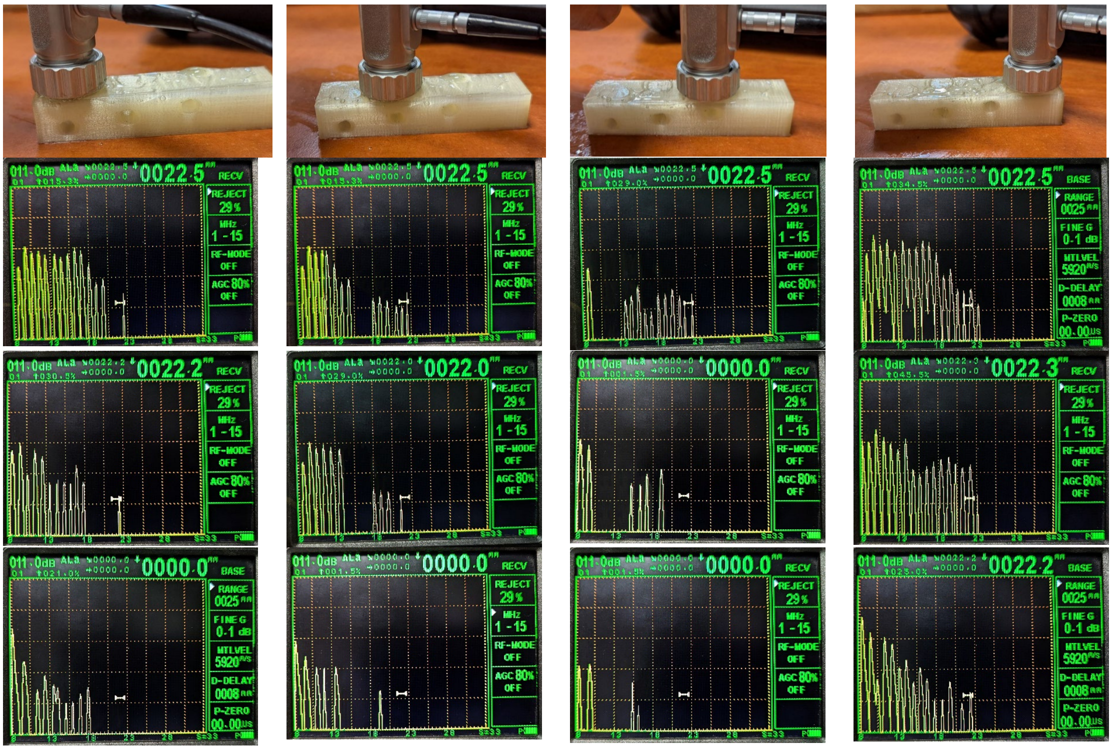

Figure 5. Ultrasonic test graphs of discontinuous and discontinuity-free regions of specimens

Signals from discontinuity-free regions showed the highest echo amplitudes in 0.1 mm layers. In addition to high resolution, the echo signals were clearly distinguished. Signals from the regions between each layer were detected at a specific frequency. The homogeneous internal structure of the material provided good communication, and minimal signal attenuation was observed. Compared to specimens with a layer thickness of 0.1 mm, a decrease in signal amplitude was observed in specimens with a layer thickness of 0.2 mm. Although the first signals were strong, the clarity of the successive echoes decreased slightly. The interlayer bonding surfaces have scattered the signal to some extent. In specimens with a layer thickness of 0.4 mm, the echo height has decreased significantly, and the signal attenuation is more pronounced. The echo signals are more widespread and scattered. Bonding interfaces in thicker layers significantly disrupt wave propagation. This likely reflects increased refraction at thicker layer interfaces, which redirects and attenuates waves.

Echoes from sound regions were highly sensitive to layer thickness; acoustic heterogeneity increased as thickness rose. It has been observed that scattering and attenuation in sound wave propagation increase significantly with an increase in layer thickness. Echo intensity and clarity decreased with increasing layer thickness. The sound waves did not deviate much when passing through thick layers within the material, so the sound echoes were dispersed. Despite the presence of more bonding surfaces and environmental changes in low-layer thicknesses, it has been observed that sound is transmitted smoothly between layers in these regions. This situation can be explained by the fact that the dimensional tolerances of production are better at low layer thicknesses.

In the specimen with a layer thickness of 0.1 mm, the signal amplitudes obtained from all hole positions were high, and the echoes were intense. The sound waves echoed clearly, with minimal signal loss. In specimens with a layer thickness of 0.2 mm, the signal amplitude was observed to decrease and the echoes were observed to be less frequent. In addition, when the dimensions of the measured artificial discontinuity were compared, the dimensional results were more accurate in specimens with a layer thickness of 0.2 mm. In comparison, the dimensions of artificial discontinuity were lower in specimens with a layer thickness of 0.1 mm. For bottom-surface defects, the signal drop began at 19.5 mm for 0.1-mm layers. Considering an 8 mm signal delay, this corresponds to a depth of approximately 11.5 mm. In specimens with 0.2 mm and 0.4 mm layer thickness, the signal discontinuity for the region near the bottom surface starts at 18 mm. Again, considering the 8 mm signal delay, this indicates that the discontinuity begins at a depth of 10 mm. Accordingly, spatial accuracy was higher for 0.2 and 0.4 mm layers. This may stem from the greater number of interfaces in thinner layers. The large number of echoes created by the increased number of layer interface surfaces resulted in a smaller discontinuity image. As the layer thickness increased, the echo gap associated with the artificial discontinuity widened. The closest measurements were observed at a layer thickness of 0.2 mm, while a smaller discontinuity size was observed in specimens with a layer thickness of 0.1 mm. In specimens with a layer thickness of 0.4 mm, the echoes obtained after the discontinuity were measured from deeper regions, and therefore a larger discontinuity size was observed in specimens with a layer thickness of 0.4 mm.

When the ultrasonic sound signals obtained from the artificial discontinuity located near the upper surface were examined, the error location was detected in all specimens. In the specimen with a layer thickness of 0.1 mm, the sound echoes could continue to the back surface within the material, but in the specimens with layer thicknesses of 0.2 and 0.4 mm, only a small amount of echo was received from the region after the artificial discontinuity. The effect created by the artificial discontinuity on the upper surface prevented the sound waves from reaching the lower layers. Therefore, the proximity of the discontinuity to the upper surface prevented the sound waves from advancing to the lower region. This effect became more pronounced with the increase in layer thickness and made it more difficult to detect the echoes. The discontinuity in the middle region was observed in all three specimens with different layer thicknesses, but in the specimen with a 0.4 mm layer thickness, sound waves could not reach the lower surface of the specimen. This situation was observed in all artificial discontinuities in the specimen with a 0.4 mm layer thickness.

Overall, ultrasonic transmission degraded as layer thickness increased. While signals were received in specimens with a layer thickness of 0.1 mm, almost no echo was measured in specimens with a layer thickness of 0.4 mm in areas containing discontinuities. These results highlight how internal architecture governs detectability: thicker layers absorbed more energy, masking echoes.

According to the experimental results of the study, an increase in layer thickness directly affects the detectability of discontinuities by ultrasonic examination. In specimens with a layer thickness of 0.1 mm, the location of discontinuities could be determined more clearly thanks to the sound transmission advantage provided by the smoother and more homogeneous structure. The discontinuity size was measured more clearly in specimens with a layer thickness of 0.2 mm. However, this situation is affected by the location of the discontinuity. In contrast, in specimens with a layer thickness of 0.4 mm, the scattering and reflection of sound waves increased, making it difficult to interpret the echoes.

4. CONCLUSIONS

In this study, the capability and sensitivity of ultrasonic testing techniques in detecting artificial internal discontinuities at various depths in PLA components produced with MEX were evaluated. Comparing signals from defect-free and defective regions allowed us to isolate the effects of depth and layer thickness on detection. A comparative evaluation of ultrasonic signals corresponding to different discontinuity locations and printing parameters is presented. Signal characteristics—amplitude, intensity, and attenuation—were analysed to assess detectability and resolution. The effect of production parameters, particularly layer thickness, on signal clarity and discontinuity visibility is also discussed in detail.

Ultrasonic detectability decreased markedly with increasing layer thickness. It was observed that discontinuities were more clearly detected in specimens with a layer thickness of 0.1 mm, where holes in the middle position could be detected more reliably than others, but discontinuity dimensions were more clearly measured in specimens with a layer thickness of 0.2 mm. In addition, it has been found that discontinuities located near the bottom surface are more difficult to detect due to the signals travelling longer distances, which leads to increased attenuation.

This work systematically demonstrates layer-thickness effects on ultrasonic inspection performance in MEX-printed PLA. The findings indicate that lower layer thicknesses provide an advantage in terms of more successful detection of discontinuities. Future work should examine other printing parameters and materials to generalise these findings.

REFERENCES

1. Thomas, D.S.; Gilbert, S.W., “Costs and Cost Effectiveness of Additive Manufacturing A Literature Review and Discussion.”, 10-89, NIST Special Publication, Washington, 2014.

2. Khan, L.S.; Yousaf, G.A.; Hussain, I. “3D Printing Techniques: Transforming Manufacturing with Precision and Sustainability.” International Journal of Multidisciplinary Sciences and Arts, Vol.3, Issue 3, 2024.

3. Zhou, L.; Miller, J.; Vezza, J.; Mayster, M.; Raffay, M.; Justice, Q.; Al Tamimi, Z.; Hansotte, G.; Sunkara, L.D.; Bernat, J. “Additive Manufacturing: A Comprehensive Review.” Sensors, Vol.24, Issue 9, Page 2668-2024, 2024.

4. Khan, I.; Barsoum, I.; Abas, M.; Al Rashid, A.; Koç, M.; Tariq, M. “A Review of Extrusion-Based Additive Manufacturing of Multi-Materials-Based Polymeric Laminated Structures.” Composite Structures, Vol.349-350, Issue 118490, 2024.

5. Jasik, K.; Lucjan´, L.; Zek, L.; Kluczy´nski, J.; Kluczy´nski, K. “Additive Manufacturing of Metals Using the MEX Method: Process Characteristics and Performance Properties—A Review.” Materials, Vol. 18, Issue 12, Page 2744, 2025.

6. Bacak, S.; Özkavak, H.V.; Tatlı, M. “FDM Yöntemi ile Üretilen PLA Numunelerin Çekme Özelliklerine İşlem Parametrelerinin Etkisinin İncelenmesi” Mühendislik Bilimleri ve Tasarım Dergisi, Vol.9, Issue 1, Page 209–216, 2021.

7. Bacak, S.; Özkavak, H.V.; Sofu, M.M. “Comparison of Mechanical Properties of 3D-Printed Specimens Manufactured Via FDM with Various Inner Geometries” Journal of the Institute of Science and Technology, Vol.11, Issue 2, Pages 1444–1454, 2021.

8. Camargo, J.C.; Machado, Á.R.; Almeida, E.C.; Silva, E.F.M.S. “Mechanical Properties of PLA-Graphene Filament for FDM 3D Printing” International Journal of Advanced Manufacturing Technology, Vol.103, Pages 2423–2443, 2019.

9. García Plaza, E.; Núñez López, P.J.; Caminero Torija, M.Á.; Chacón Muñoz, J.M. “Analysis of PLA Geometric Properties Processed by FFF Additive Manufacturing: Effects of Process Parameters and Plate-Extruder Precision Motion” Polymers, Vol.11, Issue 10, Pages 1581, 2019.

10. Erdaş, M.U.; Yıldız, B.S.; Yıldız, A.R. "Experimental Analysis of the Effects of Different Production Directions on the Mechanical Characteristics of ABS, PLA, and PETG Materials Produced by FDM" Materials Testing, Vol.66, Issue 2, Pages 198–206, 2024.

11. Kechagias, J.; Chaidas, D.; Vidakis, N.; Salonitis, K.; Vaxevanidis, N.M. "Key Parameters Controlling Surface Quality and Dimensional Accuracy: A Critical Review of FFF Process." Materials and Manufacturing Processes, Vol.37, Issue 9, Pages 963–984, 2022.

12. Gonabadi, H.; Yadav, A.; Bull, S.J. "The Effect of Processing Parameters on the Mechanical Characteristics of PLA Produced by a 3D FFF Printer." International Journal of Advanced Manufacturing Technology, Vol.111, Pages 695–709, 2020.

13. Ameri, B.; Taheri-Behrooz, F.; Aliha, M.R.M. "Evaluation of the Geometrical Discontinuity Effect on Mixed-Mode I/II Fracture Load of FDM 3D-Printed Parts." Theoretical and Applied Fracture Mechanics, Vol.113, Issue 102953, 2021.

14. Doğru, A.; Sözen, A.; Neşer, G.; Seydibeyoğlu, M.Ö. "Numerical and Experimental Investigation of The Effect of Delamination Defect at Materials Of Polyethylene Terephthalate (PET) Produced By Additive Manufacturing on Flexural Resistance." International Journal of 3D Printing Technologies and Digital Industry, Vol.6, Issue 3, Pages 382–391, 2022.

15. Havva, Y.; Özdemir, N.; Sözen, A.; Demir, M.; Doğru, A.; Seki, Y.; Özdemir, H.N. "Production of Waste Jute Doped PLA (Polylactic Acid) Filament for FFF: Effect of Pulverization." International Journal of 3D Printing Technologies and Digital Industry, Vol.7, Issue 1, Pages 124–128, 2023.

16. Doğru, A.; İrez A.B., "The microstructural evolution of material extrusion based additive manufacturing of polyetheretherketone under different printing conditions and application in a spinal implant." Polymer Engineering & Science, Vol.64, Issue 11, Pages 5486–5502, 2024.

17. Doğru, A.; Kaçak, M.; Seydibeyoğlu, M.Ö. "Examination of Mechanical Properties of Fasteners Produced with PET and PLA Materials in Extrusion-Based Additive Manufacturing Method." International Journal of 3D Printing Technologies and Digital Industry, Vol.8, Issue 3, Pages 407–415, 2024.

18. Baechle-Clayton, M.; Loos, E.; Taheri, M.; Taheri, H. "Failures and Flaws in Fused Deposition Modeling (FDM) Additively Manufactured Polymers and Composites." Journal of Composites Science, Vol.6, Issue 7, Pages 202, 2022.

19. Alo, O.A.; Mauchline, D.; Otunniyi, I.O. "3D-Printed Functional Polymers and Nanocomposites: Defects Characterization and Product Quality Improvement." Advanced Engineering Materials, Vol.24, Issue 10, 2022.

20. Attalla, R.; Ling, C.; Selvaganapathy, P. "Fabrication and Characterization of Gels with Integrated Channels Using 3D Printing with Microfluidic Nozzle for Tissue Engineering Applications." Biomed Microdevices, Vol.18, Issue 1, Pages 1–12, 2016.

21. Pérez, B.; Nykvist, H.; Brøgger, A.F.; Larsen, M.B.; Falkeborg, M.F. "Impact of Macronutrients Printability and 3D-Printer Parameters on 3D-Food Printing: A Review." Food Chemistry, Vol.287, Pages 249–257, 2019.

22. Zanjanijam, A.R.; Major, I.; Lyons, J.G.; Lafont, U.; Devine, D.M. "Fused Filament Fabrication of PEEK: A Review of Process-Structure-Property Relationships." Polymers, Vol.12, Issue 8, Pages 1665, 2020.

23. Triyono, J.; Sukanto, H.; Saputra, R.M.; Smaradhana, D.F. "The Effect of Nozzle Hole Diameter of 3D Printing on Porosity and Tensile Strength Parts Using Polylactic Acid Material." Open Engineering, Vol.10, Issue 1, Pages 762–768, 2020.

24. Sandhu, K.; Singh, S.; Prakash, C. "Analysis of Angular Shrinkage of Fused Filament Fabricated Poly-Lactic-Acid Prints and Its Relationship with Other Process Parameters." IOP Conference Series: Materials Science and Engineering, Vol.561, Issue 012058, 2019.

25. Allum, J.; Moetazedian, A.; Gleadall, A.; Mitchell, N.; Marinopoulos, T.; McAdam, I.; Li, S.; Silberschmidt, V. V. "Extra-Wide Deposition in Extrusion Additive Manufacturing: A New Convention for Improved Interlayer Mechanical Performance." Additive Manufacturing, Vol.61, Issue 5, 2023.

26. Gardner, J.M.; Hunt, K.A.; Ebel, A.B.; Rose, E.S.; Zylich, S.C.; Jensen, B.D.; Wise, K.E.; Siochi, E.J.; Sauti, G. "Machines as Craftsmen: Localized Parameter Setting Optimization for Fused Filament Fabrication 3D Printing." Advanced Materials Technologies, Vol.4, Issue 3, 2019.

27. Inês Silva, M.; Malitckii, E.; Santos, T.G.; Vilaça, P. "Review of Conventional and Advanced Non-Destructive Testing Techniques for Detection and Characterization of Small-Scale Defects." Progress in Materials Science, Vol.138, Issue 101155, 2023.

28. Gupta, M.; Khan, M.A.; Butola, R.; Singari, R.M. "Advances in Applications of Non-Destructive Testing (NDT): A Review." Advances in Materials and Processing Technologies, Vol.8, Isssue 4, Pages 2286–2307, 2022.

29. Fayazbakhsh, K.; Honarvar, F.; Amini, H.; Varvani-Farahani, A. "High Frequency Phased Array Ultrasonic Testing of Thermoplastic Tensile Specimens Manufactured by Fused Filament Fabrication with Embedded Defects." Additive Manufacturing, Vol.47, 2021.

30. Butt, J.; Bhaskar, R.; Mohaghegh, V. "Non-Destructive and Destructive Testing to Analyse the Effects of Processing Parameters on the Tensile and Flexural Properties of FFF-Printed Graphene-Enhanced PLA." Journal of Composites Science, Vol.6, Issue 5, Page 148, 2022.

31. BASF 3D Printing Solutions BV Sales@basf-3dps.Com Www.Basf-3dps.Com General Information.