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Testing of Materials for Rapid Prototyping Fused Deposition Modelling Technology

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***Abstract*—**Paper presents knowledge about types of test in area of materials properties of selected methods of rapid prototyping technologies. In today used rapid prototyping technologies for production of models and final parts are used materials in initial state as solid, liquid or powder material structure. In solid state are used various forms such as pellets, wire or laminates. Basic range materials include paper, nylon, wax, resins, metals and ceramics. In Fused Deposition Modeling (FDM) rapid prototyping technology are mainly used as basic materials ABS (Acrylonitrile Butadiene Styrene), polyamide, polycarbonate, polyethylene and polypropylene. For advanced FDM applications are used special materials as silicon nitrate, PZT (Piezoceramic Material - Lead Zirconate Titanate), aluminium oxide, hydroxypatite and stainless steel.

***Keywords*—**Rapid prototyping, materials, testing of materials.

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I. INTRODUCTION

MOST of the rapid prototyping processes can create parts from multiple common and special materials. For better application of some rapid prototyping method in industrial practice is needed to realize comparison of various applications and uses, based on an average rating of the materials used in the specific processes. Used rapid prototyping materials depend of the type of used rapid prototyping technology. Stereolithography (SLA) process use photosensitive resins cured by a laser that traces the parts cross sectional geometry layer by layer. SLA produces accurate models with a variety of material choices. Selective Laser Sintering (SLS) using a CO_2 laser to sinter or fuse a powder material. The laser traces the parts cross sectional geometry layer by layer. SLS creates accurate and durable parts but finish out of machine is relatively poor. 3D printing presents ink-jet based process that prints the parts cross sectional geometry on layers of powder spread on top of each other. This process enables models to be built quickly and affordably. Models may also be printed in colour. Fused Deposition Modelling (FDM) process using molten plastics or wax extruded by a nozzle that traces the parts cross sectional geometry layer by layer. FDM creates tough parts that are ideal for functional usage [1].

II. TESTING OF POLYMER PARTS PRODUCED BY LAMINATED OBJECT MANUFACTURING

Rapid prototyping procedures make it possible to produce relatively complicated geometries based on the computer 3D model of products in relatively short time. This requires that the respective product features have good quality, good mechanical properties, dimensional accuracy and precision. However, the number of available materials that can be used for prototyping is limited and their properties can differ significantly from the properties of the finished product. However, RP parts are not inexpensive and sometimes it is difficult to decide which procedure to use to manufacture them in order to obtain their maximal usability. The Laminated Object Manufacturing (LOM) procedure can be used to produce low cost polymeric products (from polyvinyl chloride) that have to meet certain mechanical properties, especially if they are used to perform functional tests. Past studies in LOM procedure have been carried out mainly with paper, and a few on metal. The workers of Faculty of Mechanical Engineering and Naval Architecture of University of Zagreb (Croatia) realised testing the influence of the position of products in the machine working area on the mechanical properties (tensile and flexural properties) of the product [2].

Physical objects produced by rapid prototyping are mainly used as prototypes or models for other manufacturing processes. However, there is a tendency to improve these procedures, so that the prototypes can be used also as functional and finished products, and this requires the knowledge about the properties of the materials, e.g. mechanical, thermal, and electrical properties. Apart from paper and metal that had been used until now, with LOM procedure it is possible to use also polymeric films, thus achieving improved mechanical properties. Apart from the procedure, the mechanical properties of the materials are affected also by some manufacturing parameters; e.g. the position of the product in the working area (it may influence the mechanical properties and aesthetic appearance of the prototype).

LOM procedure is used to manufacture a prototype by lamination and laser finishing (cutting) of materials such as paper, polymeric films and foils and metal laminates. With polymeric foils better mechanical properties are achieved than with paper. The sheets are laminated into solid blocks by adhesion joining, clamping and ultrasonic welding. Using heat and pressure each sheet, foil or paper is adhered to the block and a new layer is formed. The material is supplied by means of a roller on one side of the machine and taken to another side. The heated roller provides pressure and heat necessary for the new layer to be glued to the already produced prototype part. The working platform is lowered for the foil thickness, which is usually a thickness of 0.07 mm to 0.2 mm.

The test specimens made by LOM procedure was made of PVC film. The test bodies in LOM procedure was made on the

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machine SD 300 Pro, produced by Solido. SD 300 Pro is a machine which can produce transparent prototypes of PVC film, has small dimensions, and is practical for use in offices. Tests were carried out on specimens made using various orientations in the working area (Fig. 1):

- Lxy - test specimen laid in xy plane with height in z direction 4 mm,
- Pxy - test specimen raised in xy plane with height in z direction 10 mm,
- Pz - test specimen raised in z-axis with height 75 mm and 80 mm depending on whether the specimen is for tension or bending tests.

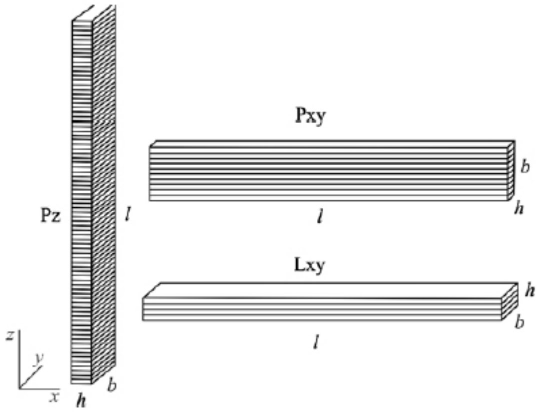

Fig. 1 Orientation of layers in test specimen produced by LOM [2]

LOM procedure provides low surface roughness parameters in all three orientations. However, the lowest are in Lxy orientation (arithmetic mean x of the mean arithmetic deviation of profile Ra = 0.03 μm) which is only logical since the final layer is pure PVC film, independent of the construction method (lamination method). In test specimens Pxy and Pz, Ra is 95 times greater (Ra = 3 μm) than in Lxy orientation.

The specimens of Lxy orientation have the highest strain, even up to an average of ε_p = 207 %, whereas the test specimens of Pz orientation have only ε_p = 24 %, which is 8.5 times lower value. However, it is interesting to note that the highest strength is not the feature of the test specimens of Lxy orientation, but the test specimens of Pxy orientation. Orientation affects also the fracture surface and in test specimens Pxy the surface is toothed, i.e. delamination of layers has occurred, whereas in Lxy and Pz the surface is flat. Such fracture in Pxy orientation occurs because the stresses are applied along each layer, and in Pz orientation the fracture occurs perpendicularly to the applied test force, and this is at the same time the layer lamination. Colour changes observed in specimens are result of macromolecular orientation of amorphous polymer in the direction of tensile stretching.

Test specimens of Pz orientation break in bending before the agreed deflection S = 1,5 x h = 6 mm defined by the standard, whereas other orientations fall within the testing device supports, so that yield flexural stress σ_{fp} and yield flexural elongation ε_{fp} are not calculated for them.

The tests carried out at LOM test specimen lead to the conclusion that Pxy orientation features optimal properties. Possibly, in case of minimal roughness requirement and higher yield stress, Lxy orientation should be selected. The price and the manufacturing speed also depend on the orientation and chamber filling, so that the orientations in z-axis direction should be avoided as much as possible.

III. ANISOTROPIC MATERIAL PROPERTIES OF FUSED DEPOSITION MODELLING ABS

Stratasys Fused Deposition Modeling (FDM) is a typical RP process that can fabricate prototypes out of ABS plastic. To predict the mechanical behavior of FDM parts, it is critical to understand the material properties of the raw FDM process material, and the effect that FDM build parameters have on anisotropic material properties. This chapter characterizes the properties of ABS parts fabricated by the FDM 1650 and realized by researchers of Gyeongsang National University Jinju (Korea) and University of California, Berkeley (USA). Using a Design of Experiment (DOE) approach, the process parameters of FDM, such as raster orientation, air gap, bead width, color, and model temperature were examined. Tensile strengths and compressive strengths of directionally fabricated specimens were measured and compared with injection molded FDM ABS P400 material. For the FDM parts made with a 0.075 mm overlap between roads, the typical tensile strength ranged between 65 and 72 percent of the strength of injection molded ABS P400. The compressive strength ranged from 80 to 90 percent of the injection molded FDM ABS. Several build rules for designing FDM parts were formulated based on experimental results [3].

The FDM process works as follows. First, a three dimensional solid model must be created. This can be accomplished in many of the commonly available CAD packages. The model is then exported to the FDM Quickslice software using the Stereolithography (STL) format. This format tessellates the part into a set of triangles. Once the STL file has been exported to Quickslice, it is horizontally sliced into many thin sections. These sections represent the two-dimensional contours that the FDM process will generate which, when stacked upon one another, will closely resemble the original three-dimensional part. This sectioning approach is common to all currently available RP processes. The software then uses this information to generate the process plan that controls the FDM machine's hardware.

In the physical process of fabrication, an ABS filament is fed through a heating element and becomes semi-molten. The filament is then fed through a nozzle and deposited onto the partially constructed part. Since the material is extruded in a semi-molten state, the newly deposited material fuses with adjacent material that has already been deposited. The head then moves around in the X-Y plane and deposits material according to the part geometry. The platform holding the part then moves vertically in the Z plane to begin depositing a new layer on top of the previous one. After a period of time, usually several hours, the head will have deposited a full physical representation of the original CAD file. The FDM machine possesses a second nozzle that extrudes support material and builds support for any structure that has an overhang angle of less than 45° from horizontal as a default. If the angle is less than 45°, more than one-half of one bead is overhanging the contour below it, and therefore is likely to fall. The machine deposits material in a directional way that results in parts with anisotropic behaviour. Experiments were performed in which the effect of several process parameters on the mechanical behaviour of FDM parts was examined.

Dozens of specimens were produced by FDM for comparison with the samples produced by injection molding. For each type of the specimen, three to five replications were fabricated and tested. The DOE showed that air gap and raster orientation were the only significant effects. Therefore, the effect of these two variables on the tensile strength of specimens was considered more closely.

Each FDM specimen consisted of 12 layers with various raster orientations. The axial specimen had 12 layers in the zero (loading) direction $[0°]_{12}$, and the criss-cross specimen had six repetitions of a 45° layer followed by a -45° layer $[45°/-45°]_6$. Default FDM parts were made with a crisscross raster in which the orientation of the beads alternates from +45° to -45° from layer to layer. Some criss-cross raster specimens were built and tested in addition to the main factorial experiment.

The [45°/-45°] raster orientation is of particular interest as the Quickslice software defaults to this raster. This orientation could be looked at as a [0°/90°] orientation if the part were rotated 45°. For these two general cases, the strength ranged between 65 and 72 percent of the injection molded P400. All specimens failed in transverse direction except the criss-cross specimen, which failed along the 45° line. The failure modes for specimens with zero air gap were identical to those with -0,003 air gap. The relationship between failure loads and failure modes required microscopic observations.

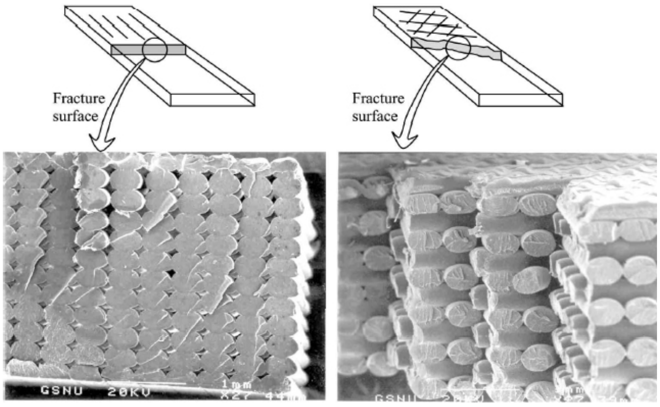

Fig. 2 Fracture surfaces of $[0°]_{12}$ and $[45°/-45°]_6$ specimen [3]

Fig. 2 shows magnified views of the fractured surfaces of the specimens. The Axial ($[0°]_{12}$) specimens showed tensile failure of individual fibers resulting in the highest tensile strength among the FDM specimens. However, this strength was lower than that of the injection molded ABS partially because the gaps between fibers reduced the effective cross sectional area. The Transverse ($[90°]_{12}$) specimens resulted in the lowest tensile strength because the tensile loads were taken only by the bonding between fibers, and not the fibers themselves. The Cross specimen ($[0°/90°]_6$) consisted of a layer of fibers oriented in the 0° direction, followed by a layer in the 90° direction. The resulting failure load for this pattern, as might be expected, fell between the $[0°]_{12}$ and $[90°]_{12}$ specimens. The Criss-cross ($[45°/-45°]_6$) specimen showed shear failure along the 45° line in the macroscopic view but the microscopic view revealed the repeated failures of individual fibers by shearing and tension. Note that the oval shape of the fibers is determined by the Quickslice software settings for road width and slice height.

IV. PROPERTIES OF MATERIALS IN FUSED DEPOSITION MODELLING RP TECHNOLOGY

On the Department of Manufacturing Technologies of the Faculty of Manufacturing Technologies of TU Košice with a seat in Prešov there is UPrint 3D FDM printer from Dimension available. It is a small 3D printer with 635 x 660 x 787 mm dimensions suitable for office environment which uses the printing principle of Fused Deposition Modelling. Maximum dimensions of printed prototype are 203 x 152 x 152 mm. This printer prints only one layer of constant thickness 0.254 mm which is as the accuracy of the print in the Z axis very acceptable [4].

This printer used as building material thermoplastic ABCplus Ivory which comes in standardized packages as fiber with a diameter of 1.6 mm rolled onto a reel. Each spool contains 500 cubic centimeters of material. The support material used is resin Soluble SR-P400 which comes in the same package as a building material [5].

FDM is one of the typical RP processes that provide functional prototypes of ABS plastic. FDM produces the highest-quality parts in Acrylonitrile Butadiene Styrene (ABS) which is a common end-use engineering material that allows you to perform functional tests on sample parts. FDM process is a filament based system which feeds the material into the heated extrusion head and extruding molten plastic that hardens layer-by-layer to form a solid part. FDM parts are tougher and more durable than those produced by SLA. ABS parts are sufficiently resistant to heat, chemicals, and moisture that allows FDM parts to be used for limited to extensive functional testing, depending upon the application. FDM materials allow you to manufacture real parts that are tough enough for prototyping, functional testing, installation, and most importantly — end use. Real production thermoplastics are stable and have no appreciable warpage, shrinkage, or moisture absorption, like the resins (and powders) in competitive processes. Because thermoplastics are environmentally stable, part accuracy (or tolerance) doesn’t change with ambient conditions or time. This enables FDM parts to be among the most dimensionally accurate. Basic FDM materials [6, 7]:

1. *ABSplus thermoplastic (Acrylonitrile Butadiene Styrene):* Environmentally stable - no appreciable warpage, shrinkage or moisture absorption, 40 percent stronger than standard ABS material.
2. *ABS-M30 thermoplastic:* 25-70 percent stronger than standard ABS material, greater tensile, impact, and flexural

strength, layer bonding is significantly stronger for durable part, versatile Material: Good for form, fit and moderate functional applications.

3. ABS-M30i thermoplastic: biocompatible (ISO 10993 certified) material, ideal material for medical, pharmaceutical and food packaging industries, sterilizable using gamma radiation or ethylene oxide (EtO) sterilization methods.
4. ABSi thermoplastic: translucent material, ideal for automotive tail lens applications, good blend of mechanical and aesthetic properties, available in translucent natural, red and amber colours.
5. PC-ABS thermoplastic (Polycarbonate ABS): most desirable properties of both PC and ABS materials, superior mechanical properties and heat resistance of PC, excellent feature definition and surface appeal of ABS, highest impact strength.

Very little effort seems to have been made to develop metallic materials for the FDM process. Rutgers University in the United States have carried out considerable work in the development of fused deposition of ceramics (FDC) and metals. They have used the process to fabricate functional components of a variety of ceramic and metallic materials such as silicon nitrate, PZT, aluminium oxide, hydroxypatite and stainless steel for a variety of structural, electroceramic and bioceramic applications. They create such components on the FDM using ceramic powders mixed with organic binder system. The properties of the mixed feedstock filament meet the flexibility, stiffness, and viscosity required for successful FDM processing. But the fabricated green parts need to undergo further processing to remove the organic binder and are subjected to sintering to achieve densification. Sintered part may be infiltrated with other type of metal materials. Work has also been carried out at Advanced Ceramics Research for part fabrication in ceramics using the FDM process. Researchers at Virginia Tech have developed a new high performance thermoplastic composite for FDM, involving thermotropic liquid crystalline polymers (TLCP) fibres, and have used it in FDM system to fabricate prototype parts. The tensile modulus and strength of this material were approximately four times those of ABS. Therefore, prototypes fabricated with these materials would have greater functionality than those fabricated with ABS. The FDM technology thus offers the potential to produce the functional parts with a variety of materials including composite materials. But little work seems to have been done in the development of metal/polymer composites for direct rapid tooling application using the FDM system. Direct rapid tooling of injection moulding dies and inserts can be conveniently performed if a strong metal based feedstock material is available for the FDM RP systems [8].

V. CONCLUSION

The initial state of material in Rapid Prototyping technologies can come in either solid, liquid or powder state. In solid state, it can come in various forms such as pellets, wire or laminates. The current range materials include paper, nylon, wax, resins, metals and ceramics. Most of the RP parts are finished or touched up before they are used for their intended applications. Applications can be grouped into design engineering, analysis and planning and tooling and manufacturing. A wide range of industries can benefit from RP and these include automotive, aerospace, biomedical, consumer, electrical and electronic products.

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