Non-conventional Methods for Shaping Plastics Parts

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Conventional methods for processing and shaping plastics parts (mold injection, thermoforming, extrusion etc) require heating (melting) process in which plastics material is soften or liquefied firstly and then imparted by using different dies and techniques. However, plastics material could be formed without any heating and for that purpose a few non-conventional procedures have been developed. An alternative to conventional shaping of plastic parts offers metal forming processes and cold forming technique.In this paper results of theoretical, numerical and experimental investigation of cold forming of plastics are present. Traditional metal forming processes such as upsetting and backward extrusion were applied for shaping billets made from HDPE and PA. Both processes are simulated by FEM and Simufact.Forging 8.1 program package. Numerically predicted load-stroke diagrams are compared to those experimentally recorded. All necessary material data and process parameters were determined according to the methodology which is used in metal forming processes.

Keywords: thermoplastics, cold forming, FEM

The conventional way to form thermoplastics is by shaping viscous molten polymer under pressure in a mold [1]. But this way of processing plastic materials show some disadvantages such as high production cost, expensive and time consuming mold manufacturing, slow production rates due to cooling steps, low mechanical properties of plastic parts etc. To overcome this, in early seventies some investigations related to possible application of metal forming techniques as a method of converting thermoplastic materials into final product were conducted [2]. Basically, there are two ways for non-conventional processing of thermoplastic materials: cold forming and solid-phase forming. In case of cold forming there is no heating of material and tooling, as the solid-forming is performed with the material that is heated below melting point and formed while in a heated solid state. In literature these terms are sometimes used interchangeably. Process of forming thermoplastics materials that is performed below the glass transition temperature is characterized by favourable fiber orientation enhancing that way mechanical properties (stiffness and strength) of final part. Further advantages of applying metal forming techniques in shaping thermoplastics are parts without flash, trim or weld lines. With other side the main disadvantage is that the advantages must economically outweigh the cost of preparing the billets.

Forming operations of thermoplastic materials are usually divided into three main groups: forging, sheet forming and drawing operations. Among forging operations closed die forging (fig.1a), open die forging, direct and backward extrusion (fig.1b) and cold heading are most frequently used. Sheet forming includes stamping, coining, bending (fig.1c), rolling, hydro-forming (fig1.d), spinning (fig1.e) and explosive forming. Drawing comprises shallow and deep drawing (fig.1f) operations.

Thermoplastic materials employed in metal forming processes must have sufficient ductility and strength so that necking does not occurs [3]. At the same time the recovery or “memory” characteristics of materials must be low in order to minimize springback effects and provide dimensional stability of final part [4]. Polymers such as polycarbonates, polypropylene, celluloses, ABS, rubber modified polymers, some glass reinforced materials etc. can be easily formed, while brittle materials such as polystyrene and acrylics can not. Soft rubbery polymers such as polyethylene can be shaped, but forming process is followed with excessive springback of workpiece. Thus, long forming cycles have to be applied. For the fast pre-selection and rating of thermoplastic materials data obtained by simple uniaxial tension and compression tests could be practiced.

Starting materials could be prepared by extrusion, compression molding or casting. Preforms in shape of billets and plates are mostly obtained by shearing and blanking extruded sheets or bars. Very often the preparation of starting material from molding compound (sheets and rod) and billet cut off are integral parts of the processing. In figure 2 an integrated system for forging of thermoplastic materials is given.

In the Laboratory for metal forming, Faculty of technical sciences Novi Sad, possibilities of applying the conventional cold metal forming techniques and standard forming tools in processing of thermoplastic materials have been investigated for few years. This paper presents some results of analytical (SLAB), numerical (FEM) and experimental investigation of free upsetting and backward can extrusion of cylindrical billets made from commercial high density polyethylene (HDPE) and polyamide (PA). Analyzed models are typical bulk metal forming processes but each other very different from stress-strain state point of view thus obtained results can offer many useful information about formability of investigated thermoplastics. In this investigation all necessary material data and process parameters essential for theoretical analysis and process simulations were determined according to the methodology used in metal forming.

Experimental part

Experimental investigations have been realized in few

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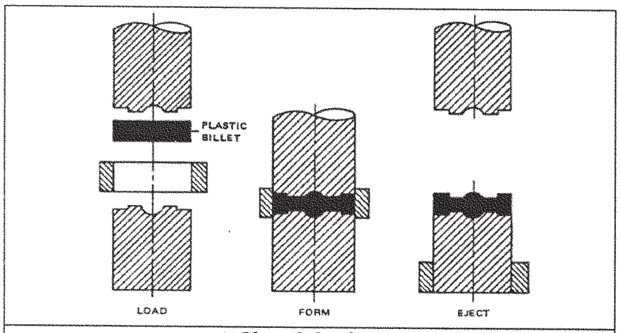
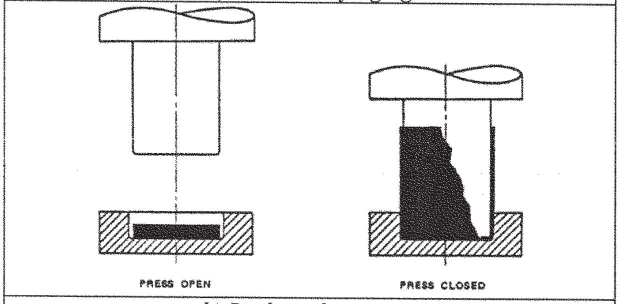
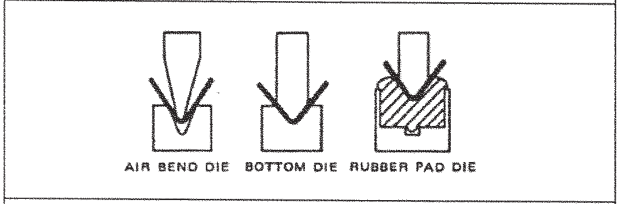


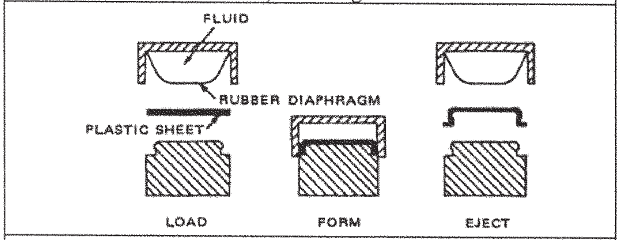
a) Closed die forging



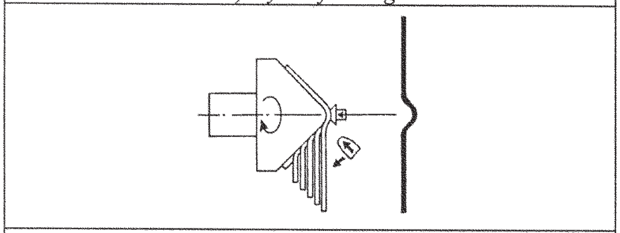
b) Backward extrusion



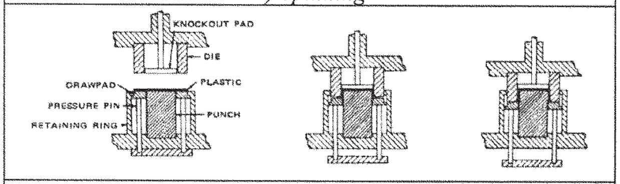
c) Bending



d) Hydro-forming



e) Spinning



f) Deep drawing

Fig. 1. Typical metal forming methods applied in processing of thermoplastics [2]

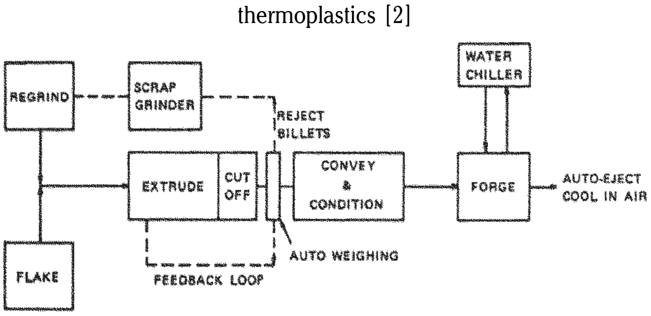


Fig. 2. Integrated forging system [2]

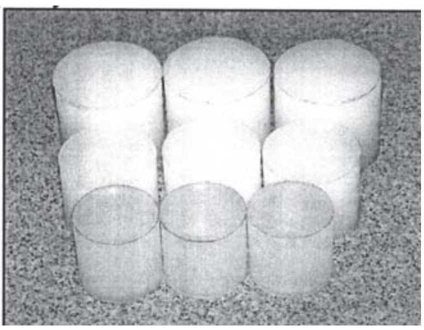


Fig. 3. Specimens made from PA and HDPE

steps. Firstly, for selected thermoplastics flow curves and friction coefficients which are necessary both for theoretical and numerical calculation, were determined. Afterwards processes of cold upsetting with flat dies and backward can extrusion are accomplished. All experiments were performed on 6.3 MN, Sack and Kiesselbach hydraulic press. Fine turning were applied for preparing specimens (fig. 3) in order to attain high surface quality.

Flow curve

Yield stress and flow curves for both materials were determined by applying Rastegaev method (fig.4) [5]. In this procedure shallow cavities on forehead surfaces of specimen are filled with lubricant (stearin here) with the goal to eliminate friction and avoid bulging process by splitting up contact surfaces between dies and specimen. It assures unaxial stress state in specimen thus effective stress can be directly calculated by dividing actual forming load and cross section of specimen. After statistical processing of experimental data the next analytical expressions for flow curves in Ludwig's form are obtained [6]:

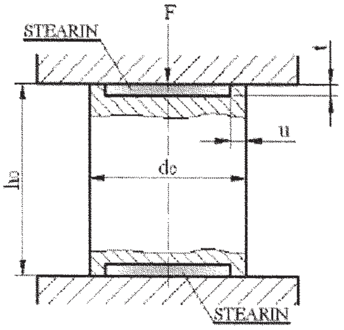


Fig. 4. Scheme of upsetting according Rastegaev method

for PA $K = 20 + 56.42 \cdot \varphi^{0.77}$

for HDPE $K = 10 + 27.2 \cdot \varphi^{0.467}$

Friction coefficient

Method of free upsetting of ring specimen was used for calculation of Amonton's coefficient of friction (μ). As it is known, the way of the inner diameter behaviour during ring upsetting depends on friction [7]. Increase of inner ring diameter indicates the lower friction and vice-versa. This had been used as a base for the design of so cold etalon-diagram in which the change of the inner diameter deformation εD with respect to deformation of ring height εH is given. By incremental way the εD - εH curves for PA and HDPE were calculated and incorporated into standard etalon diagram. Comparing the results with standard curves, the following values of the coefficient of friction when mineral oil is used as lubricant are estimated: $\mu=0.03$ for PA and $\mu=0.05$ for HDPE, [8]respectively (fig. 5).

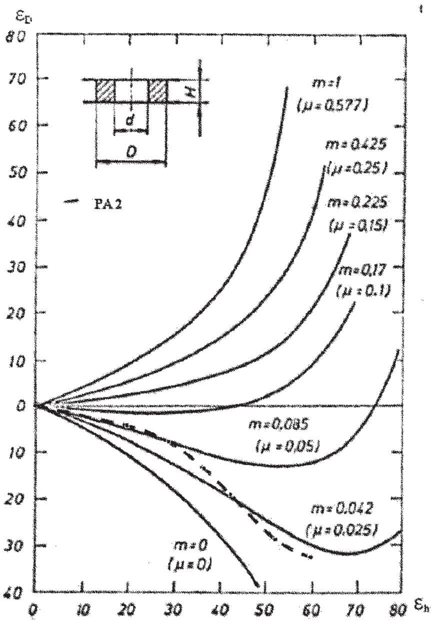


Fig. 5 a) – Etalon-diagrams applied for determination of the friction coefficients for PA

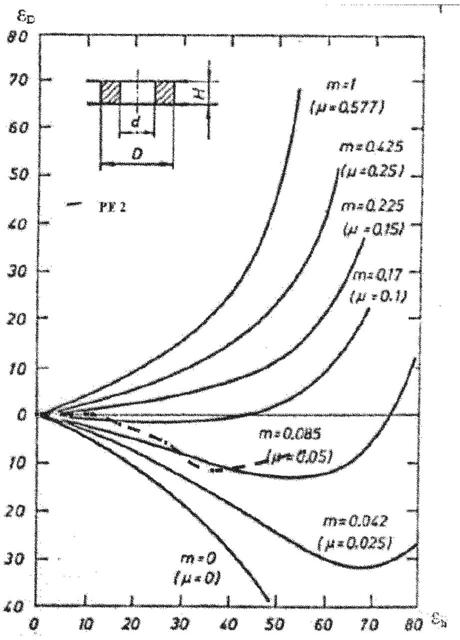


Fig. 5 b) – Etalon-diagrams applied for determination of the friction coefficients for HDPE

Free upsetting

Free upsetting is an elementary forging operation that often takes place at the beginning of deformation process in case of more complex forging operations. In free upsetting billet is firstly placed between upper and bottom flat dies and later compressed by the movement of one of the dies. Therefore its initial height is reduced. Friction between end faces of the workpiece and dies prevents the free lateral spread of the metal, resulting in a typical barrel shape. Upsetting between parallel flat dies is limited to deformation symmetrical around a vertical axis.

In experiment of free upsetting cylindrical billets (from PA and HDPE) with initial dimension ϕ20x20mm were used. During the process mineral oil was applied as lubricant. Employed hydraulic press is a special testing machine which is equipped with sensors for load and stroke measurement. It was connected with multi-channel PC data acquisition device (Hottinger-Spider 8) as forming load-stoke diagrams were plotted automatically by Catman Easy program package. Total stroke was 14mm and 127.4 kN maximum recorded load, which appears in case of specimen from PA. Specimens of PA and HDPE after free upsetting are given in figure 6.

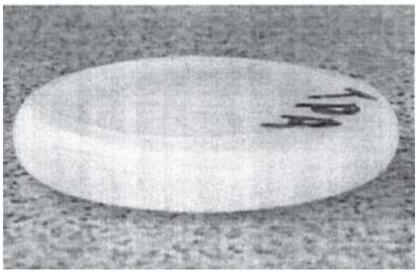


Fig.6 a) – Specimens after free upsetting PA

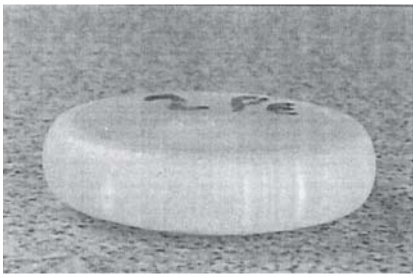


Fig.6 b) – Specimens after free upsetting HDPE

Backward extrusion

Backward extrusion process is a widely used cold forming process for the manufacturing of hollow-shape symmetric, cylindrical products. In this case moving punch press a billet placed in die extruding it upwards by means of high pressure (fig.1.b). The thickness of the extruded tubular section is a function of the clearance between the punch and the die.

Backward can extrusion of thermoplastic specimens was performed with tooling (punch and die) whose geometry is designed for specimens made from steel. In figure 7 dimensions of specimens before and after shaping are given. Process conditions and data recording procedure were identical to the experiment of free upsetting. Figure 8 shows the form of specimen made from PA after process of backward can extrusion.

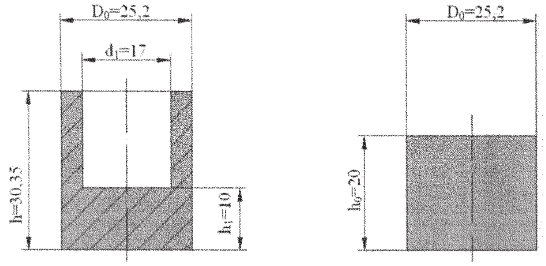


Fig. 7. Final and starting dimensions of specimen in backward extrusion

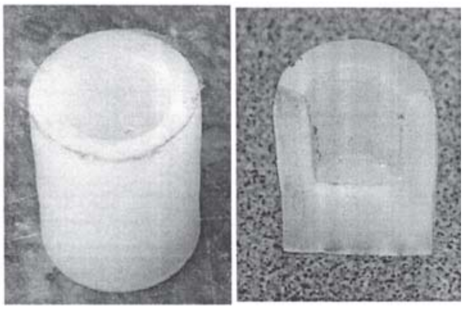


Fig. 8. Specimens of PA after backward can extrusion [8]

Theoretical approach

There are many theoretical approaches and methods for analyzing forming processes. SLAB method or procedure of solving differential equilibrium equations is commonly applied for determining stresses and loads in bulk metal forming processes especially for those with simpler workpiece geometry. Fundamentals of this method can be found in numerous literatures [5, 9] as well as the final expressions for determining forming load of forming processes here investigated. Forming load in free upsetting can be calculated from:

$$F=\frac{d^2\cdot\pi}{4}\cdot K\left(1+\frac{\mu}{3}\frac{d}{h}\right) \qquad (1)$$

where:

d, h – diameter and height of workpiece after upsetting
K – effective stress
μ – Amonton's coefficient of friction

Forming load in backward can extrusion is given by the following expression:

$$F=\frac{d_1^2\cdot\pi}{4}\cdot\left\{K_o\left(1+\frac{\mu}{3}\frac{d_1}{h_b}\right)+K_1\left[1+\frac{h_b}{s}\left(0.25+\frac{\mu}{2}\right)\right]\right\} \qquad (2)$$

where:

d1 – punch diameter
hb – bottom thickness
s – wall thickness
Ko – initial effective stress
K1 –effective stress at the end of process
μ – Amonton's coefficient of friction

FEM Analysis

The third research approach of investigated models was based on 2D axisymetric FEM analysis. Commercial software package Simufact.Forming 8.1 for simulation of bulk metal forming processes was used. For the comparison purpose with the other results, FEM analysis has been performed on the same condition with SLAB method and experiment. In process simulation model of elastic-plastic material for workpiece was chosen, as tooling is considered as rigid body. The Young's modulus, Poisson's ratio and density of investigated thermoplastics are E=3000MPa, $\nu=0.34$, $\rho=1200\text{kg/m}^3$ in case of PA and E=460Mpa, $\nu=0.34$, $\rho=1200\text{kg/m}^3$ for HDPE, respectively [10]. Amonton's friction model is applied in FEM analysis with previously determined friction coefficients.

The geometries of the tooling and billets were set in SolidEdge V.18 CAD program and exported in Simufact.Forming 8.1. The specimens were meshed with quad elements which are generated upon the size criteria. In simulation remeshing of starting elements had to be applied for highly deformed zones of workpieces. Remeshing procedure was performed on every 5 increments in order to minimize the effect of tool penetration through elements due to the large workpiece deformations.

Analysis of the results

Load – stroke diagrams obtained by experiment, SLAB method and FEM simulation are depicted in figures 9 and 10.

It can be seen from diagrams that for both investigated processes analytically calculated and FEM predicted forming loads are similar in form and show the same trend as experimentally recorded curves. However, there are certain degrees of discrepancy in absolute values between experiment and results obtained by other two ways. For

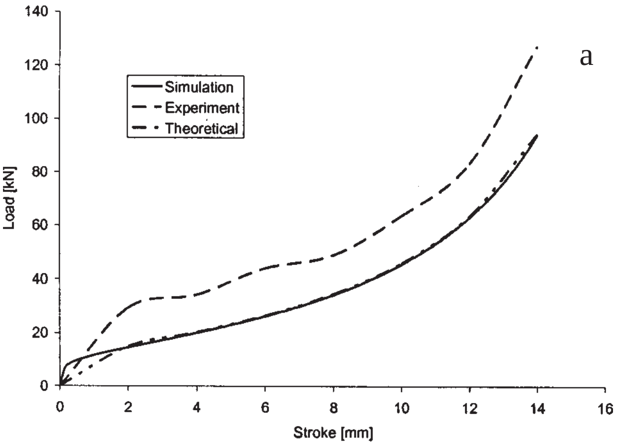


Fig. 9a. Load-stroke diagram in free upsetting for a) PA

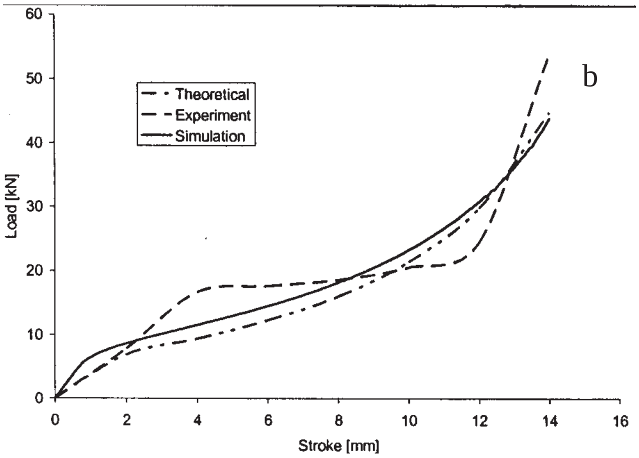


Fig. 9 b. Load-stroke diagram in free upsetting for b) HDPE

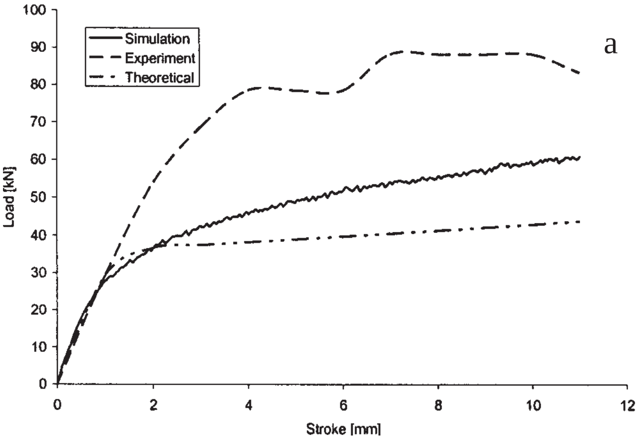


Fig. 10 a . Load-stroke diagram in backward can extrusion for a) PA

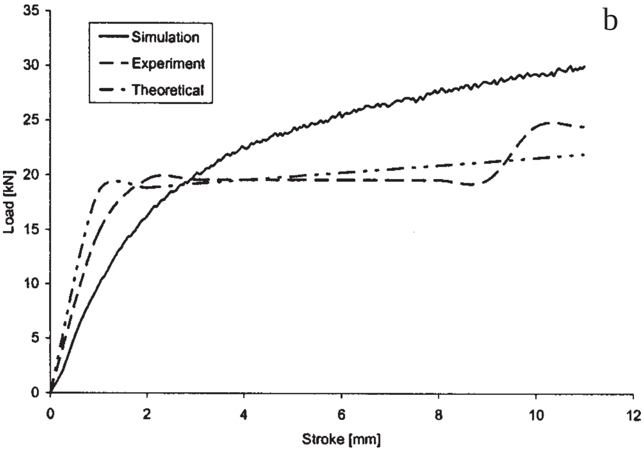


Fig. 10 b. Load-stroke diagram in backward can extrusion for b) HDPE the specimens made from PA these differences are very notable (20-50%). Maximum values of forming load are obtained by experiment as SLAB method gives minimal. These discrepancies can be explained by problem of proper description of the mechanical and physical properties of used material (PA) which are essential for accurate theoretical and numerical analysis [11]. On other side, in case of HDPE specimens differences between experimental and SLAB and FEM results are much smaller. Process of free upsetting of HDPE specimen characterizes quick increase of experimental load up to stroke of 4mm (fig.6.b). As the die stroke proceeds the load continues to increase gradually. Final phase is characterized by noticeable load rise. In case of backward extrusion (fig.7.b) there is high degree of coincidence between results of experiment and SLAB method, as FEM analysis predicts slightly higher values.

When accuracy of the specimens after forming is considered parts made from PA show less deviation from desired geometry in compassion to those from HDPE. This is a direct consequence of large springback which occurs in case of HDPE specimens. Problem with accuracy of HDPE specimens comes also from very low strength of this thermoplastic so even small contact pressure can generate local errors in part form. Also, significant differences in the quality of part surfaces can be noticed. Better quality is obtained in case of PA specimens.

Conclusions

Investigations presented in this paper confirm that non-conventional or metal forming tehniques and standard metal forming equipment can be successfully employed for processing thermoplastic materials. In addition, theoretical approach and expressions for determination of process parameters that are primary derived for metal materials give satisfactory results when thermoplastics are applied. Differences between theoretical and experimental results which appeared in some cases were mainly due to improper data for mechanical and physical properties of investigated material. To minimize these discrepancies it is necessary not only to define material data more preciously, but also attention should be paid to investigation of the mechanism of plastic deformation and material behavior during cold forming process. In particular, of great importance is mathematical interpretation of this mechanism and its incorporation in standard software for simulation forming processes.

For investigated thermoplastics, it can be concluded that excessive springback after forming process occurs in case of specimens made from HDPE which badly influence the accuracy of the final part. With other side PA possess good formability potential and satisfactory behaviour during forming while the final parts characterize good dimensional stability and surface quality. Problem with recoverable deformation in case of cold processing of HDPE may be overcome by applying long forming cycles or better using special type of HDPE such as high molecular weight HDPE.

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