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Engineering

COMPOSITE MATERIAL MANUFACTURING BY 3D PRINTING AND VACUUM RESIN INFUSION

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ABSTRACT:
ADDITIVE MANUFACTURING TECHNOLOGIES, POPULARLY KNOWN AS 3D PRINTING, ARE USED TO QUICKLY CREATE OBJECTS WITH COMPLICATED SHAPES. ONE OF THE TECHNOLOGIES IS CALLED FUSED DEPOSITION MODELLING (FDM) AND OPERATES BY ADDING LAYERS OF FILAMENT ATOP OF ONE ANOTHER TO CREATE OBJECTS. VACUUM INFUSION IS A TECHNOLOGY USED IN THE CREATION OF COMPOSITE MATERIALS THAT CREATES VACUUM IN THE OBJECT IN ORDER TO DRAW THE LIQUID THERMOSET INTO IT. THE ARTICLE EXPLORES THE ADVANTAGES AND THE VIABILITY OF COMBINING THE TWO TECHNOLOGIES TO CREATE A COMPOSITE OBJECT THAT HAS A SHAPE DEFINED BY FDM PRINTED PLA STRUCTURE AND IS REINFORCED WITH EPOXY RESIN THAT IS APPLIED WITH THE PROCESS OF VACUUM INFUSION.

KEY WORDS: 3D PRINTING, COMPOSITES, PLA, EPOXY, VACUUM INFUSION

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INTRODUCTION

Composite materials have been used since the ancient times but it was not until the introduction of composites on the polymer basis that they became widely used in the industry. They are admired for their high strength to weight ratio when compared to metallic counterparts which has led to their adoption in the fields where weight saving is crucial like the aerospace and automotive industries. As the name suggests composites are comprised of at least two different components that when combined provide exceptional mechanical properties. Conventional composites are made by combining the resin with a fiber as a reinforcement material, usually made of carbon, glass or aramid[8]. We created an unconventional composite by swapping traditionally used fibers with a matrix made by additive manufacturing that would be filled with epoxy resin with the process of vacuum resin infusion.

Additive manufacturing technologies are increasing in popularity and FDM printing of polymers is one of the most prevailing. Using these technologies, we can create objects with complex geometries with ease and low cost. The cost per manufactured object is not correlated with the number of objects manufactured thus making it suitable for making low volume parts with unique shapes such as prototypes or medical prostheses[9].

There is a variety of additive manufacturing technologies on the market that can be divided into several categories based on the underlying process that is being used. Most notable are the Stereolithography (SLA) and Digital Light Processing (DLP) that rely on the light induced polymerization, Selective Laser Sintering (SLS), Material Jetting (MJ) and Fused Deposition Modelling (FDM). This article will be focused primarily on the FDM technology since it was used to manufacture test specimens.

FDM printing works by extruding polymeric filament through a heated nozzle. There it is melted and shaped in a thin strand. CNC control is used to deposit it layer by layer in a shape of the desired object. This is done separately for every layer starting from the ground up. Schematics of the process are shown in Figure 1. It is one of the cheapest and most broadly used of the additive manufacturing technologies. Materials printed with this method are thermoplastics, usually PLA, ABS or TPU.

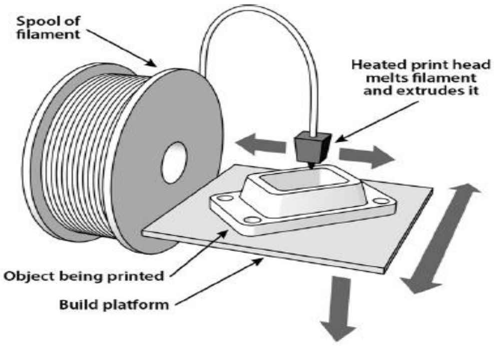

Figure 1: Schematics of FDM printing process[10]

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[8] Mazumdar, Sanjay K.; *Composites manufacturing: materials, product and process engineering*: CRC Press, 2002

[9] Lipson, Hod; Kurman Melba; Fabricated: The New World of 3D Printing. John Wiley & Sons Inc, 2012

[10] Barnatt, Christopher; *3D Printing, Third Edition*. Explainingthefuture.com, 2016

Impregnation of the object with the resin can be done in several ways, most popular being hand lamination, resin transfer molding (RTM) and vacuum infusion. We have decided to use the last method due to the accessibility of required equipment and higher quality products[11].

The goal of this research is to investigate the benefits and shortcomings of creating a composite of the FDM printed porous PLA specimen that is filled with an epoxy resin by a process of vacuum infusion and comparing it with specimens made of PLA alone. Evaluation was done by comparing the mechanical properties of the materials by conducting the three-point bend test and Charpy impact test.

MATERIALS AND METHODS

Test specimen production consisted of FDM manufacturing of porous specimens, filling them with an epoxy resin using vacuum infusion and if needed post-processing them to fit in the tolerances prescribed by standard. Standard test specimen size for the three-point bend test and the Charpy impact test is the same and measure 80x10x4 mm.

The printing was conducted on Ultimaker 3 FDM printing machine. Cura 3D printing software was used for preparing the 3D model for printing. The build volume is 215x215x200 mm in xyz dimensions or 197x215x200 mm when using both nozzles to manufacture using two different materials. According to the manufacturer the printing resolution is 12.5 µm on xy axes and 2.5 µm on z axis. The large build volume has made possible to print more than one test specimen at a time and shorten the manufacturing time.

Test specimens were made of PLA polymer that is commonly used in FDM printing due to its low cost, good workability and low ecological impact compared to other polymers. The biggest drawback of PLA is the inability to withstand elevated temperatures due to its low glass transition temperature, which may cause it to deform when products are used in warm environment. The test specimen with its details is shown in Figure 2.

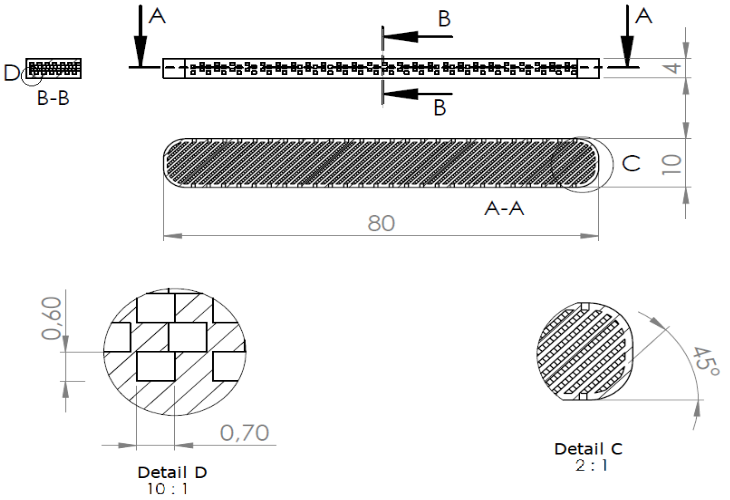

Figure 2: Test specimen. Dimensions were defined according to the standards ISO 179-1:2010 and ISO 178:2010 (80x10x4 mm). The standard does not provide the dimensions of the pores, which were added subsequently

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[11] Potter, Kevin; Resin Transfer Moulding. Chapman & Hall, 1997

In order to be able to reinforce the material with epoxy resin, the specimen had to be designed in a way that enabled the resin to penetrate into the specimen. Therefore, the specimen had to be designed with less than 100% infill density. The infill density percentage tells us how much of the object's interior is filled with the material. The custom preset had to be created. We used 50% infill density and wall, top and bottom thicknesses of 0.8 mm. To enable the resin to penetrate into the interior of the specimen, the intakes and exhaust holes were incorporated into the walls of the specimen as shown on Figure 2. Resin and PLA were interlaced in each layer to make a homogeneous composite material. The rows of materials were inclined at a 45° angle to provide isotropic mechanical properties in x and y axes. The corners were rounded to avoid bending of the specimen's corners during the printing process.

Test specimens were inspected for any defects that might have occurred during the printing process. The dimensions were checked to insure they comply with the ISO 179-1:2010[12] standard for Charpy impact test and with the ISO 178:2010[13] for determining of flexural properties with the three-point bend test.

The vacuum infusion takes place in a sealed chamber that is connected by tubes to the epoxy resin on one end and the compressor on other (Figure 3). Sealed chamber was constructed by putting the vacuum foil over specimens and sealing it with a strong adhesive. Sealing has to be done diligently to prevent any leaks in the system. Tube connections are the most critical part when it comes to potential leaks. Vacuum foil was placed over the build area with care to prevent any wrinkles from appearing. Potential wrinkles would be visible on test specimens and the dimensions of test specimens would not be in agreement with the requirements of mentioned standards. The base plate was covered with a separating agent that prevented the epoxy resin from sticking to it and made the removal of the parts simpler. The sealed chamber is shown in Figure 3.

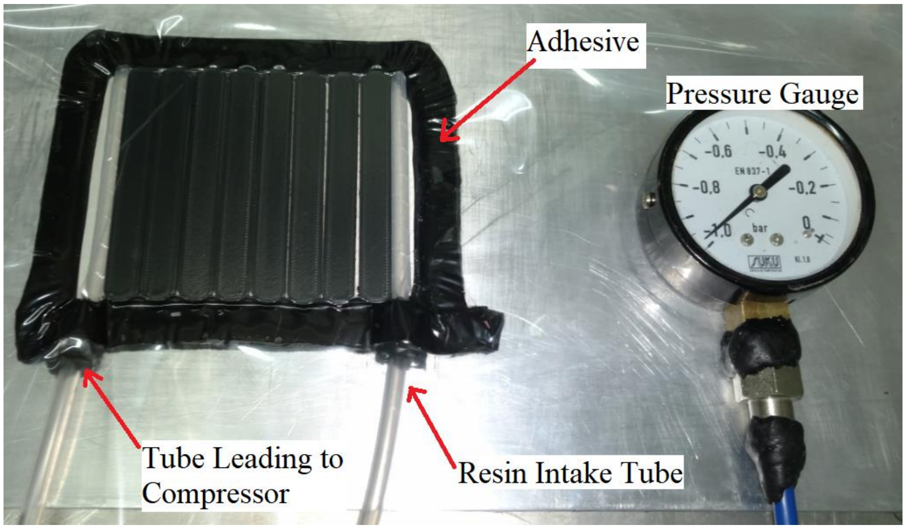

Figure 3: Vacuum infusion system

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[12] Slovenski inštitut za standardizacijo; Plastics – Determination of Charpy impact properties – Part 1: Non-instrumented impact test (ISO 179-1:2010), 2010

[13] Slovenski inštitut za standardizacijo; Plastics – Determination of flexural properties (ISO 178:2010/Amd 1:2013), 2014

To speed up the specimen production process 8 test samples were put in the vacuum infusion system at once. About a millimeter of space was left in between them to simplify the separation of samples as shown in Figure 4. Prior to pumping the resin in the specimens, the infusion system had to be checked for any leaks. This was done by placing a pressure gauge on the resin connection and turning on the pump. The desired value on the gauge was 0.02 bar of absolute pressure. The pump tube was then clenched with a clasp and the system was inspected for possible leaks that would result in an increase in pressure. Upon stable negative pressure reading the specimens were subjected to the epoxy resin infusion.

The epoxy resin used was Araldite LY 564 with the Aradur HY 951 hardener made by Huntsman. Named resin was chosen due to its low viscosity and consequentially higher potential of better impregnation. To further decrease the resin viscosity the build plate temperature was set to 60 °C. This was also the temperature held during the curing process after the infusion.

After the resin curing for 4 hours at 60 °C the specimens were removed from the build plate and were separated from one another. Separation was done by cutting a few millimeters deep in the resin between the specimens and breaking them off. This produced some excessive resin on the sides of specimens that was removed by milling and sanding. The specimens were then inspected whether their dimensions are in agreement with standards ISO 179-1:2010 and ISO 178:2010.

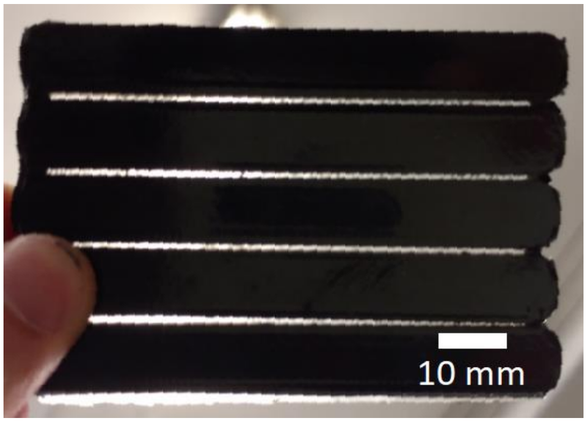

Figure 4: Test samples separated by a thin layer of epoxy resin for easier separation

Properties of specimens were tested using the Charpy test and three-point bend test. All the specimens have been printed on the same Ultimaker 3 FDM printer and are made of the filament from the same spool. 5 specimens of each material were used for the three-point bend test and 10 specimens of each material were used for the Charpy impact test.

RESULTS AND DISCUSSION

The first set of results is from the three-point bend test and is shown in Figure 5. Composite specimens made from the combination of PLA and Epoxy resin are marked as “PLAEPOX”. The reference specimens made from PLA with infill densities of 100% and 50% are marked as “PLA 100%” and “PLA 50%” respectively. Bending tests were conducted in accordance with ISO 178:2010.

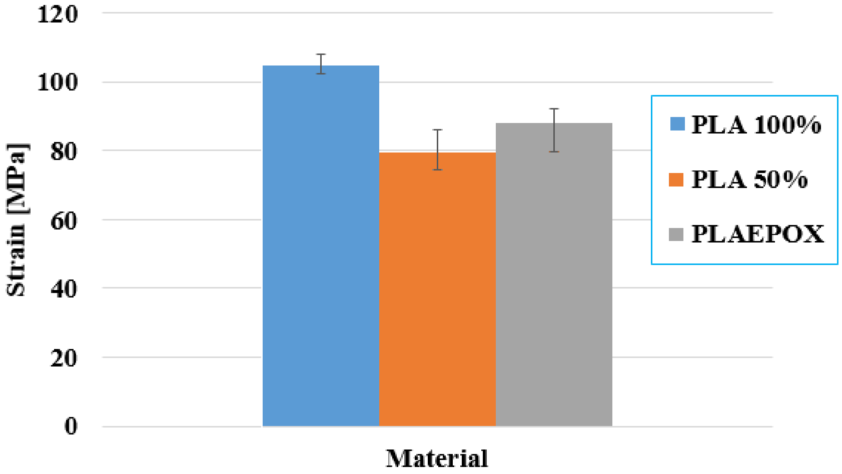

Figure 5: Chart comparing three-point bend test results (ISO 178:2010)

The best results were exhibited by the specimens made from PLA with 100% infill. They topped the chart as they endured the highest applied force and managed to achieve the biggest deformation before yielding. Composite material presented nearly identical characteristics to PLA with 100% infill but had a brittle fracture at lower load. PLA with 50% infill managed the lowest force of the three but endured bigger deformation than the composite material.

When comparing the specimen made of PLA with 50% infill density with the composite, the composite between PLA and epoxy exhibits better tensile strength. It appears as if the added epoxy resin acts like the remaining 50% of the infill due to the similarity with the results gathered from the specimens made from PLA with the 100% infill density. The lack of ductility of the composite material could be explained by the lower ductility of epoxy resin when compared to the PLA. Therefore when the epoxy component breaks the whole strain is transferred on to PLA, which can not bear the load due to its low infill density and the specimen yields.

Charpy impact test was conducted according to ISO 179-1/fU method which prescribes the usage of unnotched test specimen with flatwise blow direction. Material markings are the same as on the three-point bend test chart. The results are shown in Figure 6.

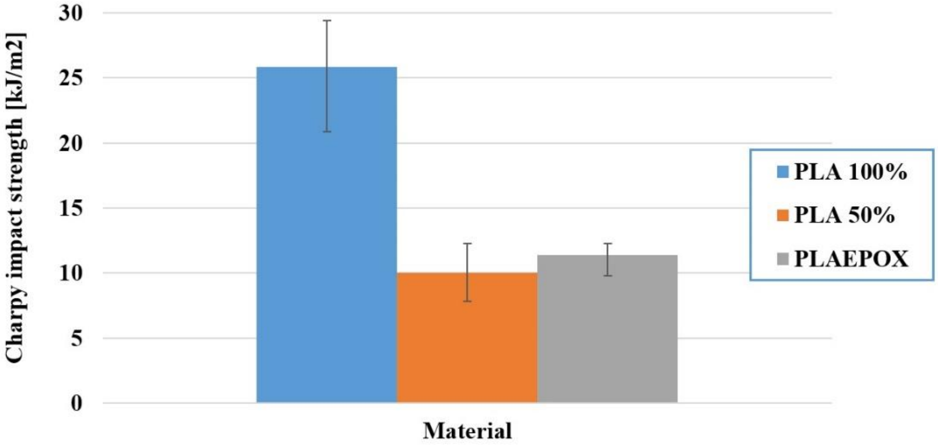

Figure 6: Charpy impact strength (ISO 179-1/1fU)

Again, the PLA with 100% showed the best properties with highest Charpy impact strength. It is followed by composite made from PLA and epoxy resin with 11,4% higher impact strength than PLA with 50% infill.

Relatively close performances by the PLA with 50% infill density and the composite material could be explained by the fact that the PLA is more ductile compared to epoxy resin, consequentially absorbing the majority of the dissipated energy. Epoxy component does help by a small amount, resulting in a modest increase in the impact strength of the composite compared to PLA with the 50% infill. PLA with the 100% infill has the most ductile load bearing material and achieves the best result.

CONCLUSION

Gathered results show no benefit regarding mechanical properties of test specimens by going from PLA with 100% infill density to the composite made of 50% PLA and 50% epoxy resin, although it performed better than PLA with 50% infill density.

Given the results there are doubts whether the additional complexity of manufacturing the composite part is worth the trouble. Looking solely at measured values there is no point of creating PLA-epoxy composite, however there might be applications where adding epoxy yields improvements. For example, PLA has low glass transition temperature, becoming soft and potentially deforming at temperatures in excess of 50-60 °C. In that case adding epoxy component might decrease the chance of deformation and increase the rigidity at those temperatures. Presently, the ABS filament is commonly used when better performance at elevated temperatures is desired. Easier to print PLA with added epoxy resin might be justified to use instead due to easier FDM manufacturing process. This should be investigated in further experiments.

The main drawback of using the proposed process chain is the amount of additional time and labour required to make a composite part. If one was able to simplify the production process the PLA-epoxy composite could become an interesting alternative.

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6. **Slovenski inštitut za standardizacijo**; Plastics – Determination of flexural properties (ISO 178:2010/Amd 1:2013), 2014.