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TENSILE PROPERTIES OF POLYPROPYLENE ADDITIVELY MANUFACTURED BY FDM

ZATEZNA SVOJSTVA POLIPROPILENA PROIZVEDENOG ADITIVNOM TEHNOLOGIJOM FDM

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- Fused Deposition Modeling (FDM)
- polypropylene
- additive manufacturing parameters
- tensile properties

Abstract

Polypropylene (PP) is an extensively studied and tested environment-friendly polymer, whose applications range from product packaging in the food industry to biomedical applications. It is a non-toxic, lightweight material, relatively simple for processing. Research findings show that PP material has higher elongation than any other thermoplastic material used in Fused Deposition Modeling (FDM) technology, which is the most developed and used extrusion-based additive technology. In FDM, many printing parameters must be set before the actual additive manufacturing process, and they have a decisive influence on the mechanical properties of fabricated parts. In this research, layer height, infill density, and raster orientation are the parameters considered in the analysis, resulting in four specimen batches being prepared for tensile testing.

Ključne reči
- modeliranje deponovanjem topljenog materijala
- polipropilen
- parametri aditivne proizvodnje
- zatezna svojstva

Izvod

Polipropilen (PP) je opsežno proučavan i ispitivan ekološki prihvatljiv polimer, čija primena obuhvata različite oblasti, od pakovanja proizvoda u industriji hrane do biomedicine. Materijal je netoksičan, male mase i relativno jednostavan za obradu. Rezultati dosadašnjih istraživanja pokazuju da polipropilen može da se deformiše više od bilo koje termoplastike korišćene u tehnologiji modeliranja deponovanjem topljenog materijala, koja je najrazvijenija i najkorišćenija aditivna tehnologija zasnovana na ekstruziji materijala. FDM zahteva definisanje većeg broja parametara aditivne proizvodnje, koji dokazano utiču na mehanička svojstva dobijenog dela. U ovom istraživanju, visina sloja, gustina ispune i orijentacija raster linija su uključeni u analizu, radi čega su pripremljene četiri serije uzoraka za ispitivanje na zatezanje.

INTRODUCTION

Fused deposition modeling (FDM) is the most utilised and developed extrusion-based AM technology for polymer materials, mainly due to low production and maintenance costs, and a broad range of available materials, /1-4/. The main production principle of FDM is the melting of thermoplastic polymer filaments in the extruder mechanism, and afterward, the selective deposition of a melted polymer through a nozzle onto a build platform. FDM has a relatively slow production process, limited to polymer materials with a low melting point, /5/. Utilisation of this particular technology is quite easy even for a beginner, thus explaining the worldwide presence of FDM not only in industrial but even in home environments.

The most common thermoplastic polymers used in FDM are PLA (polylactic acid), ABS (acrylonitrile butadiene styrene), PC (polycarbonate), PP (polypropylene), and PA (nylon). Studies related to mechanical property estimation are still ongoing, /6-11/. PP is commonly used in many fields ranging from product packaging to biomedical applications. Due to chemical inertness, PP is considered for surgical sutures and meshes, or as a hernia, ligament, and tendon repair material, /12/. Due to thermoplastic properties, PP can be melted, reheated, or remodelled in order to be used again in different applications.

Compared to other commercial polymers, PP has a high melting point in the range 130 to 184 °C, depending on microstructure and crystallinity. It can be categorized as atactic (aPP), syndiotactic (sPP), and isotactic (iPP), depending on methyl group (-CH_3) alignment, Fig. 1. In aPP, methyl groups are randomly aligned, in sPP they are alternating, and evenly arranged in iPP. The most common commercial variant is iPP, which is also used to make AM-grade PP. Next, the crystallinity is higher in densely packed structures. Thus, well-chemically processed PP with a high degree of crystallinity has a high melting temperature, /13/. Polymer materials for FDM applications need to have low material shrinkage upon cooling to achieve high geometrical accuracy and to cause less failure during AM part fabrication process. Just recently, PP became available in FDM technology, but only a few research papers cover the AM-grade PP properties /14, 15/. Worth pointing out is that PP exhibits a significantly higher elongation than any other FDM thermoplastic material /12, 16/.

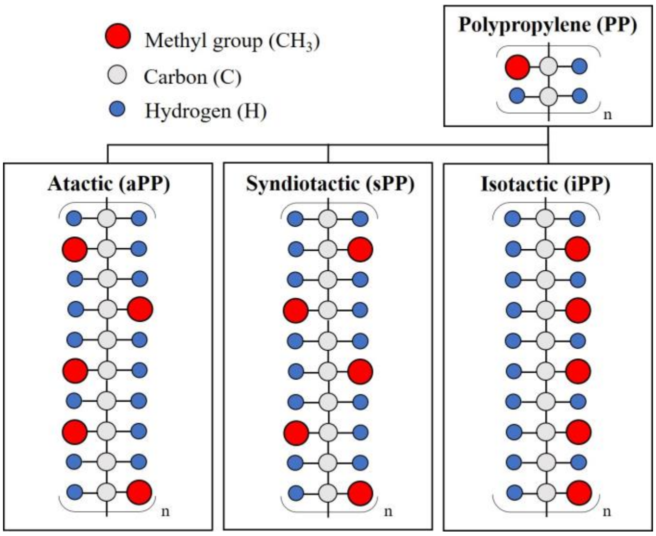


Figure 1. PP molecular structure.

The subject of this research is the analysis of AM parameter influence on mechanical properties of AM-grade PP material, more precisely tensile properties. Generally, the main issue with AM-grade polymers is the bonding between adjacent layers, i.e. whether it is sufficient for the manufacturing of functional parts /12/. The considered parameters in the research are layer height, infill density, and raster orientation.

ADDITIVE MANUFACTURED SPECIMENS

The AM-grade PP filament is supplied by 3D Republika Company, Belgrade, Serbia. Tensile specimens are manufactured according to ISO 527-2:2012 standard, /17/. Four specimen batches are fabricated, each containing five specimens. Specimen dimensions are shown in Fig. 2.

The specimen model is created in dedicated CAD software (SolidWorks, Dassault Systèmes SE, Vélizy-Villacoublay, France) and converted to STL file format, to be then used in the slicer software (Simplify3D, Cincinnati, OH, USA). Specimens are manufactured using FDM machine RepRap X400 (InnovatiQ GmbH, Kapellenstraße, Feldkirchen, Germany) with the largest flat surface facing the build platform.

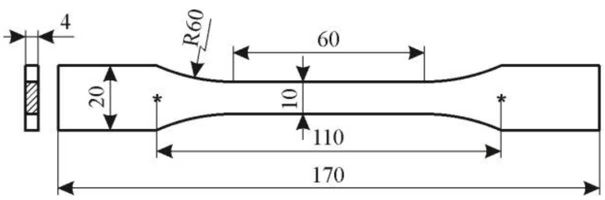


Figure 2. Tensile specimen engineering drawing, according to ISO 527-2:2012, Type 1A (units in mm).

Two different layer heights (namely, 0.2 and 0.1 mm), infill densities (50 and 100 %), and raster orientations (rectilinear and circular), are arranged as follows:

- 1st batch: 0.1 mm layer height, 50 % infill density, rectilinear raster orientation;
- 2nd batch: 0.1 mm layer height, 100 % infill density, rectilinear raster orientation;
- 3rd batch: 0.1 mm layer height, 100 % infill density, circular raster orientation;
- 4th batch: 0.2 mm layer height, 50 % infill density, rectilinear raster orientation.

This arrangement gives an insight into the influence of each of the FDM parameters with the lowest number of test batches. There are a few FDM parameters that are not the subject of this research and thus they were constant for all tested batches, namely: filament diameter (i.e., 1.75 mm); nozzle diameter (0.4 mm); nozzle temperature (200 °C); build platform temperature (60 °C); nozzle speed (60 mm/s). All AM fabricated specimen batches are used for tensile testing in an as-build state.

TENSILE TESTS AND RESULTS

Tensile tests are conducted using the Universal testing machine Shimadzu AGS-X of 100 kN load cell capacity. The straining rate is 1 mm/min in accordance with the recommendation from ISO 527-2:2012 standard. Maximal straining (vertical displacement) on the machine was 500 mm.

The sequence of images in Fig. 3 shows the deformation of a PP specimen from the 2nd batch (specimen no.3) until fracture. Images are arranged from the test start to the failure point, from left to right-hand side. In the first two images, one can see the formation of the first stress-whitening regions presented as white lines perpendicular to the force direction on the machine. These white lines visible to the naked eye are a multitude of voids created in the material as a result of polymer grouping in bundles i.e., fibrils /18, 19/. From the point of mechanical testing view, visible white lines are locations where the polymer is plastically deformed. In an undeformed state, polymer chains crystallize as spherulites, which correspond to grains in metals. Spherulites are not monocrystals, but they consist of densely packed chains interlinked by amorphous zones. During deformation, these spherulites gradually deform and disappear allowing the formation of fibrils, which have superior tensile strength, /20/. As the test advances (see Fig. 3) these white lines are increasing in number. At the finishing stages, the interlayer (when individual layers are intact, but separated from each other), and in-layer fracture (when individual layers fractured) /21/ had occurred before actual specimen failure i.e., when the specimen broke in two pieces. Interlayer and in-layer fractures can be recognised on stress-strain diagrams as the drop in force value before actual specimen failure.

Clear plastic deformation is recognized on the fractured surface. Mentioned fibrils are seen as threads protruding from the material. Due to high uniaxial deformation, the specimen has shrunk in its cross-section significantly. Eventually, the entire specimen has plastically deformed before failure.

Engineering stress-strain diagrams for all PP specimens are arranged in four diagrams in Fig. 4, one for each of the specimen batches.

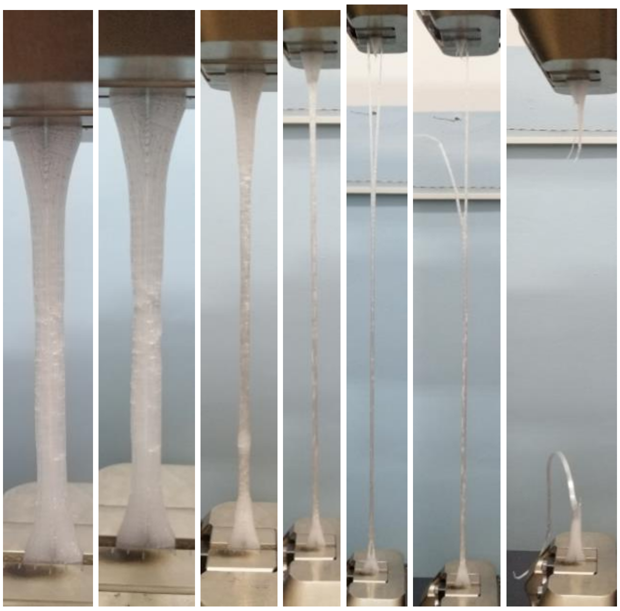
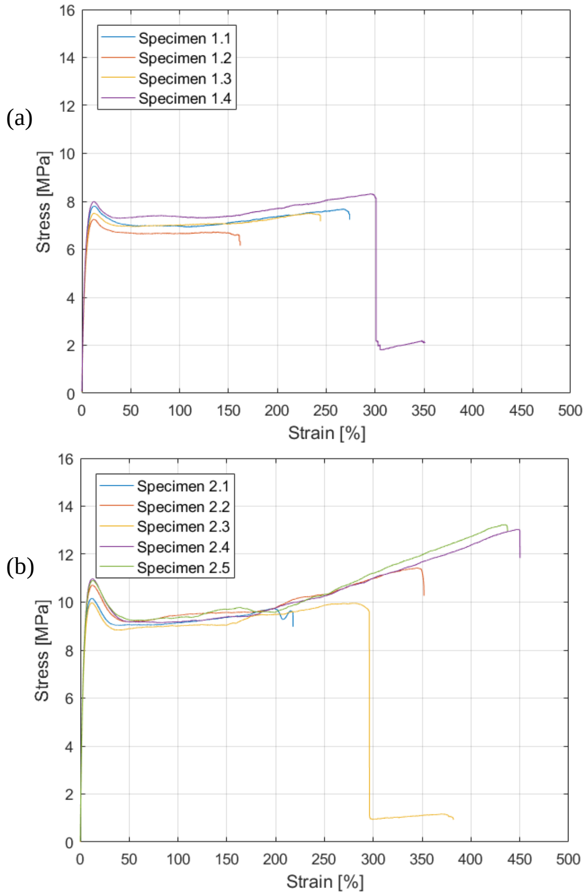


Figure 3. Tensile testing of PP specimen, from start to failure.

It should be emphasized that tensile tests continued even after the substantial force value drop, i.e., when interlayer, or in-layer fracture occurred. Points of large force value drop are considered failure points, and the strain up to the failure point and after is summed as the ‘maximal strain’. As for the stress, yield stress in some of the specimens is higher than failure stress (which is the most common situation in the 1st test batch), hence the term ‘maximal stress’ is applied to highlight the maximal stress value in the tensile test.



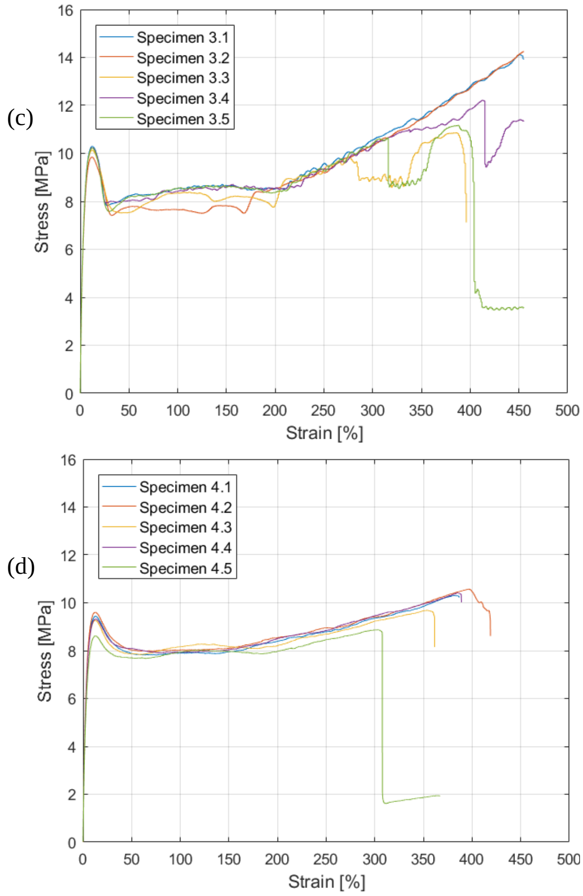


Figure 4. Engineering stress-strain diagrams for: a) 1st batch; b) 2nd batch; c) 3rd batch; d) 4th batch.

Properties obtained from tensile tests are presented in Table 1. From Table 1 it is obvious that PP is a ductile material with high elongation and tensile toughness values (area under stress-strain curve). The 2nd and 3rd batches have the highest stiffness due to 100 % infill density, while the 1st batch has the lowest. Yield strain is about the same in all batches, approx. 12 %. The lowest maximal and failure strain values are 258 and 236 %, in respect. Neither of 4 specimens of the 3rd batch reached failure before maximal tensile machine stroke of 500 mm, so according to our collected data, average maximal strain is 439 %, and average failure strain is 418 %. Yield stress is significantly higher in full-infill density batches, with an average above 10 MPa, and similar to that, maximal and failure stress is the highest in 100 % density batches, and the lowest in the 1st batch. The 2nd and 3rd batches have the highest tensile toughness, 155.7 and 180.9 J, in respect. The 0.2 mm layer height batch has approximately two times higher toughness than the 0.1 mm layer batch with the same 50 % infill density. As expected, the 100 % infill density has a clear advantage over the other FDM parameter sets, with circular raster orientation as a better option over rectilinear, since the load is in the same direction. In batches with 50 % infill density, the 0.2 mm layer height proved better than its 0.1 mm counterpart, probably because of low adhesion between layers in PP, due to double the number of layers in the latter case.

Table 1. Tensile properties of PP material, in relation to the selected batches.

Batch number	Elastic modulus [MPa]	Yield strain [%]	Failure strain [%]	Maximum strain [%]	Yield stress [MPa]	Failure stress [MPa]	Maximum stress [MPa]	Tensile toughness [J]
1	136.9	12.34	236	258	7.65	7.56	7.73	78.6
2	260.7	12.31	344	368	10.55	11.49	11.57	155.7
3	226.7	12.19	418	439	10.16	12.53	12.53	180.9
4	200.4	12.73	364	385	9.26	9.98	9.98	141.6

CONCLUSIONS

The FDM of materials such as PP is used nowadays in many industry fields, but there is still a lack of knowledge concerning its behaviour and mechanical properties in AM environment. The aim of this research is to observe the influence of FDM parameters on the tensile properties of PP material, e.g. layer height, infill density, and raster orientation.

Infill density proved to be most beneficial for the mechanical properties of PP material, therefore both full-infill batches showed overall better results. Due to the nature of the load, circular raster orientation has shown its benefits over rectilinear orientation. Overall, the 0.2 mm layer height produced better mechanical properties than its 0.1 mm counterpart. Clarification of this effect can be explained by low bonding between layers in PP material.

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