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VERIFICATION OF MECHANICAL PROPERTIES OF ABS MATERIALS USED IN FDM RAPID PROTOTYPING TECHNOLOGY

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Abstract: *In this paper, information about common and advanced materials used for manufacturing of products by Fused Deposition Modelling (FDM) rapid prototyping technology is presented. In different rapid prototyping technologies the initial state of material can come in either solid, liquid or powder state. The current range materials include paper, nylon, wax, resins, metals and ceramics. In FDM as basic materials ABS - Acrylonitrile Butadiene Styrene, polyamide, polycarbonate, polyethylene and polypropylene are mainly used. Main part of the paper is focused on experimental testing of rapid prototyping materials realized by different research teams and presents outputs of testing of ABS material in FDM technology realized by authors.*

Key words: *fused deposition modeling, Acrylonitrile Butadiene Styrene, mechanical properties.*

1. INTRODUCTION

Rapid Prototyping (RP) can be defined as a group of techniques used to quickly fabricate a scale model of a part or assembly using three-dimensional computer aided design (CAD) data. What is commonly considered to be the first RP technique, Stereolithography, was developed by 3D Systems of Valencia, CA, USA. The company was founded in 1986, and since then, a number of different RP techniques have become available. Rapid Prototyping has also been referred to as solid free-form manufacturing, computer automated manufacturing, and layered manufacturing. RP has obvious use as a vehicle for visualization. In addition, RP models can be used for testing, such as when an airfoil shape is put into a wind tunnel. RP models can be used to create male models for tooling, such as silicone rubber moulds and investment casts. In some cases, the RP part can be the final part, but typically the RP material is not strong or accurate enough. When the RP material is suitable, highly convoluted shapes (including parts nested within parts) can be produced because of the nature of RP. There is a multitude of experimental RP methodologies either in development or used by small groups of individuals. Next sections will focused on RP materials and materials experiments in Fused Deposition Modelling (FDM) technology [1, 2].

2. FUSED DEPOSITION MODELING METHOD

Fused Deposition Modelling (FDM) was developed by Stratasys in Eden Prairie, Minnesota. In this process, a plastic or wax material is extruded through a nozzle that traces the part's cross sectional geometry layer by layer. The build material is usually supplied in filament form, but some setups utilize plastic pellets fed from a hopper instead. The nozzle contains resistive heaters that keep the plastic at a temperature just above its melting point so that it flows easily through the nozzle and forms the layer. The plastic hardens immediately after flowing from the nozzle and bonds to the layer below. Once a layer is built, the platform lowers, and the extrusion nozzle deposits another layer. The layer thickness and vertical dimensional accuracy is determined by the extruder die diameter, which ranges from 0.013 to 0.005 inches. In the $X–Y$ plane, 0.001 inch resolution is achievable. A range of materials are available including ABS, polyamide, polycarbonate, polyethylene, polypropylene, and investment casting wax [3, 4].

For better orientation of user in process of setting of suitable parameters during the preparation of printing there was algorithm elaborated which accumulates all

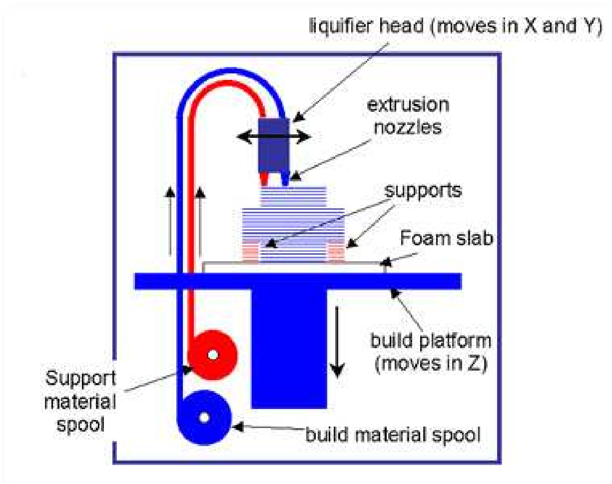

Fig. 1. Fused Deposition Modelling technology.

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Fig. 2. FDM device UPrint from Dimension.

factors and steps that lead to selection of most suitable variant. All the attempts were realized as a part of preparation stage for printing on UPrint machine that utilize FDM technology to build the prototype. This technology, developed by Stratasys, uses the software program to orient the model and generate building slices. Printer dispenses with basic building material and support material which is used if necessary for creation of holes, cavities, drafts, etc. Each material has its own nozzle. Creation of particular prototype layers with use FDM method is shown in Fig. 1.

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 (Fig. 2). It is a small 3D printer with 635 × 660 × 787 mm dimensions suitable for office environment which uses the printing principle of Fused Deposition Modeling. Maximum dimensions of printed prototype are 203 × 152 × 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 [5].

These 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. After printing the prototype it is necessary to clean the prototype of the auxiliary material.

For this printer we use Catalyst program which serves to complete printing settings such as disposition of components on working desktop or set-saving modes where savings can be achieved by building and supporting material to 40% depending on the shape and parts at the expense of strength of the prototype. In a first step we generated STL data in the CAD system that can be loaded to the Catalyst program for layered rendering of the model. After starting of print cycle the system warms up printing jet and whole work area for working temperature. This lasts about 15 minutes, during which the nozzle and purifying device are calibrated. Followed by the print itself, the nozzle is moving over $X - Y$ pad and working in the *Z* axis. After printing it is necessary to separate the support material from the building one. In the semi-simple components the support material can be separated without any problems, as because of reducing temperature it is particularly fragile. However, for complex parts with cavities there is need to use the washer to remove support material from places that are not accessible for any instrument. The last step is gear assembly, which consists of forty parts and testing of prototype functionality. During the functional testing, we used an electric motor with a speed regulator connected to the input shaft. The test showed flawless shifting and fixing of rates in the desired position [7].

3. ACRYLONITRILE BUTADIENE STYRENE

Fused Deposition Modeling 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 for 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) does not change with ambient conditions or time. This enables FDM parts to be among the most dimensionally accurate. Basic FDM materials [8, 9]:

1. ABS - An ABS prototype has up to 80% of the strength of injection moulded ABS meaning that it is extremely suitable for functional applications.
2. ABSi - ABSi is an ABS type with high impact strength. The semi-translucent material used to build the FDM parts is USP Class VI approved.
3. ABS-M30 - ABS-M30 is 25–75% stronger than the standard ABS material and provides realistic functional test results along with smoother parts with finer feature details.
4. ABS-ESD7 – ABS-ESD7 is a durable and electrostatic dissipative material suited for End-use components, Electronic products, Industrial equipment and Jigs and fixtures for assembly of electronic components.
5. PC-ABS – PC-ABS is a blend of polycarbonate and ABS plastic which combines the strength of PC with the flexibility of ABS.
6. PC-ISO – PC-ISO blends are widely used throughout packaging and medical device manufactures. The PC-ISO material used to build the FDM parts is USP Class VI approved and also ISO 10993-1 rated.
7. ULTEM 9085 – ULTEM 9085 is a pioneering thermoplastic that is strong, lightweight and flame retardant (UL 94-V0 rated). The ULTEM 9085 material

opens up new opportunities for the direct additive construction of production grade components.

4. MECHANICAL PROPERTIES OF PLASTICS

Plastics have the characteristics of both a viscous liquid and a spring-like elastomer, traits known as a viscoelasticity. These characteristics are responsible for many of the characteristic material properties displayed by plastics. Under mild loading conditions, such as short-term loading with low deflection and small loads at room temperature, plastics usually react like springs, returning to their original shape after the load is removed. Under long-term heavy loads or elevated temperatures many plastics deform and flow similar to high viscous liquids, although still solid.

Creep is the deformation that occurs over time when a material is subjected to constant stress at constant temperature. This is the result of the viscoelastic behavior of plastics.

Stress relaxation is another viscoelastic phenomenon. It is defined as a gradual decrease in stress at constant temperature.

Recovery is the degree to which a plastic returns to its original shape after a load is removed.

Specific gravity is the ratio of the weight of any volume to the weight of an equal volume of some other substance taken as the standard at a stated temperature. For plastics, the standard is water.

Water absorption is the ratio of the weight of water absorbed by a material to the weight of the dry material. Many plastics are *hygroscopic*, meaning that over time they absorb water.

Tensile strength at break is a measure of the stress required to deform a material prior to breakage. It is calculated by dividing the maximum load applied to the material before its breaking point by the original cross-sectional area of the test piece.

Tensile modulus (modulus of elasticity) is the slope of the line that represents the elastic portion of the stress-strain graph.

Elongation at break is the increase in the length of a tension specimen, usually expressed as a percentage of the original length of the specimen.

Compressive strength is the maximum compressive stress a material is capable of sustaining. For materials that do not fail by a shattering fracture, the value depends on the maximum allowed distortion.

Flexural strength is the strength of a material in bending expressed as the tensile stress of the outermost fibers of a bent test sample at the instant of failure.

Flexural modulus is the ratio, within the elastic limit, of stress to the corresponding strain.

Izod Impact is one of the most common ASTM tests for testing the impact strength of plastic materials. It gives data to compare the relative ability of materials to resist brittle fracture as the service temperature decreases. For finding hardness, *Rockwell Number* is the net increase in depth of impression as the load on a penetrator is increased from a fixed minimum load to a high load and then returned to a minimum load.

Thermal conductivity is the ability of a material to conduct heat; a physical constant for the quantity of heat that passes through a unit cube of a material in a unit of time when the difference in temperature of two faces is 1°C.

Limiting oxygen index is a measure of the minimum oxygen level required to support combustion of the polymer.

Absorption. Polymers have a potential to absorb various corrodents the come to contact with, particularly organic liquids. This can result in swelling, cracking and penetration to the substrate of the component.

From these mechanical properties of plastic materials is very important tensile strength at break and will researched for ABS material used in Fused Deposition Modeling rapid prototyping technology.

5. TENSILE STRENGTH OF ABS MATERIAL

Experimental testing tensile strength of ABS plastics must be realized according to international standard EN ISO 527-1 Plastics - Determination of tensile properties - Part 1: General Principles and international standard EN ISO 527-2 Plastics - Determination of tensile properties; test conditions for moulding and extrusion plastics.

The test methods are selectively suitable for use with the following range of materials:

- rigid and semirigid thermoplastics moulding, extrusion and cast materials, including compounds filled and reinforced by e.g. short fibres, small rods, plates or granules but excluding textile fibres (see ISO 527-4 and ISO 527-5) in addition to unfilled types;
- rigid and semirigid thermosetting moulding and cast materials, including filled and reinforced compounds but excluding textile fibres as reinforcement (see ISO 527-4 and ISO 527-5);
- thermotropic liquid crystal polymers.

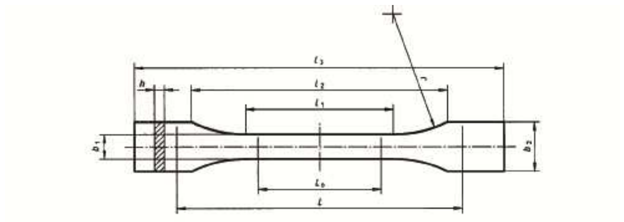
The methods are not suitable for use with materials reinforced by textile fibres (see ISO 527-4 and ISO 527-5), with rigid cellular materials or sandwich structures containing cellular material.

The methods are applied using specimens which may be either moulded to the chosen dimensions or machined, cut or punched from injection- or compression-moulded plates. The multipurpose test specimen is preferred (see ISO 3167:1993 *Plastics – Multipurpose test specimens).*

5.1. Test specimens

Wherever possible, the test specimens shall be dumb-bell-shaped types 1A and 1B as shown in Fig. 3. Type 1A is preferred for directly-moulded multipurpose test specimens, type 1B for machined specimens. Types 1A and 1B test specimens having 4 mm thickness are identical to the multipurpose test specimens according to ISO 3167, types A and B, respectively.

Test specimens shall be prepared in accordance with the relevant material specification. When none exists, or unless otherwise specified, specimens shall be either directly compression- or injection moulded from the material in accordance with ISO 293, ISO 294 or ISO 295, as appropriate, or machined in accordance with ISO 2818 from plates that have been compression- or injection-moulded from the compound.



Dimensions in millimetres

	Specimen type	1A	1B
l_3	Overall length	≥ 150 1)	
l_1	Length of narrow parallel-sided portion	80 ± 2	60,0 ± 0,5
r	Radius	20 to 25	≥ 60 2)
l_2	Distance between broad parallel-sided portions	104 to 113 3)	106 to 120 3)
b_2	Width at ends	20,0 ± 0,2	
b_1	Width of narrow portion	10,0 ± 0,2	
h	Preferred thickness	4,0 ± 0,2	
L_0	Gauge length	50,0 ± 0,5	
L	Initial distance between grips	115 ± 1	$l_2{}^{+5}_{0}$

Fig. 3. Test specimens type 1A and 1B.

All surfaces of the test specimens shall be free from visible flaws, scratches or other imperfections. From moulded specimens all flash, if present, shall be removed, taking care not to damage the moulded surface.

Test specimens from finished goods shall be taken from flat areas or zones having minimum curvature. For reinforced plastics, test specimens should not be machined to reduce their thickness unless absolutely necessary. Test specimens with machined surfaces will not give results comparable to specimens having non-machined surfaces.

5.2. Production of test specimens by FDM method

To prototype successfully, first select an appropriate rapid prototyping tool. There are hundreds of rapid prototyping tools available. They range from simple graphics packages that allow you to draw screens to complex systems that allow you to create animation. Each tool is better for some functions than for others. Although several rapid prototyping techniques exist, all employ the same basic five-step process. The steps are [6]:

1. Creation of CAD models of the product parts.
2. Conversion of CAD models into STL formats.
3. Use of STL files in Rapid Prototyping devices.
4. Production of the parts by one layer atop another.
5. Cleaning of parts and assembly of the product.

Model of selected part was created and subsequently modified in CAD/CAM/CAE system Pro/ENGINEER. Transfer of models between Pro/ENGINEER and another CA systems was implemented using the exchange format IGES where they were treated. On Fig. 4 is example of CAD model of parts in Pro/ENGINEER. On the start of the production process are generated STL data in the Pro/ENGINEER system and these STL data are next loaded to the Catalyst program for layered rendering of the model (Fig. 5).

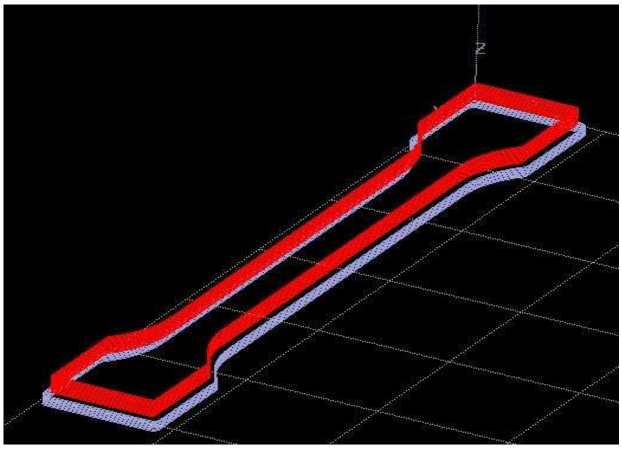


Fig. 5. Layered model of specimen in Catalyst software.

For RP methods there are specific production devices (3D printers) that use their own software based on principle of reading and processing of input STL data. In spite of different manufacturers, such programs have the same characteristic features: settings for single layer resolution, settings for density of model material, settings for density of support material, STL processing to layer mode.

All these software solutions allow their user to change large number of different settings. Changes are made by user himself. Programs for preparation of FDM production make many actions easier and more automatic, but deciding process about particular parameters is still up to user. In case of using the automatic mode these decisions are made by program without explanation, so there is space for optimization of setting contrary to user criteria. Solution could be realized in implementation of deciding steps or automatic decision with actual information about reasons running on background, eventually together with information about parts already produced. First step is to define the surfaces and constructional points that represent functional features of part and thus they should condition requirements on quality. Higher parameters of quality means longer printing times and higher energy consumption, but utilization possibility of such models is much higher as they can be used instead of real functional parts. Next step in 3D printing preparation process is to define the location of the model on

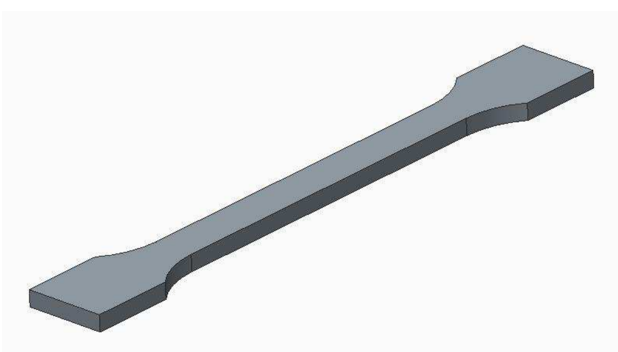


Fig. 4. CAD model of specimen realized in Pro/ENGINEER.

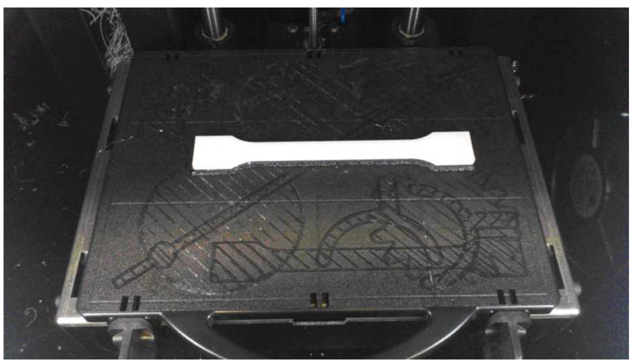


Fig. 6. Produced prototype of 3D specimen by FDM method.

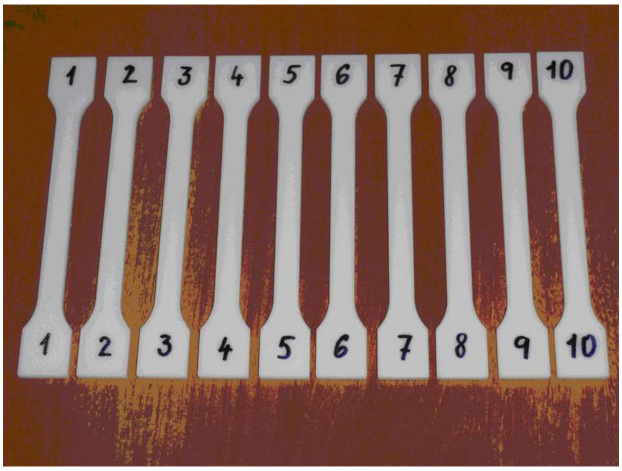


Fig. 7. Specimens prepared for realization of experiment.

Fig. 8. Test machine TIRA-test 2300.

working board of printer. On Fig. 6 is view of workplace of 3D FDM printer UPrint with printed part and on Fig. 7 are specimens prepared for realization of tensile strength experiments [8].

5.3. Realization of ABS tensile strength experiments

Experimental tests for definition of tensile strength of ABS material was realized in Laboratory of mechanical and technological experiments of Department of technologies and materials of Technical University of Kosice with use of test machine TIRA-test 2300 (Fig. 8).

Readings for tensile testing of test specimens of ABS plastic are presented by Fig. 9.

5.4. Statistical treatment of test results

Statistical interpretation of test results-estimation of the mean and confidence interval is defined by ISO 2602 standard. The scope of this International Standard is limited to a special question. It concerns only the estimation of the mean of a normal population on the basis of a series of tests applied to a random sample of individuals drawn from this population, and deals only with the case

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Skúšobný protokol č.: Marcincinova
Číslo objednávky:

Laboratórium mechanických a technologických skúšok

Výrobca: FVT TUKE   Materiál: ABS plast

Druh skúšky:

MECHANICKÉ VLASTNOSTI - ŤAH PLASTY

Poradové číslo	označenie vzorky	a_0 [mm]	b_0 [mm]	A_0 [mm^2]	L_0 [mm]	L [mm]	F_Y [N]	F_m [N]	σ_y [MPa]	σ_m [MPa]	ε_m [%]
1	1.	9,95	4,20	41,79	50,00	2,37	0,00	1093	0	26	4,75
2	2.	9,95	4,23	42,09	50,00	2,51	0,00	1208	0	29	5,02
3	3.	9,93	4,26	42,30	50,00	2,43	0,00	1194	0	28	4,86
4	4.	9,93	4,24	42,10	50,00	2,40	0,00	1190	0	28	4,81
5	5.	9,92	4,27	42,36	50,00	2,53	0,00	1176	0	28	5,05
6	6.	9,93	4,20	41,71	50,00	2,41	0,00	1214	0	29	4,82
7	7.	9,96	4,23	42,13	50,00	2,40	0,00	1181	0	28	4,80
8	8.	9,94	4,20	41,75	50,00	2,30	0,00	1212	0	29	4,60
9	9.	9,93	4,22	41,90	50,00	2,51	0,00	1160	0	28	5,01
10	10.	9,93	4,24	42,10	50,00	2,53	0,00	1163	0	28	5,06

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Fig. 9. Readings for tensile testing of test specimens of ABS plastic.

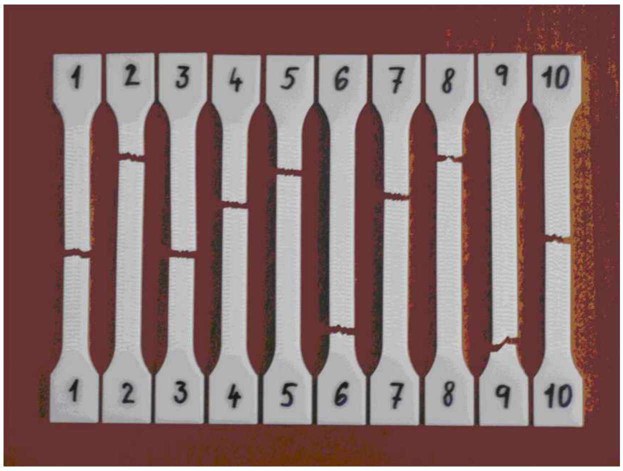

Fig. 10. Test specimens after realized experiment.

where the variance of the population is unknown. It is not concerned with the calculation of an interval containing, with a fixed probability, at least a given fraction of the population (statistical tolerance limits).

It is recalled that ISO 2854 relates to the following collection of problems (including the problem treated in this International Standard):

- estimation of a mean and of the difference between two means (the variances being either known or unknown);
- comparison of a mean with a given value and of two means with one another (the variances being either known or unknown, but equal);
- estimation of a variance and the ratio of two variances;
- comparison of a variance with a given value and of two variances with one another.

The statistical treatment of the results allows the calculation of an interval which contains, with a given probability, the mean of the population of results that would be obtained from a very large number of determinations, carried out under the same conditions. In the case of items with a variability, this International Standard assumes that the individuals on which the determinations are carried out constitute a random sample from the original population and may be considered as independent.

The interval so calculated is called the confidence interval for the mean. Associated with it is a confidence level (sometimes termed a confidence coefficient), which is the probability, usually expressed as a percentage, that the interval does contain the mean of the population. Only the 95 % and 99 % levels are provided for in this International Standard.

Estimation of the mean of the measured values of ultimate tensile strength σ_M [MPa] test specimens of ABS plastic is implemented through ungrouped results. Case results grouped into classes are considered at a sufficiently high number of measurements, for example over 50. After the elimination of any problem of measurement data includes the measured series $n = 10$ measurements x_i (where $i = 1, 2, 3, ..., n$), some of which have the same value.

The mean m of the underlying normal distribution is estimated by the arithmetic mean z of the n results:

$$\overline{\sigma_{M1}} = \frac{1}{n}\sum_{i=1}^{n}\sigma_{Mi} = \frac{1}{10}(26+29+28+28+28+29+28+29+28+28),$$

$$\overline{\sigma_{M1}} = 28.1 \text{ Mpa.} \qquad (1)$$

Confidence interval for the average file is calculated from the estimated mean and standard deviation. The estimate of the standard deviation σ is calculated set of squares of deviations from the arithmetic mean by the formula (2):

$$s_1 = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\sigma_{M1i} - \overline{\sigma_{M1}}\right)^2};$$

$$s_1 = 0.8756 \text{ Mpa.} \qquad (2)$$

Two-sided confidence interval for the average file is for a confidence level of 95% determined by the following two-sided inequality:

$$\overline{\sigma_{M1}} - \frac{t_{0.975}}{\sqrt{n}}.s_1 < m < \overline{\sigma_{M1}} + \frac{t_{0.975}}{\sqrt{n}}.s_1 \qquad (3)$$

$$28.1 \text{ MPa} - 0.715 \,.\, 0.8756 \text{ MPa} < m < 28.1 \text{ MPa} + 0,715 \,.\, 0.8756 \text{ Mpa};$$

$$27.473946 \text{ MPa} < m < 28.726054 \text{ Mpa.} \qquad (4)$$

The actual value of ultimate tensile strength of test specimens of ABS plastic is σ_{M1} = (28.1 ± 0.626) MPa with a probability of 95%.

7. CONCLUSIONS

This paper was focused on optimization of FDM samples preparation processes. It described the steps that lead to selection of suitable settings. Output values obtained from production software are presented. Assets for the future could lie in possibility of having all the necessary information at once and thus to make the right decision on proper settings variant based on real facts. Realization of such innovation can be achieved through generation of database that would process and archive all output data after production of part models. Relations would be observed between chosen parameters of basic and support material, times of production and quality, all including economical aspects. This supportive database system would together with software philosophy based on described steps for selection of suitable parameters assure maximal economy while keeping comfort and effective way of selection.

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