Isaak Trajković[1], Martina Balać[2], Miloš Milošević[1], Bojan Međo[3]*

APPLICATION OF THE DIC METHOD IN DETERMINING FRACTURE MECHANICS PARAMETERS ON RING-SHAPED SPECIMENS WITH A SHARP NOTCH MANUFACTURED USING THE FDM TECHNIQUE

PRIMENA DIC METODE U ODREĐIVANJU PARAMETARA MEHANIKE LOMA NA EPRUVETAMA OBLIKA PRSTENA SA OŠTRIM ŽLEBOM DOBIJENIH FDM TEHNIKOM

Originalni naučni rad / Original scientific paper
Rad primljen / Paper received: 05.03.2025
https://doi.org/10.69644/ivk-2025-01-0127

Adresa autora / Author's address:
[1] Innovation Center of the Faculty of Mechanical Engineering, Belgrade, Serbia, *email: trajkovicisaak@gmail.com
I. Trajković https://orcid.org/0000-0001-6671-4733
M. Milošević https://orcid.org/0000-0002-2418-1032
[2] University of Belgrade, Faculty of Mechanical Engineering, Belgrade, Serbia M. Balać https://orcid.org/0000-0002-2135-0179
[3] University of Belgrade, Faculty of Technology and Metallurgy, Belgrade, Serbia B. Međo https://orcid.org/0000-0001-8100-7519

Keywords

- fracture mechanics
- fused deposition modelling
- PRNT - pipe ring notch tension specimens
- polylactide acid (PLA)
- digital image correlation

Ključne reči

- mehanika loma
- modeliranje deponovanjem topljenog materijala
- epruveta oblika prstena sa žlebom izložena zatezanju
- polilaktidna kiselina (PLA)
- korelacija digitalnih slika

Abstract

This paper focuses on the evaluation of fracture mechanics parameters of thin-walled pipeline components using 3D printing and digital image correlation (DIC) techniques. The experimental study is conducted on 3D-printed polymer specimens made of PLA (polylactide acid) using the FDM (Fused Deposition Modelling) process. All specimens were tested on a universal materials testing machine, with strain measurements by the Aramis 2M system based on DIC. This setup allowed for the accurate analysis of key fracture mechanics parameters, including crack mouth opening displacement (CMOD) and crack tip opening displacement (CTOD-δ_5). A new test geometry - the Pipe Ring Notched Tension (PRNT) was compared to standard single-edge notched tension (SENT) specimens and their properties were compared to provide a more realistic assessment of the mechanical behaviour of pipeline materials. This research is particularly important given the increasing use of additive manufacturing to produce functional spare parts, which are increasingly integrated into pressure-containing process equipment, highlighting the importance of accurate fracture mechanics assessment in ensuring component reliability and safety.

Izvod

Ovaj rad se fokusira na procenu parametara mehanike loma komponenata tankozidnih cevovoda korišćenjem 3D štampe i digitalne korelacije slike (DIC). Eksperimentalna ispitivanja su sprovedena na 3D štampanim uzorcima polimera napravljenim od PLA (polilaktidne kiseline) korišćenjem FDM (Fused Deposition Modelling) procesa. Svi uzorci su testirani na univerzalnoj mašini za ispitivanje materijala, uz merenje deformacije pomoću sistema Aramis 2M zasnovanog na DIC-u. Ova postavka je omogućila preciznu analizu ključnih parametara mehanike loma, uključujući pomeranje otvaranja usta prsline (CMOD) i pomeranje otvaranja vrha prsline (CTOD-δ_5). Nova geometrija epruvete oblika prstena sa oštrim žlebom opterećena na zatezanje (PRNT) - upoređena je sa standardnim uzorcima sa zarezom sa jednom ivicom (SENT) i njihova svojstva su upoređena da bi se obezbedila realnija procena mehaničkog ponašanja materijala cevovoda. Ovo istraživanje je posebno važno s obzirom na sve veću upotrebu aditivne proizvodnje za proizvodnju funkcionalnih rezervnih delova, koji su sve više integrisani u procesnu opremu pod pritiskom, naglašavajući važnost tačne procene mehanike loma u obezbeđivanju pouzdanosti i bezbednosti komponenata.

INTRODUCTION

Fracture mechanics plays a key role in the analysis and design of pressure equipment: tanks, pipelines, and boilers made of materials with pronounced elastoplastic behaviour. Fracture mechanics parameters such as the stress intensity factor *K*, crack tip opening displacement (CTOD), crack mouth opening displacement (CMOD), J-integral, and crack growth resistance curve allow engineers to accurately quantify and predict the behaviour of materials under different loading conditions. Therefore, innovative methods for assessing pipeline integrity and predicting potential problems are an important focus of research, thus facilitating the assessment of when pipeline repair is necessary.

Since the early 1980s, additive technologies have advanced significantly. The choice of the right additive manufacturing technology depends on the specific needs of the particular project, including materials, costs, speed, resolution and mechanical requirements, /1/. Techniques such as Fused Deposition Modelling (FDM) and Selective Laser Sintering (SLS) have wide application range, including the fabrication of complex geometries, functional assemblies and parts of various dimensions, thereby optimising the use of materials and production time /2-6/. The influence of manufacturing parameters on the tensile and fracture properties of FDM 3D-printed PLA specimens are examined and presented in /7/. The study evaluates different printing orientations, layer thicknesses, specimen thickness, filament colours, and different printer types to determine their impact on mechanical behaviour. Tensile strength, Young's modulus, and fracture toughness are experimentally measured and validated using FEM simulations.

Investigation of additively manufactured specimens and the evaluation of their mechanical properties using tensile testing is given in /8, 9/. The /8/ focuses on Pipe Ring Notched Tension (PRNT) specimens made from PA12 polyamide using Selective Laser Sintering (SLS), while the study /9/ examines polypropylene (PP) specimens fabricated by Fused Deposition Modeling (FDM). Both studies analyse stress-strain behaviour with Digital Image Correlation (DIC) used to track deformations in PRNT specimens, whereas the PP study investigates the effects of printing parameters (layer height, infill density, raster orientation) on tensile properties. These investigations contribute to a deeper understanding of additively manufactured structures and their potential engineering applications.

The study /10/ examines the impact of testing speed on the tensile and mode I fracture behaviour of FDM-printed PLA specimens. Results show that higher test speeds increase tensile strength and Young's modulus but reduce J-integral values and fracture resistance, leading to a more brittle failure. The Digital Image Correlation (DIC) method was used for strain measurements during the tensile tests. The results from DIC and finite element analysis (FEM) show a high correlation in predicting fracture and material behaviour at different test speeds. Research shows the importance of testing speed in evaluating the mechanical properties of additively manufactured components, providing insights for optimising FDM-printed materials.

In their study /11/, Travica et al. present the development of a methodology for testing PRTS (Pipe Ring Tensile Specimens), using DIC method to measure deformations in polylactic acid (PLA) PRTS specimens during tensile testing. The specimens were tested using a specially designed tool with D-blocks, examining different geometries (single PRTS and double PRTS) and material infill percentages: 60 %, 90 %, and 100 %. In papers /12, 13/ a new non-standard method for testing cylindrical structures under pressure through the examination of PRNT specimens from PA12 (polyamide PA 2200) material is presented. For this purpose, new PRNT-Pipe Ring Notched Tension specimens are developed. During testing of these specimens, the initial sharp notch length is varied. A numerical analysis is carried out to calculate the stress intensity factor K_I, providing a deeper understanding of material behaviour under loading /12/. Parameters such as CMOD (crack mouth opening displacement) and CTOD-δ_5 (crack tip opening displacement) are measured, along with crack growth /13/ using the digital image correlation method. Authors demonstrate that the method is repeatable and can serve as a basis for further development of testing procedures for both polymeric and metallic pipelines.

According to all previously mentioned, researchers are trying to define and adapt new test specimen geometries that could provide valid results when testing pipeline fracture resistance. The aim of this research is to determine the fracture mechanics parameters of a ring-shaped specimen exposed to tension, with a sharp stress concentrator in the longitudinal direction. Research includes the development of a procedure for testing polymeric materials, a methodology for determining fracture mechanics parameters and an application that will overcome the problems that arise when applying existing fracture resistance testing procedures to thin-walled pipeline materials. Thanks to the experimental tests based on the method DIC, the initial parameters are obtained: force, displacement, CMOD and CTOD-δ_5.

MATERIALS AND METHODS

PLA (polylactic acid), is a polymer material used in the first steps of developing a new tube geometry using additive manufacturing, specifically FDM manufacturing technique, based on joining materials by melting. Due to its material properties, PLA polymer obtained from lactic acid is a key component in the transition towards a circular economy in the field of application of plastic materials, /14/. Although PLA is degradable under industrial conditions, there is a growing interest in its chemical recycling through methods such as hydrolysis, alcoholysis, and pyrolysis. Due to the presence of PLA polymer in various industries /15-17/, the determination of its physical and mechanical properties has been the subject of research by several research groups whose results are summarised in Table 1, /18-24/.

Table 1. Physical and mechanical properties of polymers PLA /18-24/.

Characteristics	PLA
Density (g/cm^3)	1.21-1.30
Tensile strength (MPa)	15.5-150
Modulus of elasticity (GPa)	2.7-16
Deformation at fracture (%)	2-10
Glass transition temperature (°C)	60-65
Melting point (°C)	130-180

Due to the high prevalence of PLA polymers in mechanical assemblies, several research groups have contributed to a better understanding of the fracture resistance of 3D printed objects using standard procedures /25, 26/. For the purposes of developing the test procedure, PLA (German, RepRap) material is used in this research due to its good properties

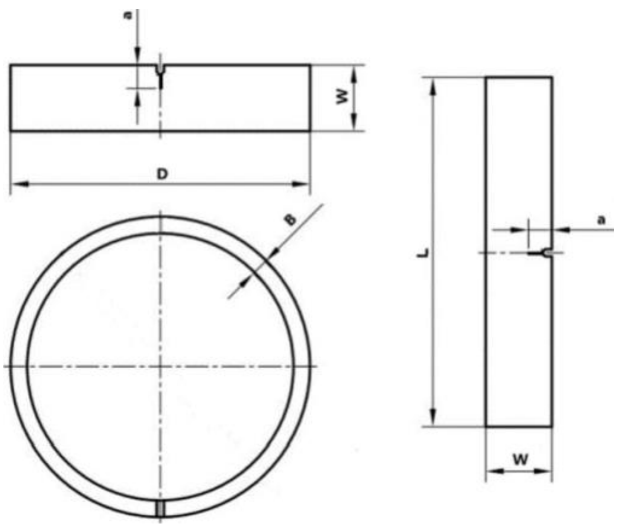

Figure 1. Drawing of PRNT specimen (left); SENT specimen (right), /13/.

when making models by 3D printing. Figure 1 shows the ring-shaped specimen with a sharp groove loaded in tension (PRNT) and flat specimen for tension with an edge crack (SENT - single edge notched tension) with indicated sizes.

Tables 2 and 3 show dimensions. One group of test specimens is intended for testing one day after manufacturing, and another after 14 days, to determine the effect of aging.

Table 2. Dimensions and markings of test specimens: PRNT and SENT - for testing two weeks after production.

	External diameter D (mm)	Wall thickness B (mm)	Specimen width W (mm)	Length of sharp notch a_0 (mm)
PRNT(PLA) 1-5	42.2	2.3	9.2	2.8
PRNT(PLA) 6-7	42.2	2.3	9.2	4.6
	Length L (mm)	Wall thickness B (mm)	Specimen width W (mm)	Length of sharp notch a_0 (mm)
SENT(PLA) 1-4	80.0	2.3	9.2	2.6
SENT(PLA) 5-8	80.0	2.3	9.2	4.6

Table 3. Dimensions and markings of test specimens: PRNT and SENT - for testing one day after production.

Dimension	External diameter D (mm)	Wall thickness B (mm)	Specimen width W (mm)	Length of sharp notch a_0 (mm)
PRNT(PLA) 1.1-3.1	42.2	2.3	9.2	2.8
PRNT(PLA) 4.1-6.1	42.2	2.3	9.2	4.6

Manufactured PRNT and SENT test specimens are shown in Figs. 2 and 3. Three test specimens from each series are tested.

Figure 2. PRNT test specimens made by FDM technique from PLA material.

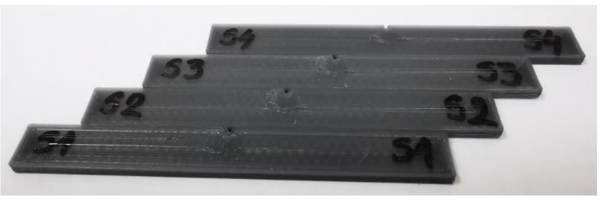

Figure 3. SENT specimens made by FDM technique from PLA material.

For the purposes of this research, ring-shaped test specimens with a sharp groove and SENT test specimens are made on the device of the German manufacturer German RepRap (model X400). The manufacturing parameters as well as the orientation of the model, are defined through the Simplify3D software and are shown in Table 4.

Table 4. Test specimen production parameters.

Nozzle diameter	0.4 mm
Extrusion speed	60 mm/s
Amount of filling	100 %
Fill type	honeycomb
Extruder temperature	210 °C
Substrate temperature	60 °C

The test specimen in production is oriented so that fibres are directed in the direction of the load in order to obtain maximum load capacity. In order to ensure the most horizontal direction of stress concentration in the plane of the crack, the test specimens are made with a total of two layers of outer walls. The first step in the preparation of test specimens for measurements performed with the Aramis system required initial sharp grooves applied to PRNT and SENT polymer test specimens using a 0.25 mm scalpel.

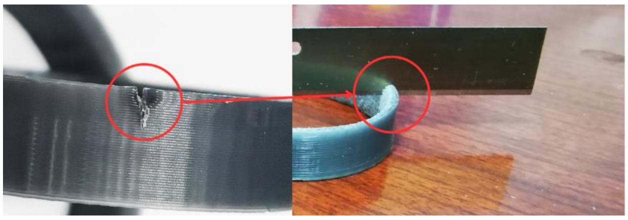

Figure 4. Applying a sharp stress concentrator to polymer PRNT specimen.

The test specimens are cut by pressing the blade into the polymer until the first two layers of polymer are pierced (Fig. 4), i.e., until desired groove length is achieved. Stoia et al. used this way of obtaining the initial crack in their research, /27/.

A black and white stochastic pattern is applied to the test specimens (Fig. 5).

Figure 5. Polymer rings with applied stochastic pattern.

After cutting test specimens, they are prepared for measurements using a non-contact method for measuring the field of displacement and deformations on tested specimens (DIC). In order to achieve satisfactory visibility of objects and reduce the reflection of directional lighting, the test specimens are first coated with matte white paint which formed the basis for the dispersion of black dots on the surface of test specimens. The dispersion of black dots that make up the template for establishing the measurement system is obtained by spraying matte black spray on a dry white base.

Test specimens are tested on a machine for testing mechanical properties of materials Shimadzu AGS-X 100 kN, at a speed of 0.5 mm/min. For each test specimen in the TrapeziumX software, the Pre-test option is applied, which ensures the beginning of the force measurement when the machine registers a force of 10 N, which guarantees that displacement values will not be registered during reaching full contact. The Aramis 2M system is calibrated on a 90 × 72 mm plate with a facet size of 15 × 13 pixels. The system is calibrated at a calibration deviation of 0.034 pixels.

RESULTS AND DISCUSSION

Some of the test specimens made from PLA are examined on the same day they are produced, while another set is tested 14 days later to evaluate how aging affects the material's fracture behaviour. Upon testing 14-day-old PRNT specimens, an uneven ring fracture is observed (Fig. 6).

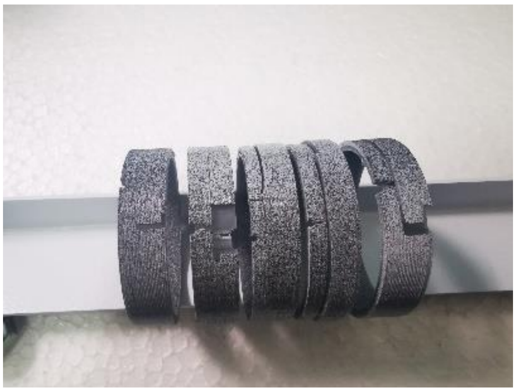

Figure 6. PRNT test specimens 14 days old.

In this case, it is not possible to monitor crack propagation; however, the maximal force values and those measured immediately before final failure are recorded (Table 5).

Table 5. Max. and break force values for PRNT spec. 14 days old.

Specimens	Max. force (N)	Break force (N)
PRNT-1	1110.1	683.1
PRNT-2	1105.6	760.3
PRNT-3	1004.4	631.4
PRNT-4	1109.3	689.1
PRNT-5	1217.6	652.6
PRNT-6	732.1	732.1
PRNT-7	988.6	929.1

As previously indicated, testing is also performed on the same day the specimens are produced (all specimens are printed using identical 3D printing parameters). These specimens display slightly improved properties, and unlike the batch manufactured 14 days prior to testing, it is possible to measure not only the maximal force values and forces at failure (Table 6), but also the CMOD and CTOD-δ_5 values.

The average maximal force for specimens labelled PRNT-1.1 through PRNT-3.1 is 1470 N, while the average fracture force is 1251 N. For the group PRNT-4.1 through PRNT-6.1, the average maximal force is 1316 N, and the average fracture force is 1025 N. Compared to the results obtained from testing specimens that were 14 days old, the average maximal force for one-day-old specimens is roughly 32 % higher for those with a smaller a_0/W ratio. The difference in the average maximal force for specimens with a larger a_0/W ratio is about 53 %. Figure 7 presents the force-displacement diagram recorded by the universal testing machine during testing of one-day-old specimens. Figure 8 illustrates how specimen behaviour depends on the deformation rate. The highest maximal force is achieved at the greatest deformation rate, while the maximal displacement at the loading point is approximately the same in all three cases.

Table 6. Max. and break force values for PRNT specimens 1 day old.

Specimens	Max. force (N)	Break force (N)
PRNT-1.1	1406.1	1228.5
PRNT-2.1	1416.2	1259.7
PRNT-3.1	1586.8	1265.6
PRNT-4.1	1340.6	1083.5
PRNT-5.1	1222.2	815.6
PRNT-6.1	1388	1178.8

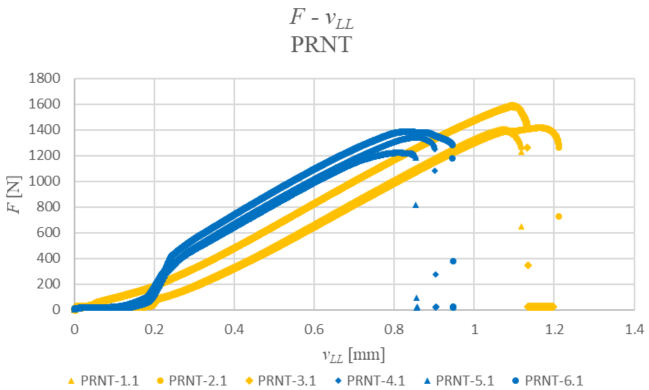

Figure 7. Force vs. displacement for PRNT1.1 – PRNT6.1 series.

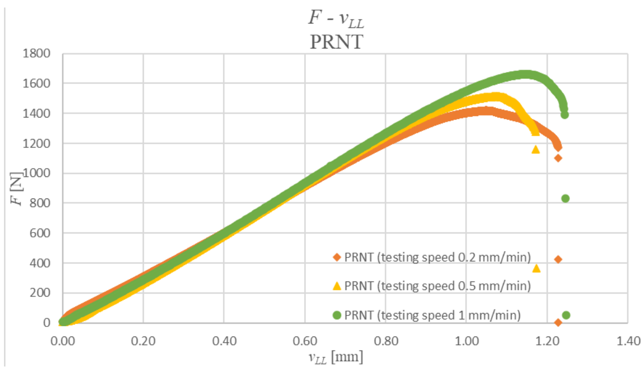

Figure 8. Force vs. displacement for different testing speeds (0.2 mm/min, 0.5 mm/min, and 1 mm/min).

Based on these diagrams, we can conclude that specimens exhibit predominantly brittle failure regardless of the testing speed. In FDM-manufactured specimens, certain fracture irregularities are observed during testing, with initial indications appearing when 14-day-old specimens are examined. Consequently, uneven load distribution stemming from 3D printing imperfections led to delamination in the remaining specimen ligament. Sometimes, due to uneven sample construction, the outer wall carries more load than the inner wall, resulting in discrepancies between the external and internal failure surfaces. Figure 9 shows a representative example of delamination occurring under higher load values. Similar changes are noted in other instances where delamination took place.

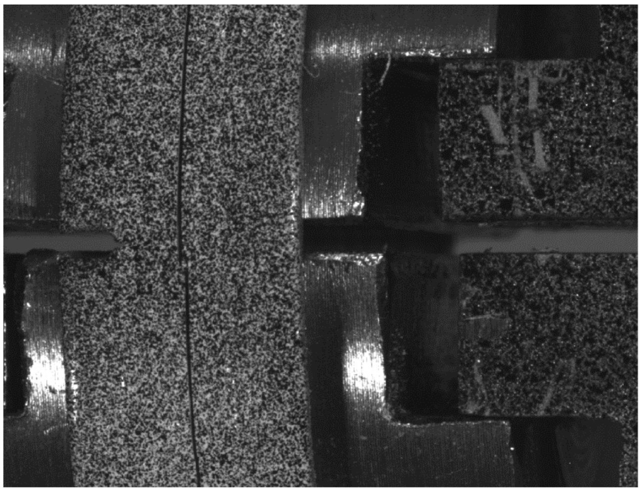

Figure 9. Delamination of specimen ligament.

The DIC method is a well-known non-contact optical method for measuring the field of deformations and displacements on tested specimens in order to determine the mechanical properties of the material and parameters of fracture mechanics. The DIC method is based on a local correlation approach that compares the position of measuring points during loading of specimens, /28-31/.

By employing the Aramis system (DIC), the CMOD and CTOD-δ_5 are measured, representing the first instance of recording fracture mechanics parameters during testing.

In the Aramis software, the CMOD and CTOD-δ_5 values are obtained using the point-point-distance command at each two-second interval (each ‘stage’). CMOD is determined by positioning markers at the upper and lower edges of the initial crack mouth, while CTOD-δ_5 is measured at the crack tip by selecting two points spaced 5 mm apart, perpendicular to the stress concentrator axis (Fig. 10). The same point-point-distance command is used for both CMOD and CTOD-δ_5.

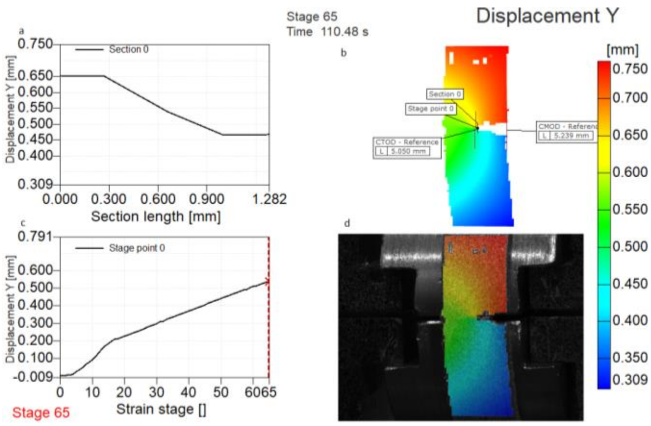

Figure 10. Method and place of marking initial position of points on PRNT test specimen for determining CMOD and CTOD parameters in figure b.

Although the used DIC system can measure surface displacements in all three coordinate directions, only vertical displacements are used for point-point-distance measurements. One of the reasons for this choice is that any displacements in the other directions are negligible and do not significantly influence vertical displacement values. The force-CMOD relationship for PRNT-1.1-6.1 specimen series is shown in Fig. 11, while Fig. 12 illustrates the force-CTOD-δ_5 relationship.

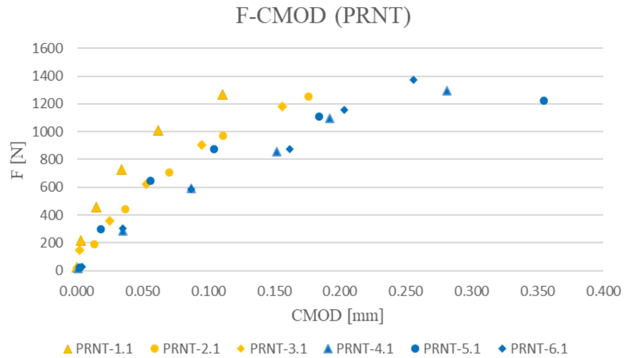

Figure 11. Force dependence on CMOD.

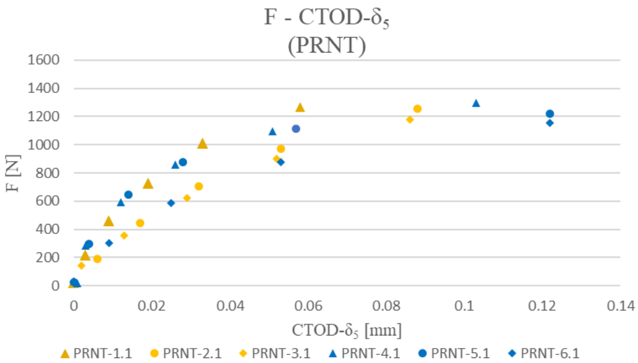

Figure 12. Force dependence on CTOD-δ_5.

Based on Figs. 11 and 12, a similar trend of curves can be observed for ring-shaped specimens, whether they feature shorter or longer crack length. The only difference lies in CMOD values for specimens PRNT-4.1 through PRNT-6.1 which are about 50 % higher.

Data from these diagrams do not indicate the maximum CMOD and CTOD-δ_5 values because the diagrams are generated using data recorded at 1-second intervals to synchronize the Aramis 2M system with the universal testing machine. Since the maximal values of these two parameters are reached very quickly as the force drops, that information does not substantially affect this type of diagram. In addition to displacement data captured by the Aramis 2M system, equivalent Von Mises strain values are also recorded for both specimen types.

The highest values of equivalent Von Mises strain occur at the crack growth location (Fig. 13b), with no indications of irregular crack propagation in view of how the specimens were manufactured which is further corroborated by the appearance of diagram in Fig. 13a. The diagram in the same figure shows that large equivalent Von Mises strain values appear only around the crack zone, including the maximum value at the crack tip. The force-displacement relationships obtained from the testing machine software for evaluated SENT specimens are presented in Fig. 14.

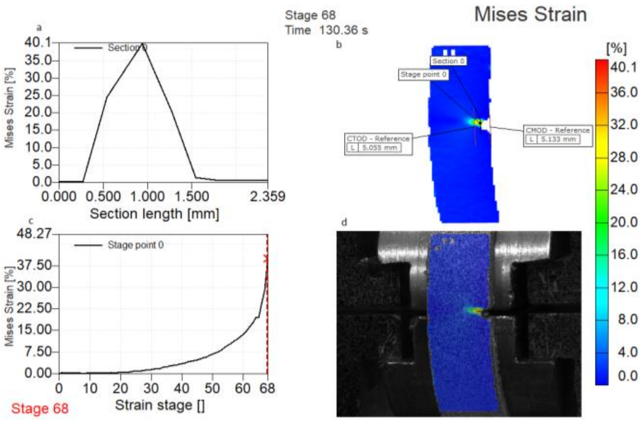

Figure 13. Equivalent Von Mises strain value for PRNT specimen of PLA material.

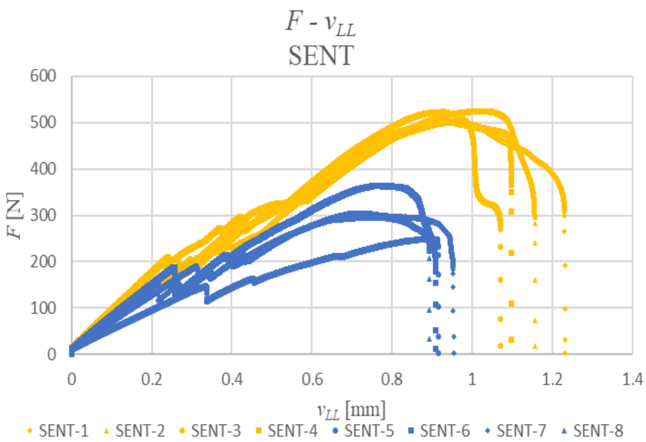

Figure 14. Force vs. displacement for SENT specimens.

Plotted curves exhibit sudden force drops, followed by several iterations of force increase. Based on prior experience with testing PRNT specimens which showed irregularities at failure, it is assumed that these drops correspond to the failure of individual fibres within the material. For the same group of specimens, the final values of CMOD and CTOD-δ_5 parameters are presented in Table 7, since the material's brittleness prevents the development of a force vs. parameter diagram.

Table 7. Maximal values of CMOD and CTOD-δ_5 parameters for SENT specimens.

Specimens	Max. CMOD (mm)	Max. CTOD-δ_5 (mm)
SENT-1	0.989	0.631
SENT-2	0.962	0.611
SENT-3	0.912	0.681
SENT-4	0.730	0.442
SENT-5	0.930	0.677
SENT-6	0.847	0.602
SENT-7	0.906	0.642
SENT-8	0.898	0.590

CONCLUSION

Test specimens produced by the FDM technique from PLA material show very brittle properties of the material, especially those produced 14 days before the test. The values of CMOD and CTOD-δ_5 parameters for this material could only be monitored on one-day-old test specimens, where the failure of the material is followed by failure of one strand of material at a time. The results of testing of these specimens provide a basis for further research. The production of test specimens using the FDM technique gave a great advantage in the speed of test specimen production for testing PRNT specimens. However, it can be concluded that due to the irregular crack growth and failure mode, this polymer (PLA made using the FDM technique) is not suitable for tests that include fracture and material damage analysis. Unlike the results presented in /12/, it is not possible to easily obtain fracture mechanics parameters for PLA specimens produced using FDM technique; specifically, determining the crack propagation location, as shown in the study (indicated at 15 % stress).

Future research will be based on testing different types of materials with this technique to more precisely define the problem, whether it is in the fabrication technique or in the materials for FDM print.

ACKNOWLEDGMENTS

This paper is dedicated to the late Prof. Dr. Marko Rakin (1966-2023), who was an integral part and driving force of this research in the previous period. Authors of this paper would like to express their gratitude to the Ministry of Education, Science, and Technological Development, Republic of Serbia, for supporting our work (contr. 451-03-66/2024-03/200213 and 451-03-65/2024-03/200135).

REFERENCES

1. Rajaguru, K., Karthikeyan, T., Vijayan, V. (2020), *Additive manufacturing - State of art*, Mater. Today: Proc. 21(Part 1): 628-633. doi: 10.1016/j.matpr.2019.06.728
2. Rouf, S., Raina, A., Ul Haq, M.I., et al. (2022), *3D printed parts and mechanical properties: Influencing parameters, sustainability aspects, global market scenario, challenges and applications*, Adv. Ind. Eng. Polym. Res. 5(3): 143-158. doi: 10.1016/j.aiepr.2022.02.001
3. Solomon, I.J., Sevvel, P., Gunasekaran, J. (2021), *A review on the various processing parameters in FDM*, Mater. Today: Proc. 37(Part 2): 509-514. doi: 10.1016/j.matpr.2020.05.484
4. Sandanamsamy, L., Harun, W.S.W., Ishak, I., et al. (2023), *A comprehensive review on fused deposition modelling of polylactic acid*, Prog. Addit. Manuf. 8: 775-799. doi: 10.1007/s40964-022-00356-w
5. Rahim, T.N.A.T., Abdullah, A.M., Md. Akil, H. (2019), *Recent developments in fused deposition modeling-based 3D printing of polymers and their composites*, Polym. Rev. 59(4): 589-624. doi: 10.1080/15583724.2019.1597883
6. Cano, A.J., Salazar, A., Rodríguez, J. (2024), *Structural integrity of polymers processed by additive manufacturing techniques using residual strength diagrams*, Theor. Appl. Fract. Mech. 134(Part B): 104727. doi: 10.1016/j.tafmec.2024.104727
7. Marșavina, L., Vălean, C., Mărghitaș, M., et al. (2022), *Effect of the manufacturing parameters on the tensile and fracture properties of FDM 3D-printed PLA specimens*, Eng. Fract. Mech. 274: 108766. doi: 10.1016/j.engfracmech.2022.108766
8. Trajković, I., Milošević, M., Rakin, M., et al. (2022), *Additively manufactured tensile ring-shaped specimens for pipeline material fracture examination - influence of geometry*, Procedia Struct. Integr. 42: 1314-1319. doi: 10.1016/j.prostr.2022.12.167
9. Milovanović, A., Golubović, Z., Babinský, T., et al. (2022), *Tensile properties of polypropylene additively manufactured by FDM*, Struct. Integr. Life, 22(3): 305-308.

10. Zhan, J, Cai, J, Hasani, R. (2024), *Effects of testing speed on the tensile and mode I fracture behavior of specimens printed through the Fused Deposition Modeling technique*, Sci. Rep. 14(1): 3960. doi: 10.1038/s41598-024-54780-9
11. Travica, M., Mitrović, N., Petrović, A., et al. (2022), *Experimental evaluation of hoop stress-strain state of 3D-printed pipe ring tensile specimens*, Metals, 12(10): 1560. doi: 10.3390/met 12101560
12. Trajković, I., Rakin, M., Milošević, M., et al. (2023), *Selective laser sintered Pipe Ring Notched Tension specimens for examination of fracture properties of pipeline materials*, Eng. Fract. Mech. 292: 109573. doi: 10.1016/j.engfracmech.2023.109573
13. Trajković, I., Milošević, M., Travica, M., et al. (2022), *Novel method for measurement of pipeline materials fracture resistance-examination on selective laser sintered cylindrical specimens*, Sci. Sinter. 54(3): 373-386. doi: 10.2298/SOS2203373T
14. Milovanović, A., Sedmak, A., Paunić, M., et al. (2024), *Tensile properties of pure PLA polymer dedicated for additive manufacturing*, Struct. Integr. Life, 24(3): 263-268. doi: 10.69644/iv k-2024-03-0263
15. Lorite, G.S., Rocha, J.M., Miilumäki, N., et al. (2017), *Evaluation of physicochemical/microbial properties and life cycle assessment (LCA) of PLA-based nanocomposite active packaging*, LWT, 75(3): 305-315. doi: 10.1016/j.lwt.2016.09.004
16. Maga, D., Hiebel, M., Aryan, V. (2019), *A comparative life cycle assessment of meat trays made of various packaging materials*, Sustainability, 11(19): 5324. doi: 10.3390/su11195324
17. Chitaka, T.Y., Russo, V., von Blottnitz, H. (2020), *In pursuit of environmentally friendly straws: a comparative life cycle assessment of five straw material options in South Africa*, Int. J Life Cycle Assess. 25: 1818-1832. doi: 10.1007/s11367-020-01 786-w
18. Chen, C.-C., Chueh, J.-Y., Tseng, H., et al. (2003), *Preparation and characterization of biodegradable PLA polymeric blends*, Biomaterials, 24(7): 1167-1173. doi: 10.1016/S0142-9612(02) 00466-0
19. Ochi, S. (2008), *Mechanical properties of kenaf fibers and kenaf/PLA composites*, Mech. Mater. 40(4-5): 446-452. doi: 10. 1016/j.mechmat.2007.10.006
20. Yang, S.-L., Wu, Z.-H., Yang, W., Yang, M.-B. (2008), *Thermal and mechanical properties of chemical crosslinked polylactide (PLA)*, Polym. Test. 27(8): 957-963. doi: 10.1016/j.poly mertesting.2008.08.009
21. Suryanegara, L., Nakagaito, A.N., Yano, H. (2009), *The effect of crystallization of PLA on the thermal and mechanical properties of microfibrillated cellulose-reinforced PLA composites*, Compos. Sci. Technol. 69(7-8): 1187-1192. doi: 10.1016/j.com pscitech.2009.02.022
22. Lim, J.S., Park, K.-I., Chung, G.S., Kim, J.H. (2013), *Effect of composition ratio on the thermal and physical properties of semicrystalline PLA/PHB-HHx composites*, Mater. Sci. Eng. C, 33(4): 2131-2137. doi: 10.1016/j.msec.2013.01.030
23. Scaffaro, R., Botta, L., Maio, A., Gallo, G. (2017), *PLA graphene nanoplatelets nanocomposites: Physical properties and release kinetics of an antimicrobial agent*, Compos. Part B: Eng. 109: 138-146. doi: 10.1016/j.compositesb.2016.10.058
24. Sedničková, M., Pekařová, S., Kucharczyk, P., et al. (2018), *Changes of physical properties of PLA-based blends during early stage of biodegradation in compost*, Int. J Biol. Macromol. 113: 434-442. doi: 10.1016/j.ijbiomac.2018.02.078
25. Vălean, C., Marşavina, L., Mărghitaş, M., et al. (2020), *The effect of crack insertion for FDM printed PLA materials on Mode I and Mode II fracture toughness*, Procedia Struct. Integr. 28: 1134-1139. doi: 10.1016/j.prostr.2020.11.128
26. Kizhakkinan, U., Rosen, D.W., Raghavan, N. (2022), *Experimental investigation of fracture toughness of fused deposition modeling 3D-printed PLA parts*. Mater. Today: Proc. 70: 631-637. doi: 10.1016/j.matpr.2022.10.014
27. Stoia, D.I., Marşavina, L., Linul, E. (2020), *Mode I fracture toughness of polyamide and alumide samples obtained by selective laser sintering additive process*, Polymers, 12(3): 640. doi: 10.3390/polym12030640
28. Aranđelović, M., Petrović, A., Sedmak, S. (2024), *Digital image correlation application to structural integrity assessment*, Struct. Integr. Life, 24(1): 87-91. doi: 10.69644/ivk-2024-01-0087
29. Bajić, D., Momčilović, N., Maneski, T., et al. (2017), *Numerical and experimental determination of stress concentration factor for a pipe branch model*, Tech. Gazette, 24(3): 687-692. doi: 10.17559/TV-20151126222916
30. Sabik, A., Rucka, M., Andrzejewska, A., Wojtczak, E. (2022), *Tensile failure study of 3D printed PLA using DIC technique and FEM analysis*, Mech. Mater. 175: 104506. doi: 10.1016/j.mech mat.2022.104506
31. Aydın, M., Öz, Ö. (2018), *Application of digital image correlation technique to tensile test for printed PLA specimens*, Int. J 3D Print. Technol. Dig. Ind. 2(2): 1-7.