Considerations Regarding the Use of Polymers for the Rapid Prototyping of the Hydraulic Turbine Runners Designed for Experimental Research on the Model

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The manufacturing of hydraulic turbine runners designed for experimental research on the model is carried out, usually, by precision casting or CNC machining. These processes involve technological difficulties, high manufacturing times and high production costs, which are generated by the complex geometry and the small dimensions of the runner. Rapid prototyping technologies allow the manufacturing of mechanical components at a high precision and for a significantly lower manufacturing time and production costs compared to the conventional technologies. The use of components made of polymers, through rapid prototyping, in experimental research, may be limited by the properties of the polymer and the mechanical stress occurred. In order to verify the possibility of using polymers in the manufacture of turbine component models, a Pelton runner was made through rapid prototyping. The stress-strain state that occurs on the runner blade was analyzed and experimental investigations were performed on a micro-turbine equipped with the polymer runner.

Keywords: polymer, rapid prototyping, stress, Pelton runner

The experimental research done on the models, in laboratory conditions, is an important milestone in the design process of a hydraulic turbine. The components of the hydraulic turbine model mirror the geometry of the industrial turbine components, reduced with a required scaling factor. The manufacture of the turbine model blades involves technological difficulties and high costs due to the complex shape and small dimensions. Up to now, the manufacturing technologies that were used were based on the precision casting and the CNC machining. These technologies turn a profit on the manufacture of a large series of products, but involve high costs in the manufacturing of a small series and prototypes, requiring many intermediate processing steps between the design of the three-dimensional model and the execution of the final shape of the part [1].

The development of rapid prototyping technologies allows the production of mechanical components directly from the three-dimensional CAD model. There are several methods of rapid prototyping manufacture, based on the same principle: the deposition of thin successive layers [2,3]. The materials used are in particular polymers. In recent years, other materials, like ceramics and metallic powders are used. The rapid prototyping technologies involve high costs which are related to the materials, but these costs are lower than those of the manufacture by using precision casting or CNC cutting. The production time is highly reduced compared to those of conventional technologies, in most cases, the manufacture of a mechanical component through rapid prototyping requiring less than 24 h. The use of these technologies is justified mainly on the parts with complex geometry: models used in medical implants, airfoil components, hydrodynamic profile components (eg.: hydraulic turbine runner blades), artwork models, etc. [3-5]. In the field of aerodynamics and hydrodynamics, the scientific literature shows examples of parts manufactured through rapid prototyping used for the manufacture of molds for precision casting [1] and for aerodynamic flow studies [6 - 8]. The use of these parts in hydrodynamic flow research is not mentioned. The goal of the research presented in this paper was to determine the usability of hydraulic turbine runners made from polymeric materials, through rapid prototyping, in the experimental research on the model.

Experimental part

Runner Rapid Prototyping

In The Center for Numerical Simulation & Digital/Rapid Prototyping (www.csnp.roedu.ro) of the "Eftimie Murgu" University of Resita, researches on a Pelton micro-turbine (fig. 1) equipped with several geometries of runners and nozzles, manufactured through rapid prototyping [9,10], were performed. The research described below is performed on a Pelton rotor with 19 blades (buckets) and the characteristic diameter D_1 = 148 mm, made in one piece. The complexity of the blades, the small dimensions of the runner and the condition of manufacture in one piece, generate technological difficulties in the manufacturing by casting or CNC cutting.

The geometry of the blades on this type of runner is described by splines curves [11]. These curves, that characterise both longitudinal sections and cross sections of the blade, are obtained through hydrodynamic design algorithms [9]. Figure 2 shows the curves of variation of the Z coordinates with the X and Y coordinates, for the inner and outer surfaces of the runner blade (The X axis is parallel to the symmetry axis of the blade and the Y axis is parallel to the axis of the runner. The following symbols were used: Z_{SI} – coordinates on the Z axis for the inner surface of the blade, Z_{SE} – coordinates on the Z axis for the outer surface of the blade, A, B and G - the longitudinal sections on the blade, S1-S5 the cross sections in the blade). The profiles of the blades, obtained from the curves

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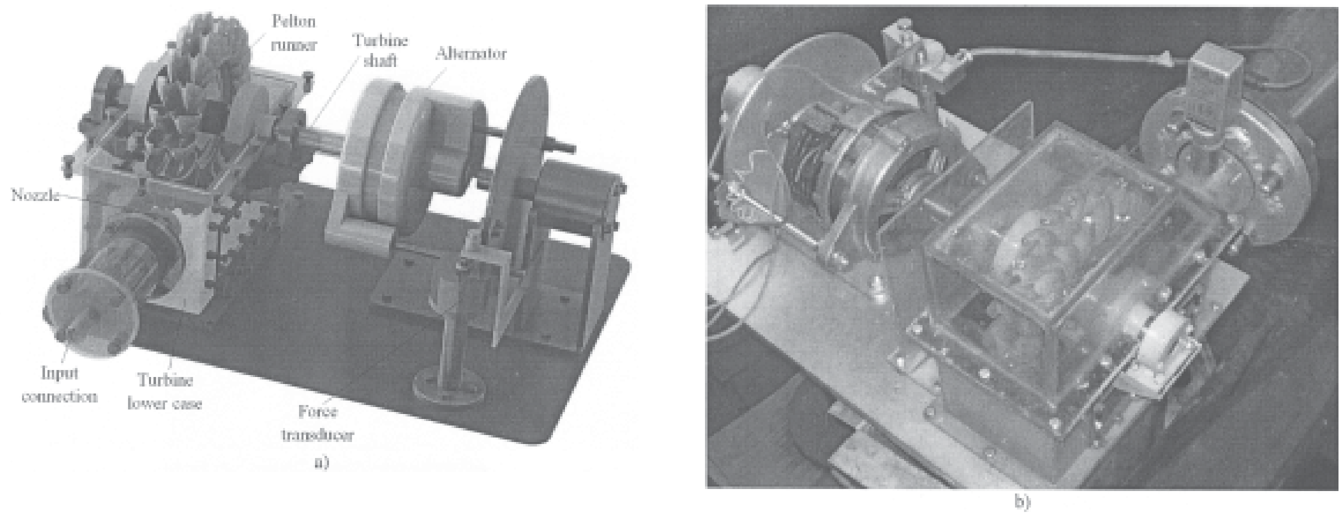
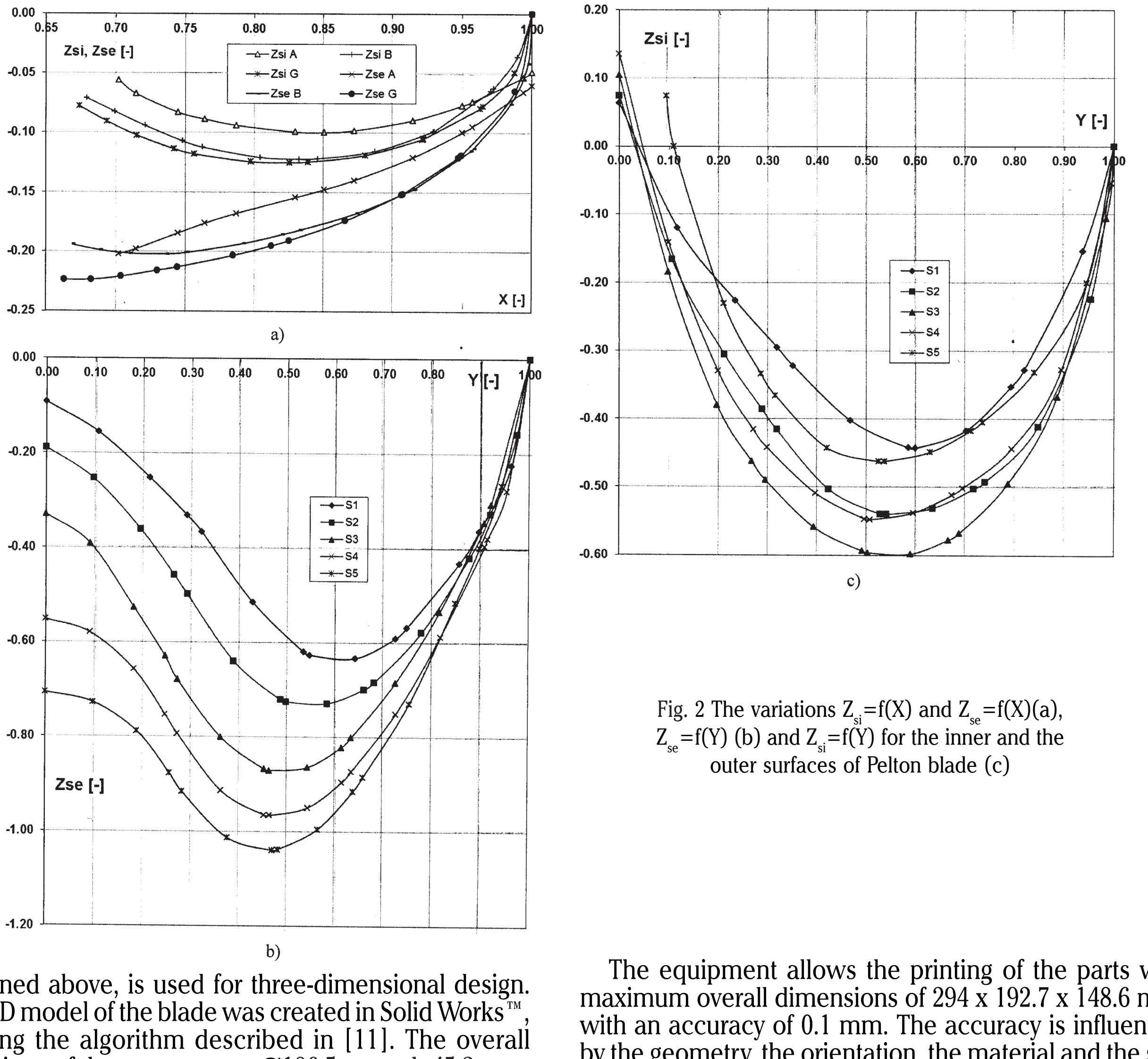


Fig. 1 The Pelton micro-turbine, CAD model (a) and testing setup (b)



a)

b)

c)

Fig. 2 The variations $Z_{si}=f(X)$ and $Z_{se}=f(X)$(a), $Z_{se}=f(Y)$ (b) and $Z_{si}=f(Y)$ for the inner and the outer surfaces of Pelton blade (c)

mentioned above, is used for three-dimensional design. The CAD model of the blade was created in Solid Works™, following the algorithm described in [11]. The overall dimensions of the runner were ∅186.5 mm x h 45.3 mm.

The rapid prototyping equipment used within the “Eftimie Murgu” University of Resita, the 3D printer Objet30™ [12], uses photo polymeric materials for the manufacture of parts. The technology used consists in the deposition of thin layers (28μm) of polymer, each layer being hardened after deposition by exposing it to a UV lamp. The printer uses two types of polymers: a base material (for the model) and a support material used to fill the cavities and to sustain the model. The support material is removed after printing, using a device with a high pressure water jet.

The equipment allows the printing of the parts with maximum overall dimensions of 294 x 192.7 x 148.6 mm, with an accuracy of 0.1 mm. The accuracy is influenced by the geometry, the orientation, the material and the size of the part. The position of the part on the printing table can be set by the user or it can be automatically calculated by the printer application. The position of the part influences the consumption of materials and the working time.

The control application of rapid prototyping equipment uses CAD models stored in STL (Stereolithography) files. These files transform the 3D solid model in a network of triangular surfaces. The accuracy of STL models is influenced by the number of triangular surfaces and it can be set at the conversion of the SLDPRT files (SolidWorks

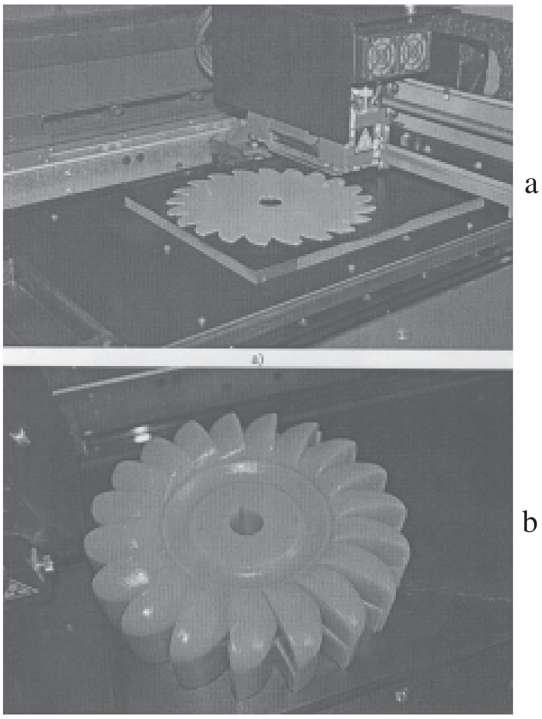


Fig. 3. The 3D printing of the runner: initial stage (a) and final stage (b)

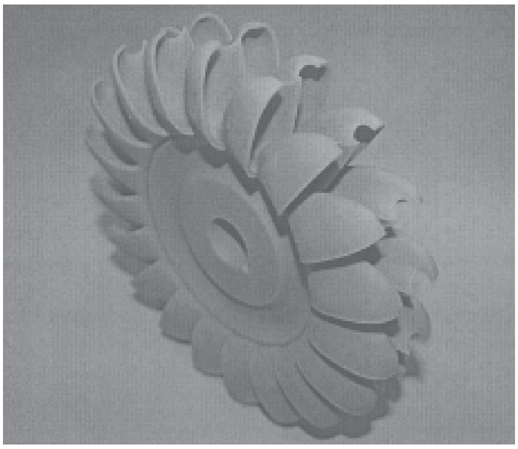


Fig. 4. The final shape of the runner

3D solid model) in STL files. The file used to print the Pelton runner had 1285098 triangular surfaces.

The Pelton runner was printed in horizontal position, with the plane of blade symmetry disposed parallel to the printer table (fig. 3). The support material was necessary to fill the cups of blades and to sustain the runner on the printing table, but it was also disposed on the side and the upper part of the runner, in order to obtain the same roughness on all surfaces (the roughness of the base material is influenced by the contact with the support material).

The runner was made by depositing 1671 layers. The total printing time was 1040 min and 839 g of base material and 726 g of support material were consumed. The geometry of the runner obtained after removing the support material (fig. 4) revealed the high precision and the high quality of the surfaces. This observation is also valid for the geometrical details with small thickness (intersection edge of the two cups of the blade).

Analysis of stress and strains state on the blade

A linear static FEM analysis, made in the *Simulation* module of *SolidWorks*™, was accomplished in order to evaluate the stress and strains, which occurred on the runner during the experimental tests. The simulation was focused on the runner blade, the most loaded area of the runner.

Table 1

MECHANICAL AND PHYSICAL PROPERTIES VEROBLUE RGD840 [13]

Parameter	**unit**	**Value**
Tensile strength, R_m	N/mm^2	50 ÷ 60
Elongation	%	15 ÷ 25
Flexural strength	N/mm^2	60 ÷ 70
Izod impact strength	J/m	20 ÷ 30
Young's modulus	N/mm^2	2000 ÷ 3000
Flexural modulus	N/mm^2	1900 ÷ 2500
Poisson' ratio	-	0.394
Shore hardness (D)	unit.	83 ÷ 86
Rockwell hardness (M)	unit.	73 ÷ 76
Heat deflection temperature HDT, °C @ 1.82MPa	°C	45 ÷ 50
Glass-transition temperature (Tg)	°C	48 ÷ 50
Water absorption	%	1.5 ÷ 2.2
Density	g/cm^3	1.18 ÷ 1.19

The material used for 3D printing, VeroBlue RGD840™ [13], has high tensile and bending strength, compared to other polymeric materials [14-17]. The mechanical and physical properties of the material, as indicated by the manufacturer, are given in table 1 [13].

The loads applied on the runner blade are the forces generated by the water flow and the centrifugal force. The analysis was done for the most dangerous situation: the water flow acting on a blocked runner. The force generated by the water flow is given by the equation (1):

$$F = \rho \cdot Q \cdot V \cdot (1 - \cos(\theta_2)) \qquad (1)$$

where:

V – Water flow velocity on the input edge of the blade;

θ_2 – Angle made by the flow on the exit from the blade;

Q – Discharge;

ρ – Water density;

For the limit situation with $\theta_2 = 180°$, using the velocity obtained by numerical flow simulation V = 15.42 m / s [9], the density $\rho \simeq 1000$ kg / m^3 and the discharge Q = 3.67472 . 10^{-3} m^3 / s, calculated for a nozzle with ∅16.3 mm, the value of the force will be F=113.3 N. This force acts perpendicular on the blade, on a region defined by the projection of the nozzle diameter (fig. 5).

The centrifugal force was defined in accordance with the rotation axis of the runner. The restrain (*fixed* – zero degree of freedom) was applied on the surface that connects the runner disk with the blade (fig. 5). Analysis of a single blade allowed the set-up of a high resolution mesh and a computational model with 164102 nodes and 110913 tetrahedral finite elements (fig. 6) was used.

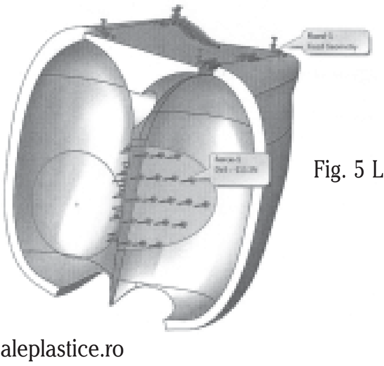


Fig. 5 Loads and restrain applied to the blade

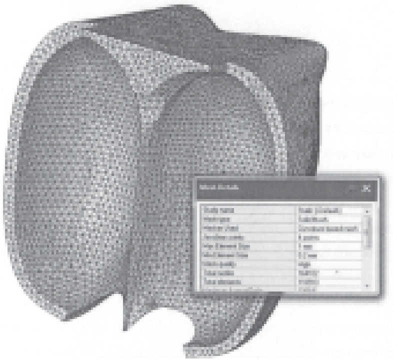


Fig. 6 The mesh applied to the blade

Results and discussions

The distribution of the von Mises equivalent stress (fig. 7) indicates maximum values of 5 N/mm^2, occurred in the area where the flow meets the blade. The maximum stress is ten times lower than the VeroBlue RGD840 polymer tensile strength, R_m = 50 N/mm^2. The maximum displacements δ_{max} = 0.067 mm (fig. 8) occurs on the tip of the blade. These low maximum values lead to the conclusion that the polymer runner can be used in the experimental research.

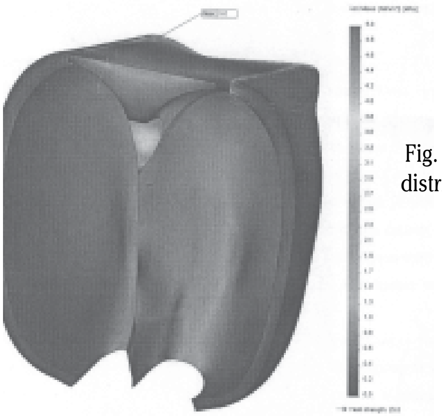


Fig. 7 von Mises stress distribution (σ_{max} = 5 N/mm^2)

The experimental research done on the micro-turbine aim to determine the energetic performance, draw the hill chart of the runner and validate the results of the static FEM analysis. Measurements of discharge (Q), runner speed (n), head and force were performed and the results were used to calculate the power absorbed by the turbine, the angular velocity, the torque on the turbine shaft, the power output and the turbine efficiency (η). Using this data, the variations $\eta/\eta_{max}=f(n_{11})$ were drawn and the hill chart of the turbine was calculated by the HydroHillChart software (fig. 9) (www.cchapt.ro/oferta/HydroHillChart.html). The values of the efficiency in the hill chart are dimensionless in conjunction with the efficiency maximum value.

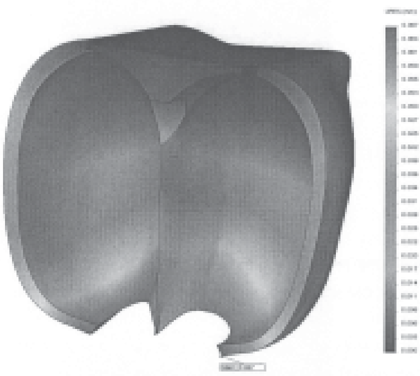


Fig. 8 Displacements distribution (σ^{max} = 0.067 mm)

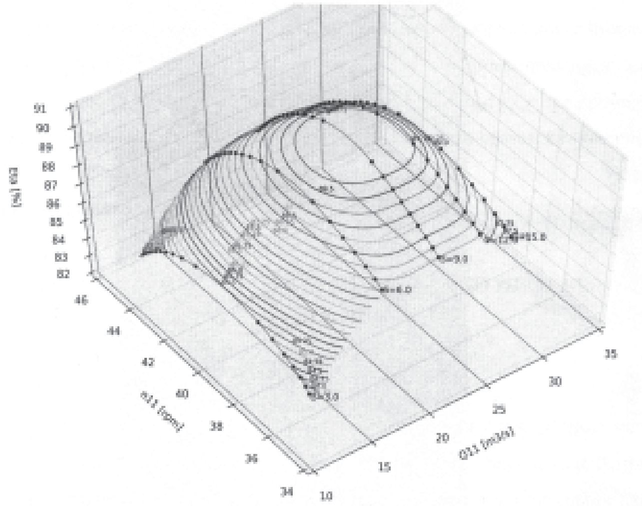


Fig. 9 Hill chart of the runner

The analysis of the runner surfaces after the experimental research revealed no occurrences of cracks or plastic deformation, confirming the results of the numerical simulations.

Conclusions

Numerical and experimental investigations performed on a Pelton runner made of VeroBlue RGD840 polymer, through rapid prototyping, point to the usability of this polymer for the manufacture of hydraulic turbine runners designed for laboratory research.

The analysis of the rapid manufacturing process of the Pelton runner points out the high quality and the high accuracy of the runner surfaces, the short manufacturing time and the lower production costs, compared to conventional technologies based on casting or CNC cutting.

The numerical analysis of the maximum stresses and strains that occur during experimental tests is a method to validate the usability of the runners made of polymeric materials. Future research will focus on determining the behavior of the runners on variable loads and fatigue. The study of the influence of environmental factors (the physico-chemical properties of water, the presence of inclusions, temperature variations) on the mechanical characteristics of the models made from this polymer will also be performed.

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References

1.CHICA E., AGUDELO S., SIERRA N., Lost wax casting process of the runner of a propeller turbine for small hydroelectric power plants**,** Renewable Energy**, 60**, 2013, p. 739–745

2.UPCRAFT S., FLETCHER R., The rapid prototyping technologies, Assembly Automation, **23**, no. 4, 2003, p.318 – 330

3.GUO N, LEU C.G., Additive manufacturing: technology, applications and research needs, Frontiers of Mechanical Engineering, **8**, no. 3, 2013, p. 215-243

4.HANEMANN T., BAUER W., KNITTER R., WOIAS P., Rapid Prototyping and Rapid Tooling Techniques for the Manufacturing of Silicon, Polymer, Metal and Ceramic Microdevices, in MEMS/NEMS. Handbook Techniques and Applications, ISBN: 978-0-387-24520-1, 2006, pp. 801-869

5.HOQUE M.E., Advanced applications of rapid prototyping technology in modern engineering, Intech, 2011, ISBN 978-953-307-698-0
6.OLASEK K., WIKLAK P., Application of 3D printing technology in aerodynamic study, XXI Fluid Mechanics Conference, Journal of Physics, Conference Series, **530**, 012009, 2014
7.SHUN S, NOOR A. Rapid prototyping of aerodynamics research models, Applied Mechanics and Materials, **217**, 2012, p. 2016-2025
8.AGHANAJAFI C. DANESHMAND S., Integration of Three-Dimensional Printing Technology for Wind-Tunnel Model Fabrication, Journal of Aircraft, **47**, No. 6, 2010, p. 2130-2135
9.AVASILOAIE R.C., Theoretical and experimental research on microturbines
for high head and low discharges, PhD thesis, Eftimie Murgu University of Resita, 2013
10.NEDELCU, D., AVASILOAIE, R., FLOREA, D., RAJIC, A., Applications of the Rapid Prototyping Technology to Manufacture the Pelton Runners, Analele Universitatii "Eftimie Murgu" Resita, **20**, no. 1, 2013, p. 191-198
11.NEDELCU, D., CAMPIAN, C.V., PADUREAN, I., Stress and Deformations on Pelton Blade Turbine calculated by Finite Elements Method, The International Conference on Hydraulic Machinery and Equipments, Timisoara, HME 2008, Scientific Bulletin of the "Politehnica" University of Timisoara, Transaction on Mechanics, **53** (67), 2008, p. 137-142
12.*** Objet30™ 3-D Printer System, User Guide, Objet Geometries Ltd., 2010
13.*** PolyJet™ Materials Data Sheet, 2014
14.TABACU, S., HADAR, A., MARINESCU, D., MARIN, D., DINU, G., IONESCU, S.D., Structural performances of thermoplastic manufactured parts, Mat. Plast., **45**, no. 1, 2008, p. 113
15.MARSAVINA L., CERNESCU A., LINUL E., SCURTU D., CHIRITA C., Experimental Determination and Comparison of Some Mechanical Properties of Commercial Polymers, Mat. Plast., **47**, no. 1, 2010, p. 85
16.GHITA, E., GILLICH, G.R., BORDEASU, I., VODA, M., TROI ,C., Aspects Concerning Polymers Behaviour under Tension, Mat. Plast., **44**, no. 2, 2007, p. 158
17.HAGUE R., MANSOUR S., SALEH N., HARRIS R., Materials analysis of stereolithography resins for use in Rapid Manufacturing, Journal Of Materials Science, 39, 2004, p. 2457 – 2464

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