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An investigation on mechanical properties of 3D pen fused zones for additive manufactured parts

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A B S T R A C T

Additive manufacturing has been one of the most used techniques in the recent years because of its capabilities to fabricate complex structures as required by customer and industrial need from a 3D computer-aided design model without the usage of any tooling, dies and heavy machinery makes it a step ahead in the present manufacturing techniques. In the current study the author's focus on the welding or joining of additive manufactured Polylactic acid (PLA) parts made by Fused Deposition Modeling (FDM). There are several techniques for welding these additive manufactured parts. This study mainly focuses on the joining of 3D printed PLA parts using a 3D pen and investigations on its mechanical properties experimentally. It is a very cheap and effective technique when compared to the other welding methods. This could overcome the drawback of small bed size in most 3D printers by joining smaller parts and it can also be used for repairing the defects caused during the 3D printing. Moreover the experimental testing of the mechanical properties also confirmed that the tensile, flexural and impact strength of 3D pen welded specimens retrieved above 70% of the strength to the original PLA specimen proving it to be a very effective method.

1. Introduction

The process of fabricating a three-dimensional model from a Computer Aided Design model is known as additive manufacturing, or 3D printing. There are many techniques in additive manufacturing for which materials are added together, usually layer by layer, and thereafter deposition, joining, or solidification are all controlled by computers (Srivastava & Rathee, 2021). Rapid prototyping was a more accurate word for 3D printing in the 1980s, when it was thought that it was only useful for producing functional or aesthetically pleasing prototypes. In recent years 3D printing key features like accuracy, repeatability, and material variety have improved in such a way that these techniques are viewed as practical for use in industrial production, making the terms additive manufacturing and 3D printing interchangeable (Al Rashid et al., 2020). One of the main advantages of additive manufacturing is its capacity to create extremely complex shapes or geometries that would be very hard to create manually or by other manufacturing methods, including hollow parts or parts with internal truss structures to reduce weight. As of 2020, fused deposition modeling (FDM) the most widely used 3D printing technique, which employs a thermoplastic continuous filament (Jemghili et al., 2021). By stacking 2D cross-sections that are printed using molten fibers that are extruded and deposited, complex 3D objects are made possible with FDM. Thermoplastics are by far the most frequently generated materials for FDM parts; however metals and densely filled ceramics have also been utilized (Daminabo et al., 2020). A crucial aspect of FDM is the employment of the driven filament's colder, solid part as a plunger to

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exert pressure on the molten material in the liquefier prior to deposition. Fundamentally, fused deposition modeling is an extrusion procedure. Larger FDM machines that directly extrude thermoplastic pellets have been created in order to print larger parts and structures (Wickramasinghe et al., 2020).

The large variety of materials that may be used with FDM is one of its main benefits. This comprises common thermoplastics like PLA and ABS, as well as high-performance thermoplastics like PEEK and PEI and engineering materials like PA, TPU, and PETG (Alfattni 2022). PLA filament is the most often used material for desktop FDM printers. Using PLA printing, more complex details can be added to the finished product. The natural thermoplastic polyester, Polylactic Acid (PLA) filament is recyclable and made from renewable materials like sugar cane or corn starch (Chacón et al., 2017). Under specific circumstances, the filament's high heat capacity and great mechanical strength make it biodegradable. It is non-toxic and does not release fumes or poisons when melted (Jemghili et al., 2021).

An excellent method to add to your toolkit for 3D printing is PLA welding. It joins two or more 3D printed pieces together, fill in cracks and repair parts. Stronger durable bonds can be produced PLA welding (Frascio et al., 2021). Some common situations include: 1) Cracks in badly printed or broken parts. 2) Small surface area joints that demand a strong connection. 3) Curved or spherical joints with limited space for glue. 4) Complicated shapes that are challenging to be glued. 5) Seamless joints. Some common PLA filament welding techniques are:

- Friction welding of additive manufactured parts (Vidakis et al., 2022).
- Another better solution that works well in most circumstances is superglue. It can be challenging to apply, but it works for ABS but not for PLA.
- Heat guns or soldering irons can be used to melt plastic. Even though it works well most of the time, this usually results in severely disorganized joints. Particularly soldering irons can burn PLA and leave dark stains. Additionally, melted PLA has a penchant for sticking to soldering guns, which makes cleanup a real pain.
- 3D pens are a very good method for joining parts together as well. It is not the best technique; but it is very cheap and the most simple technique when compared to others.

A 3D pen is a pen that extrudes heated or warm plastic from the pen's nozzle. It does not need any software, file transfers or a computer, and no difficult technique to master. In the current work the authors have joined two parts of a 3D printed specimen using 3D pen and the mechanical properties of the joined part is experimentally calculated and compared with the original strength of the material specimen. The main disadvantage in most of the FDM based 3D printers is its small bed size. So it is difficult to fabricate objects that are bigger than the printer's bed size (Tiwary et al., 2022). This difficulty could be neglected by the usage of 3D pens to join the smaller parts.

2. Materials and Methods

2.1 Specimen Configuration

Specimens were printed according to the ASTM standards for tensile, flexural and impact test of 3D printed specimens viz: ASTM D638, ASTM D790 and ASTM D256 respectively (Aveen et al., 2018). Four specimens were printed for each specimen and were named as T1 – T4 for tensile test, F1 – F4 for flexural test and I1 – I4 for impact test. The dimensions for the specimens were as in the Fig. 1.

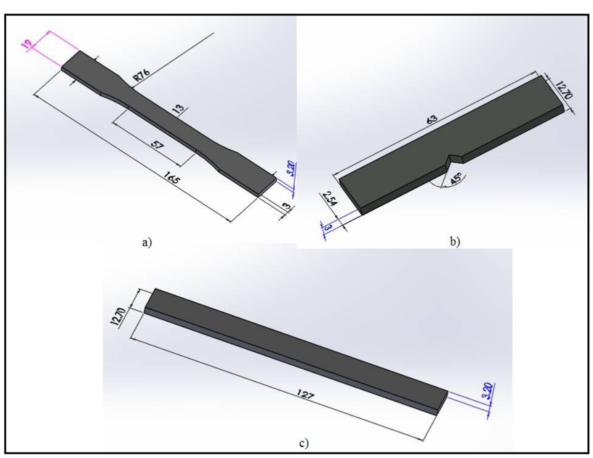


Fig. 1. Dimensions of the specimens for mechanical testing a) Tensile Test b) Impact test c) Flexural test

Specimen Fabrication

In the current investigation, the specimens were 3D printed using Flash Forge 3D printer (Make: Zhejiang Flash Forge 3D Technology Co., Ltd, Model: Flash Forge Guider 2S) and 3DXTECH PLA filament spool were used for the fabrication. The properties of PLA filament procured from the filament manufacturer are listed in Table 1.

Table 1. Properties of PLA Filament

Test Parameters	Results
Tensile Strength (MPa)	55
Tensile Modulus (MPa)	2560
Tensile Elongation at Break (%)	10
Flexural Strength (MPa)	95
Flexural Modulus (MPa)	2980
Izod Impact Strength (kJ/m2)	16.961

Fusion Deposition Modelling method is used in the 3D printer to fabricate the specimens. FDM is a method of 3D printing, in which layers of materials blend together in a pattern to fabricate an object. Because the temperature kept the incoming layer and the one that came before in a rigid state, the bonding between them was strong and allowed for the development of the necessary mechanical properties (Camargo et al., 2019). This caused the PLA specimen to be manufactured to stand firmly without bending or deforming. The specimens were fabricated in two halves as represented in Fig. 2 in order to weld the specimens using a 3D pen for the mechanical testing.

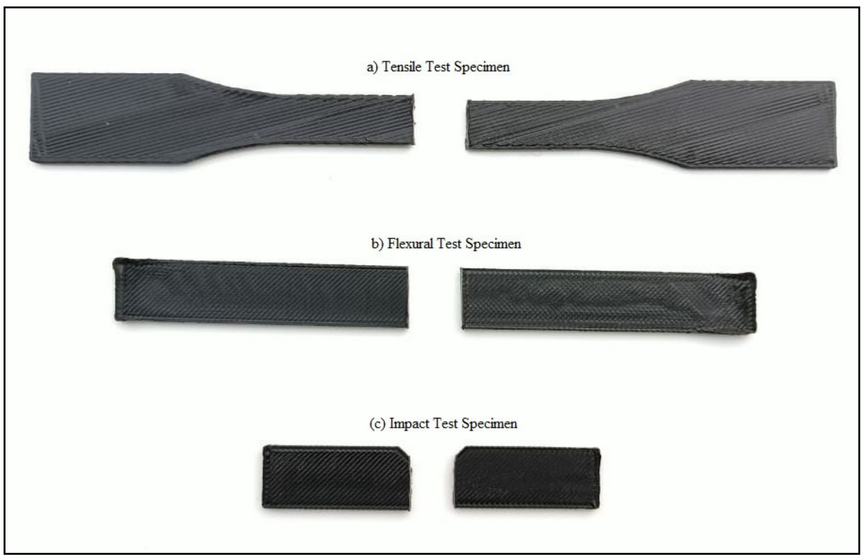


Fig. 2. 3D printed specimens for welding using 3D pen

Joining of 3D printed specimens using 3D Pen

Joining of the specimen was performed using a REES52 3D printing pen. PLA filament that was used for fabricating the specimens was also used for joining the specimens. The working temperature of the 3D pen was 165 - 200^0 C and with 0.7 mm nozzle diameter. The various parts and functions of the 3D pen are mentioned in Fig. 3.

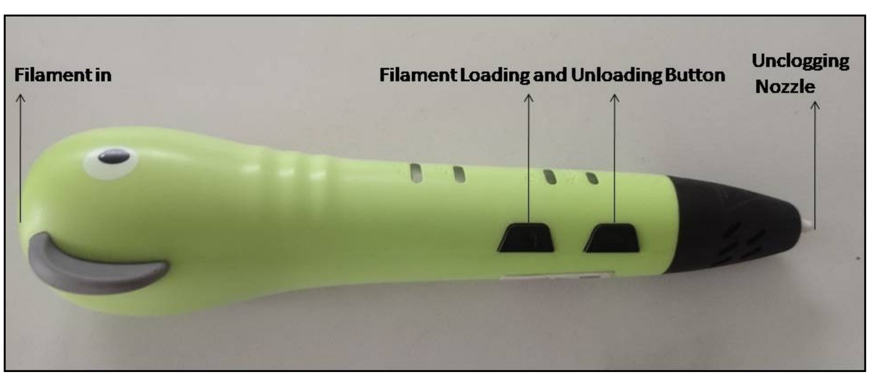
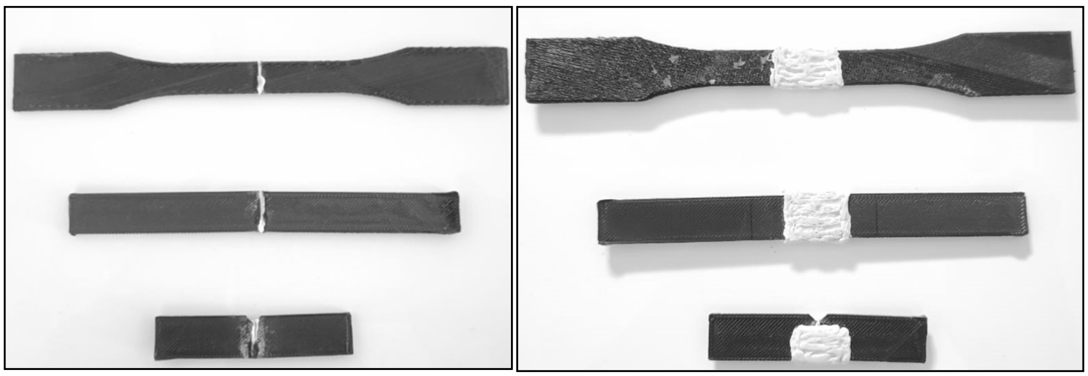


Fig. 3. Parts of a 3D pen

During the joining process, the two halves of the specimen were placed close to each other. Next, once extrusion started, the 3D pen's tip was held just below the lower half of a fractured specimen to allow a small quantity of material to build up and adhere to the outside (Manoj et al., 2021; Sigloch et al., 2020). Initially the center portion of the specimen was joined using the 3D pen as mentioned in Fig. 4 .a. The 3D pen tip was then angled against the specimen's surface while being moved up across the fractured portion and onto the upper part of the specimen. The 3D pen tip was then brought back to the lower portion, being careful to maintain a tight seal between the extruding filament and the line of previously laid down filament as well as the surface of the specimen. This was carried out all the way across a specimen, much like how MIG welding is done. This was done to each side of the specimen until the fractured portion was completely concealed. The pen tip was used to fill in any gaps that seemed to need extra filling, as needed, by pressing it against the affected area. The specimen's corners received the majority of this treatment. These freshly filled areas can even be flattened off using the pen tip's side. Fig. 4.b illustrates this pattern in detail.



(a) (b)

Fig. 4. Specimens welded using 3D pen

Tensile, Flexural and Impact Test

The 3D-printed PLA specimens joined using a 3D pen as per ASTM D638 was tested experimentally for tensile strength on a universal testing machine (UTM). Figure 5 depicts the tensile testing of the specimens in the UTM. Universal Testing Machine DTRX-50 with specifications 50 kN capacity and a maximum speed of 25 mm/sec was used for the conduct of Tensile and flexural test. 4 specimens were subjected to each test. The test data were recorded using software, combined with PC data gathering and the results were calculated. Specimens were held on to the UTM with the help of grippers, and load was applied gradually until the specimen failed, and the resultant stress and strain data and graph were procured for the specimen through the computerized data acquisition system (Hsueh et al., 2021; Brischetto et al., 2020).

Fig. 5. Tensile testing on the 3D pen welded specimen

A flexural specimen as per ASTM D790 was subjected to a three-point bending test. The specimen is placed on two supports that are 48 cm apart (L), and force was applied exactly in the middle of two supports (L/2). Computerized stress v/s strain curve is plotted to determine the maximum flexural strength of the specimen (Maqsood & Rimašauskas, 2021; García et al., 2022). The impact test specimens as per ASTM D256 were tested using Kant Plastology's Izod impact tester. Testing direction was edgewise parallel. 3D printed and joined PLA samples were tested with notched specimens (Ansari & Kamil 2022; Naik & Thakur 2021).

3. Results and Discussion

Tensile test results

The 3D pen joined specimens were tensile tested after a week time so that the filament would have dried sufficiently. All the specimens showed brittle fracture and had a good tensile strength. Two types of failure occurred in the specimen. The specimen T1, T2 and T4 failed exactly in the center of the specimen in the midway of the joined region similar to the Figure 6.a. In the specimen T3 one half of the specimen peeled away from the 3D pen joined portion similar to the Fig. 6.b. This may be due to the incorrect bonding between the specimen and the joining filament. The tensile behavior of the specimens in the flexural test is shown by plotting flexural stress vs strain in Fig. 8.a.

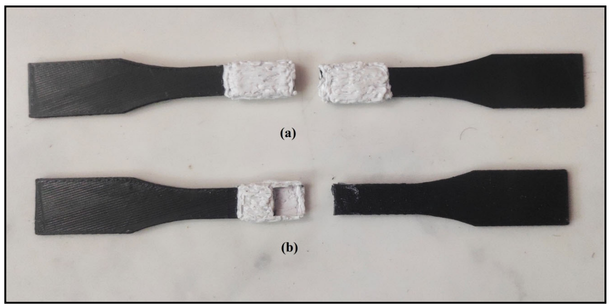


Fig. 6. Failed specimen during tensile test

A good tensile strength was noticed in three of the four specimens and the reason for one value being low could be bad bonding between the specimen and the weld. The tensile strength and young's modulus for each specimen is listed in Table 2. The average ultimate tensile strength was 38.55 MPa and the average young's modulus was 1470.93 MPa. The 3D pen welded specimen could retain the tensile strength of 70% while comparing to the tensile strength of normal PLA specimens procured from the filament manufacturer (Table 1).

Table 2. Tensile and Flexural test results

Sample	Standard	Ultimate Tensile Strength (MPa)	Young's Modulus (MPa)
T1	ASTM D 638	41.01	1541.77
T2		40.84	1552.85
T3		30.10	1275.42
T4		42.27	1513.69
Sample	**Standard**	**Ultimate Flexural Strength (MPa)**	**Flexural Modulus (GPa)**
F1	ASTM D 790	58.85	1898.39
F2		47.22	1120
F3		45.92	1180.50
F4		61.66	1433.95

Flexural test results

The flexural behaviors of the specimens are shown by plotting flexural stress vs strain in Fig. 8.b. The average ultimate flexural strength and flexural modulus were 53.41 MPa and 1408.21 MPa, respectively, based on the data collected during the test. The 3D pen welded specimen could retain the ultimate flexural strength of nearly 60% while comparing to the tensile strength of normal PLA specimens procured from the filament manufacturer.

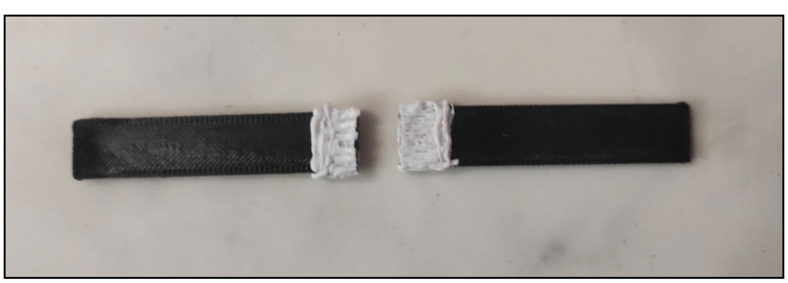
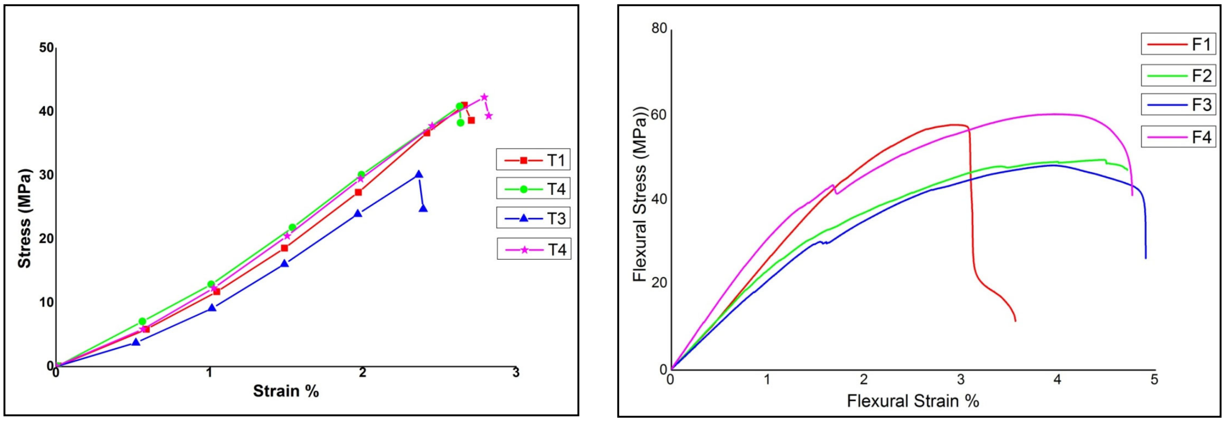


Fig. 7. Failed specimen during flexural test

All of the specimens experienced a collapse with a quick drop in load after reaching a peak value. The inner specimen remained unbroken until the test reached its displacement limit in the specimens F2 and F3. Only the outer welded layer failed during the test.



(a) (b)

Fig. 8. Stress vs Strain Graph (a) Tensile Test (b) Flexural test

Impact test results

The results of the izod impact test of the specimens are represented in Fig. 9. The average value of the impact strength was 11.45 KJ/m^2 which is nearly 70% of the impact strength of the normal PLA specimen. Notched specimens were considered for the impact tests.

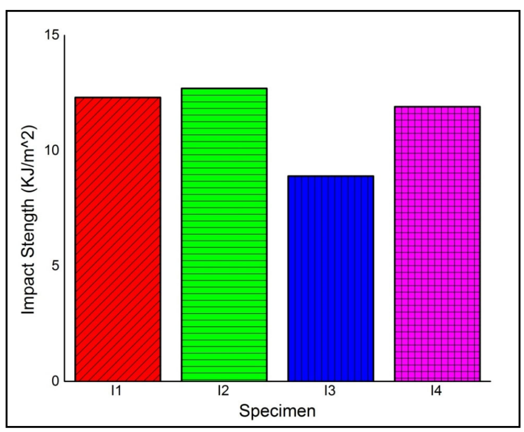


Fig. 9. Impact test graph

4. Conclusion

In this research, the joining behavior of PLA specimens using 3D pen has been investigated. The performance of 3D pen weld of PLA has been evaluated in mechanical properties viz: tensile, flexural and impact strength. The salient findings drawn from the present work are summarized as follows:

- The fusion between the PLA specimen and the weld using 3D pen was very good and it could be confirmed by the mechanical testing results.
- The welded specimen retained almost 70, 60, 70 percent of tensile, flexural and impact strength of the original PLA specimen mentioned in the filament manufacturers technical data sheet. Even though the results seem to be moderate the cost involved in this technique is very low when compared to the other welding techniques such as friction welding. The 3D pen welding process is also very simple and it does not need any special skilled workforce.
- This 3D pen could possibly be used for applications such as joining of large sized 3D printed parts which is difficult to print due to the small bed size of the 3D printers. It can also be used for repairing and filling the damaged areas caused during the 3D printing.
- Although the investigation is limited to the repair of 3D-printed components, the 3D printing pen may have applications in other industries. Using a 3D printing pen, all the thermoplastic-made parts could be joined together.

References

Al Rashid, A., Khan, S. A., G. Al-Ghamdi, S., & Koç, M. (2020). Additive manufacturing: Technology, applications, markets, and opportunities for the built environment. *Automation in Construction, 118*, 103268.

Alfattni, R. (2022). Comprehensive study on materials used in different types of additive manufacturing and their applications. *International Journal of Mathematical, Engineering and Management Sciences, 7*(1), 92-114.

Ansari, A. A., & Kamil, M. (2022). Izod impact and hardness properties of 3D printed lightweight CF-reinforced PLA composites using design of experiment. *International Journal of Lightweight Materials and Manufacture, 5*(3), 369-383.

Aveen, K. P., Vishwanath Bhajathari, F., & Jambagi, S. C. (2018). 3D Printing & Mechanical Characteristion of polylactic acid and bronze filled polylactic acid components. *IOP Conference Series: Materials Science and Engineering, 376*, 012042.

Brischetto, S., & Torre, R. (2020). Tensile and compressive behavior in the experimental tests for PLA specimens produced via fused deposition modelling technique. *Journal of Composites Science, 4*(3), 140.

Camargo, J. C., Machado, Á R., Almeida, E. C., & Silva, E. F. (2019). Mechanical properties of pla-graphene filament for FDM 3D printing. *The International Journal of Advanced Manufacturing Technology, 103*(5-8), 2423-2443. doi:10.1007/s00170-019-03532-5

Chacón, J., Caminero, M., García-Plaza, E., & Núñez, P. (2017). Additive manufacturing of PLA structures using fused deposition modelling: Effect of process parameters on mechanical properties and their optimal selection. Materials & Design, 124, 143-157.

Daminabo, S., Goel, S., Grammatikos, S., Nezhad, H., & Thakur, V. (2020). Fused deposition modeling-based additive manufacturing (3D printing): Techniques for Polymer Material Systems. *Materials Today Chemistry, 16*, 100248.

Frascio, M., Moroni, F., Marques, E., Carbas, R., Reis, M., Monti, M., Da Silva, L. (2021). Feasibility Study on hybrid weld-bonded joints using additive manufacturing and conductive thermoplastic filament. *Journal of Advanced Joining Processes, 3*, 100046.

García Reyes, M., Bataller Torras, A., Cabrera Carrillo, J. A., Velasco García, J. M., & Castillo Aguilar, J. J. (2022). A study of tensile and bending properties of 3D-printed biocompatible materials used in dental appliances. *Journal of Materials Science, 57*(4), 2953-2968.

Hsueh, M., Lai, C., Chung, C., Wang, S., Huang, W., Pan, C., Hsieh, C. (2021). Effect of printing parameters on the tensile properties of 3D-printed polylactic acid (PLA) based on fused deposition modeling. *Polymers, 13*(14), 2387.

Jemghili, R., Ait Taleb, A., & Khalifa, M. (2021). A bibliometric indicators analysis of Additive Manufacturing Research Trends from 2010 to 2020. Rapid Prototyping Journal, 27(7), 1432-1454.

Manoj, G. S., Kulkarni, N. B., & Shah, V. D. (2021). 3D printing pen: A novel adjunct for indirect bonding. *The Journal of Contemporary Dental Practice, 22*(8), 964-968.

Maqsood, N., & Rimašauskas, M. (2021). Tensile and flexural response of 3D printed solid and porous CCFRPC structures and fracture interface study using image processing technique. *Journal of Materials Research and Technology, 14*, 731-742.

Naik, M., & Thakur, D. G. (2021). Experimental investigation of effect of printing parameters on impact strength of the bio-inspired 3D printed specimen. *Sādhanā, 46*(3).

Sigloch, H., Bierkandt, F., Singh, A., Gadicherla, A. K., Laux, P., & Luch, A. (2020). 3D printing - evaluating particle emissions of a 3D printing pen. *Journal of Visualized Experiments,* (164).

Srivastava, M., & Rathee, S. (2021). Additive manufacturing: Recent trends, applications and future outlooks. *Progress in Additive Manufacturing*, *7*(2), 261–287.

Tiwary, V. K., Ravi, N., Arunkumar, P., Shivakumar, S., Deshpande, A. S., & Malik, V. R. (2020). Investigations on friction stir joining of 3D printed parts to overcome bed size limitation and enhance joint quality for Unmanned Aircraft Systems. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 234*(24), 4857-4871.

Vidakis, N., Petousis, M., Korlos, A., Mountakis, N., & Kechagias, J. D. (2022). Friction stir welding optimization of 3D-printed acrylonitrile butadiene styrene in hybrid additive manufacturing. *Polymers, 14*(12), 2474.

Wickramasinghe, S., Do, T., & Tran, P. (2020). FDM-based 3D printing of Polymer and associated composite: A review on mechanical properties, defects and treatments. *Polymers, 12*(7), 1529.