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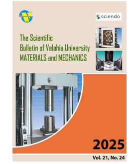

STUDIES ON THE MECHANICAL STRESS BEHAVIOR OF POLYTETRAFLUOROETHYLENE (PTFE) USED IN THE CONSTRUCTION OF MECHANICAL RING ELEMENTS

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Abstract: *This paper presents the study of the mechanical behavior of polytetrafluoroethylene (PTFE) during tensile tests performed at different strain rates, using standard samples. Test pieces are measured using a non-contact video extensometer. This procedure is particularly precise, as large deformities are involved. The results are compared with a mathematical model to predict the mechanical behavior observed in the experiments. The main objective is to predict the stress-strain curve at different strain rates (6.0 × 10−4, 7.7 × 10−2, 9.2 × 10−2 and 1.3 × 10−1 s−1) using model equations that combine enough mathematical simplicity to allow their use in engineering problems with the ability to describe complex nonlinear mechanical behavior.*

The material constants (PTFE) that appear in the model equations can be easily identified from tests performed at constant and different strain rates. The virtual studies were carried out using the FEM program under the Solidworks software (Simulation) in which a virtual material was created with the mechanical properties of the analyzed material. The studies contain simulations of tensile, bending and impact tests according to standardized standards.

Keywords: *PTFE, tensile properties, flow rate, virtual testing*

1. INTRODUCTION

In recent times, polytetrafluoroethylene (PTFE) has received considerable attention due to its special physical characteristics, such as high melting point, very good chemical resistance and extremely low friction. The complex nonlinear behavior of polytetrafluoroethylene remains one of the most severe limitations for its even wider use in the chemical and petrochemical industries.

In many experiments conducted by researchers, PTFE samples have been tested for compression and stretching, with varying distorted temperatures [1-4]. Experimental PTFE tension relaxation tests were developed and the results were compared with the Maxwell model prediction [5-7]. The behavior of PTFE has been studied at high temperatures. A single-sample normalization technique was used to evaluate the impact strength of PTFE, for a range of temperatures and charge rates. Several constitutive models have also been proposed to predict the complex mechanical behavior of thermoplastics and thermosets. The strain rate and temperature-dependent behavior of polymers were described using constitutive models. In addition, some studies have been done to report deformed damage in solid polymers. The mechanical behavior of polymers at high deformation rates has been presented in the literature [8-12]. The mechanical characterization of PTFE using a non-contact, full-field optical method was proposed.

The combined effect of velocity dependence and very large inelastic deformations can be extremely complex. The mechanisms proposed so far to explain the behavior of the material under the microscope are not able to elucidate all aspects of these coupled phenomena. In a way, the behavior of PTFE material can be considered superplastic.

A wide class of materials – metals, ceramics, intermetallics, nanocrystalline, polymers, etc. – exhibit superplastic behavior under special processing conditions. The most important characteristic of a superplastic material is its high sensitivity to the rate of deformation of flow stress, which gives it a high resistance to neck development and results in large elongations characteristic of superplastic behavior. Superplastic deformed material in tensile tests thins very evenly, rather than forming a "neck" (a local narrowing), resulting in a rupture [13-17].

Although to date, there is no precise physical definition of the phenomenon of super plasticity in polymer materials; Phenomenologically, super plasticity can be defined as very large deformations before a local failure. In the case of tensile tests with controlled strain rate, this means very large elongations of the specimens before failure.

Even though there is no way to define a fundamental mechanism for superplastic behavior, evaluating the influence of deformation rate on the superplastic properties of a polymer film material is a basic requirement for its economic use. This is achieved by performing a series of tensile tests at different speeds. The purpose of this paper is to see if a mathematical model is good at describing the mechanical behavior of PTFE under tensile stress at different strain rates.

2. PTFE TENSILE TESTING

The material used in this document is commercially available PTFE (DuPont Teflon®), which has the following characteristics:

- densitate: 2180 kg/m^3;
- Total temperature: ~327^{0}C.

Standard tensile test specimens were manufactured from PTFE with the shape and size specified by ASTM D-638-08 (Type I) [18]. The initial length l0 and the initial section A0 are as follows:

- l_0 = 50 mm;
- A_0 = 26 mm^2 (13 x 2 mm).

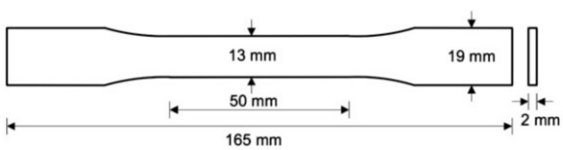


Figure 1. PTFE sample – tensile test

Tensile tests were performed using a Shimadzu AG-X universal electromechanical testing machine. The elongation of the calibrated length of the PTFE samples was measured using an optical method. The non-contact experimental method is based on two CCD cameras.

Video extensiometers produce a real-time image of the useful portion of the sample, which is used to measure the elongation of the coordinate length. It is important to note that all experiments were carried out at room temperature, i.e. 25 °C. Strain rates: (6.0×10^{-4}, 7.7×10^{-2}, 9.2×10^{-2} and 1.3×10^{-1} s^{-1}) were controlled using the measured elongation as input to the control system of the test machine.

Using the prescribed elongation and the applied force F(t) measured experimentally, in addition to the initial length l_0 and the initial section A_0, the technical strain *e* and the *recorded stresses* are given by:

$$e(t)=\frac{\Delta l(t)}{l_0}, \quad s(t)=\frac{F(t)}{A_0} \qquad (1.1)$$

At constant volume, the actual strain and the actual stress, as a function of *e* and *s*, are defined as follows:

$$\varepsilon = \ln(1+e) \text{ și } \sigma = s\cdot(1+e) \qquad (1.2)$$

Figures 2 and 3show the PTFE stress-strain curves for different constant strain rates e (6.0×10^{-4}, 7.7×10^{-2}, 9.2×10^{-2} and 1.3×10^{-1} s^{-1}).

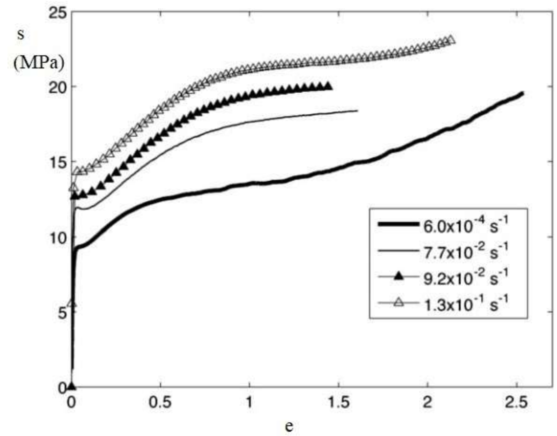


Figure 2. σ–ε curves for PTFE

These results were obtained from experimental data using equations (1.1) and (1.2). The curves show a strong dependence on the strain rate, where the flow stress increases with the strain rate [19-23].

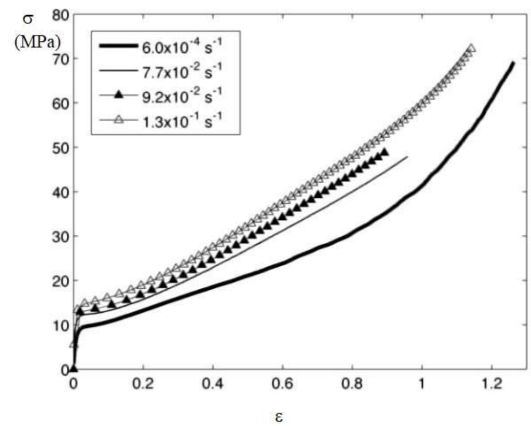


Figure 3. σ – ε the curves for PTFE [21]

One of the characteristics of PTFE is that it exhibits large deformations under tension before a local failure [24-27].The high sensitivity of the deformation rate of flow stress gives a high resistance to the development of choking, the sample thins very evenly, instead of forming a "blockage". Usually, the failure is localized and characterized by a crack perpendicular to the traction axis.

3. VIRTUAL TESTS ON THE MECHANICAL BEHAVIOR OF PTFE

The tests are performed as part of a 3D modeling program that, using finite element analysis [28-31], can determine stresses σ and ε strain in mechanically tested samples.

In the 3D program, the samples will be constructed to the dimensions corresponding to the SR EN ISO 6892-1:2010 standard and will be subjected to stresses that may cause them to break or deform excessively to determine the stresses and deformations of the PTFE material.

3.1 Virtual tensile testing of PTFE samples

The properties of virtual material are consistent with those of real material.

Table 1. PTFE Virtual Properties

Property	Value	Units
Elastic Modulus	500	N/mm^2
Poisson's Ratio	0.46	N/A
Shear Modulus	300	N/mm^2
Mass Density	2200	kg/m^3
Tensile Strength	20	N/mm^2
Compressive Strength		N/mm^2
Yield Strength	5	N/mm^2
Thermal Expansion Coefficient		/K
Thermal Conductivity	0.24	W/(m·K)
Specific Heat	1000	J/(kg·K)
Material Damping Ratio		N/A

- longitudinal modulus of elasticity: E = 500 MPa;
- Poisson's ratio: ν = 0.24;
- transverse modulus of elasticity: E = 300 MPa;
- tensile strength: σr = 20 MPa;
- flow voltage: σr = 5 MPa;
- thermal conduction coefficient: 0.24 W/m·K;
- specific heat: 1000 J/kg·K.

The virtual specimen (figure 4) is fixed at the bottom, and the tensile force is applied at the top.

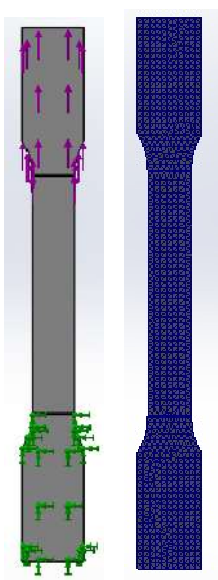
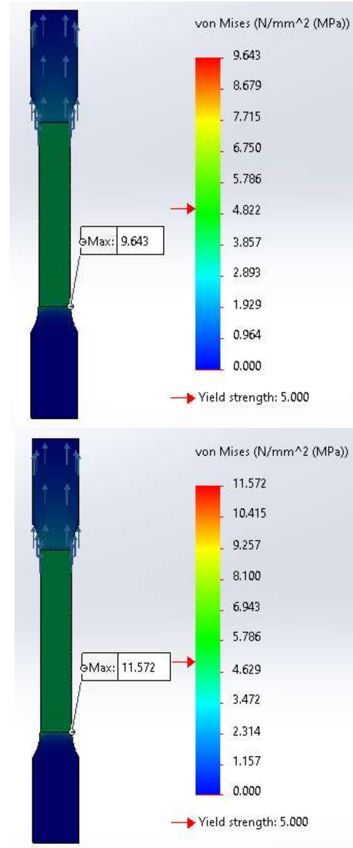


Figure 4. Fixing and applying the tensile force. Dividing the specimen into finite elements

The virtual tensile test is performed by gradually applying a force with the following values: Ft = 100 N (figure 5); Ft = 120 N; ft = 140 N ; Ft = 160 N; ft = 180 N ; Ft = 200 N and Ft = 220 N ;

The results are shown in the figure below.



Ft = 100 N

Figure 5. The virtual tensile test at a value: Ft = 100 N

Table 2. Stresses in the sample for tensile forces [N]

σ [MPa]	9,643	11,572	13,501	15,429	17,358	19,286	21,215
Ft [N]	100	120	140	160	180	200	220

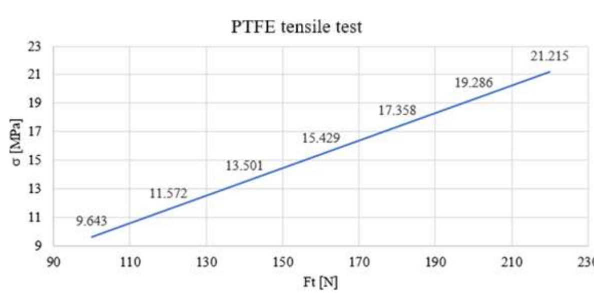


Figure 6. Tension in the sample as a function of tensile force

From the data obtained by the tensile test of the PTFE sample (figure 6), the elasticity of this material can be observed and it can be seen that when it exceeds the tensile stress (σr = 20 MPa), the sample breaks (σ = 21.215 MPa).

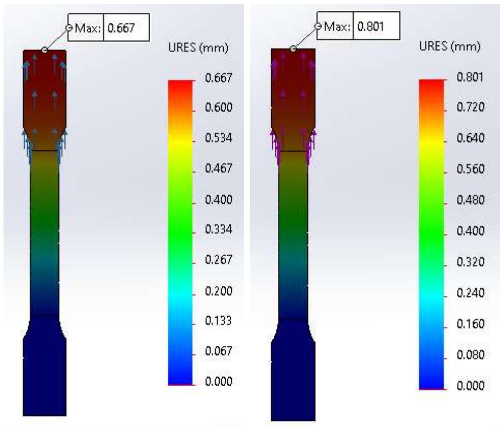


Figure 7. Tensile test results at a Ft = 100 N Ft = 120 N

Table 3. Sample deformations for tensile forces

σ [MPa]	0,667	0,801	0,934	1,067	1,201	1,334	1,468
Ft [N]	100	120	140	160	180	200	220

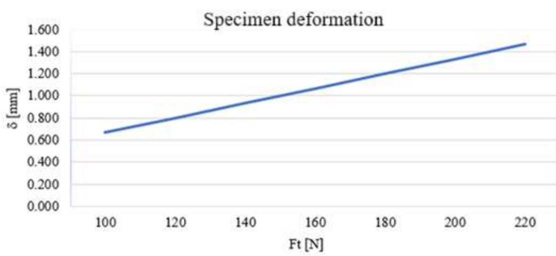


Figure 8. Sample deformations as a function of tensile force

The study of the deformation of the PTFE material shows that this material does not have a very high elasticity (E = 500 MPa), as is the property of the real material (figure 8). It deforms and the material breaks at a deformation between 1,334 m and 1,468 mm.

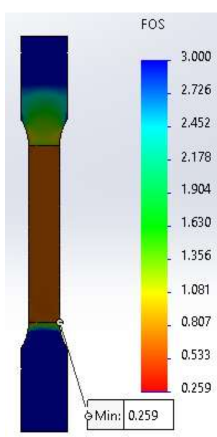


Figure 9. FOS safety factor results at a Ft = 100 N Ft = 120 N

The poor mechanical qualities of PTFE can be seen from the value of the FOS safety factor (figure 9), which is a superunit ratio between the minimum tensile strength and the usability of the material. This factor must have a value > 3 for the material to maintain its integrity in the work. From the analyses performed, it can be seen that the tensile strength is low for PTFE, especially in thin forms (2 mm), such as the sample analyzed at tensile stress.

3.2 Virtual PTFE Sample Bending Tests

The bending behavior of PTFE is different from that of traction.

The specimen is supported on two supports arranged 20 mm from the edge of the sample, so that the bending length is 80 mm according to ASTM.

The support, the application of bending force and the division of the specimen into small finite elements can be seen in the figure below (figure 10).

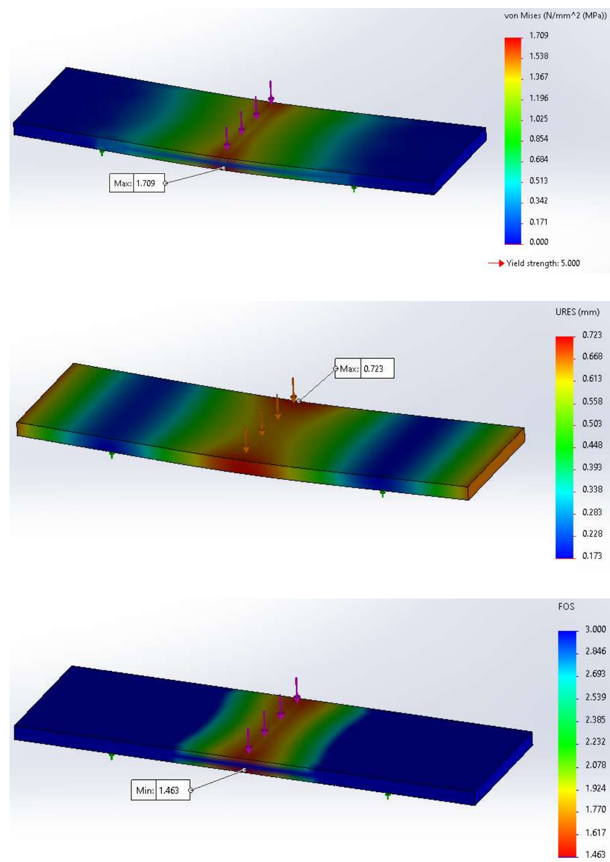


Figure 10. Stress with bending force: F = 5 N

The test tube was subjected to static stresses, progressively with the following forces:

- $F_1 = 5$ N ; $F_2 = 10$ N ; $F_3 = 15$ N ; $F_4 = 20$ N ;

The results are centralized in Table 4.

Table 4. Flexural Stress Results of PTFE Sample

Result	$F_1 = 5$ [N]	$F_2 = 10$ [N]	$F_3 = 15$ [N]	$F_4 = 20$ [N]
Voltages σ [MPa]	0,709	3,484	5,323	7,201
Deformations δ [mm]	0,723	1,467	2,156	2,782
FOS	1,463	0,717	0,470	0,347

Conclusions of the virtual bending analysis of the PTFE sample

- when applying the force of 5 N, it can be seen that there are small stresses in the PTFE material (σ = 0.709 MPa), but the deformation is large (δ = 0.723 mm), which shows that the material does not have a very compact internal structure;

- with the increase of the bending force, the stresses increase, and for a force of only 15 N, the PTFE exceeds the flow stress (5 MPa), so that the irreversible deformation of the material occurs (11);

- the safety factor shows that the material is not stable even from the force of 5 N (the contact between the force and the material is a line and the stresses are high on such a small surface (figure 12).

PTFE works very well on large surfaces.

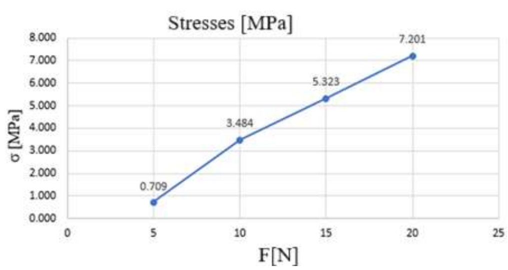


Figure 11. Stresses in PTFE

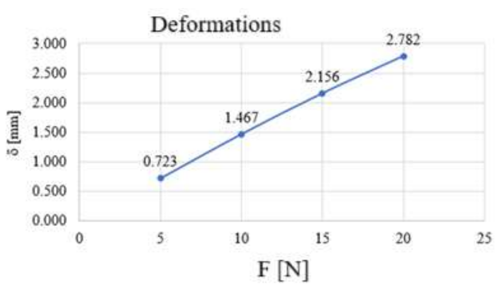


Figure 12. Deformations in PTFE

3.3 Virtual Mechanical Stress Testing of PTFE Rings

The behavior of PTFE, under mechanical stress, can be better studied when we have a part made of this material. The most well-known use of PTFE is in the construction of slip rings, due to the very low coefficient of friction (~0.05) of the material.

The figure below shows a PTFE bushing modeled in the 3F program to which the material properties have been assigned.

This type of bushing is stressed at the contact pressure on the inner and outer cylindrical surfaces and on the bushing ring surface.

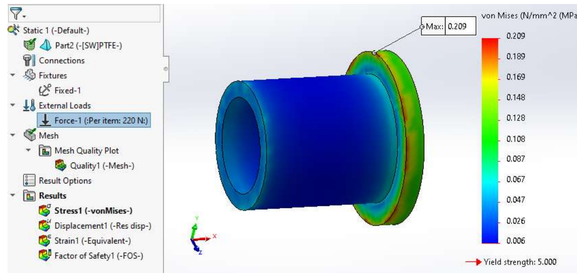


Figure 13. Maximum ring stresses for a force of 220 N

The bushing was subjected to a force equal to the maximum force in the PTFE tensile test, i.e. F = 220 N. The force was applied to the cylindrical interior and the collar of the socket. Fixing was performed as shown in Figure 13.

Due to the fact that the bushing is fixed on a large surface, the force of 220 N generated small stresses in its geometry, The maximum value is on the edge of the collar and has a value of 0.209 MPa, a very low tension. Thus, PTFE works well when stressed evenly on the fold, especially curved cylindrical contours such as valve rings and seats.

The contact displacements with the force of 220 N are very small (δ = 0.002 mm), which shows the good behavior of PTFE under contact stresses.

The safety factor has high values, only on the edge of the bush is less than 3, but it is not an important area in the operation of the bush.

4. CONCLUSIONS

The properties that make PTFE an exceptional material, compared to other thermoplastics, are: very good chemical and thermal resistance and a very low coefficient of friction. This material is easily deformable, soft, semi-crystalline, opaque, white in appearance with properties that qualify it for use in the food sector.

It has elastomer-like properties, having a high elongation, but it does not resist mechanical stresses and ultraviolet rays very well. It has a very good resistance to contact with most chemicals and retains its stability up to temperatures of 327^{0}C. These properties have led to the use of PTFE in many applications.

PTFE is a hard material with good flexibility, no elasticity (non-elastic). It has an average tensile strength, but the thermal properties are very good for a polymer. It is very resistant to the action of many thermal agents and is a very good thermal insulator. The very low coefficient of friction compared to other materials qualifies PTFE for many applications in mechanical engineering.

The poor mechanical qualities of PTFE can be seen from the value of the FOS safety factor, which is a superunit ratio between the minimum tensile strength and the usability of the material. This factor must have a value > 3 for the material to maintain its integrity in the work.

From the analyses carried out, it can be seen that the tensile strength is low for PTFE, especially in thin forms (2 mm), such as the sample analyzed at tensile stress.
The findings of the virtual bending analysis of the PTFE sample showed that when the force of 5 N is applied in the PTFE material, small stresses (σ = 0.709 MPa) are developed, but the deformation is large (δ = 0.723 mm), which shows that the material does not have a very compact internal structure.

With the increase in bending force, stresses increase, and for a force of only 15 N, PTFE exceeds the flow stress (5 MPa), so that irreversible deformation of the material occurs.

The safety factor shows that the material is not stable even from the force of 5 N (the contact between the force and the material is a line and the stresses are high on such a small surface.
PTFE works very well on large surfaces.
The virtual bushing was stressed at a force equal to the maximum force in the PTFE tensile test, i.e. F = 220 N, with the force applied to the cylindrical interior and bushing ring.

Due to the fact that the bushing is fixed on a large surface, the force of 220 N generated small stresses in its geometry, The maximum value is located on the edge of the collar and has a value of 0.209 MPa, a very low tension. Thus, PTFE works well when subjected evenly to the contour, especially curved cylindrical contours such as valve rings and seats. The contact displacements with the force of 220 N are very small (δ = 0.002 mm), which shows the good behavior of PTFE under contact stresses. The safety factor has high values, only on the edge of the bush is less than 3, but it is not an important area in the operation of the bush.

The chemical, physical, and mechanical properties of PTFE make this material special compared to other thermoplastic materials. These properties are: very good chemical and thermal resistance and a very low coefficient of friction. PTFE is easily deformable, soft, semi-crystalline, opaque, white in appearance with properties that qualify it for use in many technical fields and beyond.

REFERENCES

[1] P.J. Rae, D.M. Dattelbaum, Poly(tetrafluoroethylene) properties (PTFE) in compression polymer, 45 (2004), pp. 7615-7625

[2] P.J. Rae, E.N. Brown, Poly(tetrafluoroethylene) properties (PTFE) in tension polymer, 46 (2005), pp. 8128-8140

[3] A. Hernández-Jimánez, J. Hernández-Santiago, A. Macias-García, J. Sánchez-González Relaxation mode in PMMA and PTFE assembly by the Maxwell Polym fractional model. Test, 21 (2002), pp. 325-331

[4] Z. Zhang, X. Chen, Y. Wang, Uniaxial ratchet behavior of polytetrafluoroethylene to polym at elevated temperatures. Test., 29 (2010), pp. 352-357

[5] Z. Zhang, X. Chen, Multiaxial ratchet behavior of PTFE at room temperature Polym. Test., 28 (2009), pp. 288-295

[6] E.N. Brown, D.M. Dattelbaum, The Role of the Crystalline Phase on Fracture and Evolution of Polytetrafluoroethylene (PTFE) Polymer Microstructure, 46 (2005), pp. 3056-3068

[7] C. Ebert, W. Hufenbach, A. Langkamp, M. Gude, Modeling of Strain Behavior Dependent on the Strain Rate of Polypropylene Polym. Test., 30 (2011), pp. 183-187

[8] J. Richeton, S. Ahzi, K.S. Vecchio, F.C. Jiang, R.R. Adharapurapu, The Influence of Temperature and Strain Rate on the Mechanical Behavior of Three Amorphous Polymers: Characterization and Modeling of Compressive Elastic Stress Int. J. Solids Struct., 43 (2006), pp. 2318-2335

[9] B. Farrokh, A.S. Khan, A Strain Rate-Dependent Performance Criterion for Isotropic Polymers: Low to High Euro Charge Rates J. Mech. A/Solids, 29 (2010), pp. 274-282

[10] Erhard Krempl, Fazeel Khan, Rate-Dependent Deformation Behavior (Time): An Overview of Some Properties of Solid Metals and Polymers Int. J. Plasticity, 19 (2003), pp. 1069-1095

[11] Qin-Zhi Fang, T.J. Wang, H.G. Beom, H.P. Zhao, High Velocity-Dependent Deformation Behavior of PC/ABS Polymer, 50 (2009), pp. 296-304

[12] M. Wendlandt, T.A. Tervoort, U.W. Suter, The Nonlinear and Velocity-Dependent Work Hardening Behavior of Polymer Glass, 46 (2005), pp. 11786-11797

[13] J.S. Bergstrom, L.B. Hilbert Jr., A Constitutive Model for Predicting Thermomechanical Behavior at Large Deformation of Mech. Fluoropolymers Mater., 37 (2005), pp. 899-913

[14] C.Y. Tang, C.P. Tsui, W. Shen, C.C. Li, L.H. Peng, Modeling the Nonlinear Stress-Strain Behavior of HIPS with Crack Damage in the Tensile Load-Discharge Process, Polym. Test., 20 (2001), pp. 15-28

[15] F. Za'ri, M. Na't-Abdelaziz, J.M. Gloaguen, J.M. Lefebvre, Modeling the Elasto-Viscoplastic Deterioration Behavior of Vitreous Polymers, Int. J. Plasticity, 24 (2008), pp. 945-965

[16] C. G'Sell, J.M. Hiver, A. Dahoun, Experimental characterization of strain deterioration in solid polymers under stress and its interrelation with shrinkage, Int. J. Solids Struct., 39 (2002), pp. 3857-3872

[17] E.N. Brown, P.J. Rae, E.B. Orler, Influence of Temperature and Strain Rate on the Constitutive and Harmful Responses of Polychlorinated Trifluoroethylene (PCTFE, Kel-F 81), Polymer, 47 (2006), pp. 7506-7518

[18] Standard Test Method for Tensile Properties of Plastics. ASTM – D 638–08.

[19] N.K. Naik_, Y. Pearl, Mechanical Behavior of Acrylic Under High-Speed Tensile Load, Polym. Test., 27 (2008), pp. 504-512

[20] M. Schoßg, C. Bieröel, W. Grellmann, Thomas Mecklenburg, Mechanical Behavior of Glass Fiber Reinforced Thermoplastics Under High Deformation Rates, Polym. Test., 27 (2008), pp. 893-900

[21] A.D. Mulliken, M.C. Boyce, Mechanics of velocity-dependent elastic-plastic deformation of small to tall vitreous polymers, Int. J. Solids Struct., 43 (2006), pp. 1331-1356

[22] L.C.S. Nunes, Mechanical Characterization of Polytetrafluoroethylene Polymer Using the Full-Field Displacement Method, Opt. Lasers Eng., 49 (2011), pp. 640-646

[23] H.S. da Costa Mattos, G. Minak, F. Di Gioacchino, A. Soldà, Modeling the superplastic behavior of Mg alloy sheets under stress using a theory of continuous deterioration, Mater. Design, 30 (2009), pp. 1674-1679

[24] H.S. da Costa Mattos, I.N. Bastos, J.A.C.P. Gomes, A Simple Model for Slow Deformation Rate and Constant Load Corrosion Testing of Austenitic Stainless Steel in an Acidic Aqueous Solution Containing Sodium Chloride, Corros. Sci., 50 (2008), pp. 2858-2866

[25] H.S. da Costa Mattos, A.H. Monteiro, E.M. Sampaio, Modeling the Strength of Soldered Butt Joints, Compos. B. Eng., 41 (2010), pp. 654-662

[26] H.S. da Costa-Mattos, F.E.G. Chimisso, Modeling Creep Tests in HMPE Fibers Used in Ultra-Deep Mooring Cables, Int. J. Solids Struct., 48 (2011), pp. 144-152

[27] K. Levenberg, A Method for Solving Certain Problems in the Smallest Squares, Quart. Appl. Math., 2 (1944), pp. 164-168.

[28] Alexis Negrea, Maria Cristiana Enescu, Elena Valentina Stoian and Ivona Petre, Virtual Studies on the Behavior of Polyurethane on Mechanical Stresses Scientific Bulletin of Valahia University - Materials and Mechanics VOLUME 18 (2022): ISSUE 18 (APRIL 2022) Apr 30, 2022

[29] M.C.Enescu, Simulation de résistence à la traction et compression dans un composite macromoléculaire, U.P.B. Sci. Bull., Series B, 72, 3, 2010, p.211

[30] Enescu, M.C., Stoian, E.V., Negrea, A., Petre, I., Rusanescu, C.O., Experimental and virtual studies in mechanical applications of PP-RCT pipes with armored materials *Materiale Plastice*, 2019, 56(2), pp. 324–329

[31] M.C. Enescu, D. Ungureanu, E.V. Stoian, Simulation of tensile and compression strength of a Macromolecular composite, The Scientific Bulletin of Valahia University Materials and Mechanics, 1(5), 2007, p.19.