The Influence of the Processing Temperature by Injection and of Subsequent Pressure on Some Mechanical Properties of HDPE, PMMA, PC+ABS, Through Methods of Determining the Flexural Properties

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In the first part of the paper we touch on the influence of the processing temperature by injection of HDPE, of PMMA, and of PC+ABS blend on some mechanical flexural properties, while the other factors which could influence the injection remain unchanged. In the second part of the paper, we present the influence of the subsequent pressure in the injection of HDPE, PMMA, and PC+ABS blend on mechanical bending properties, while the other factors which could influence the injection remain unchanged. The HDPE samples were obtained at the following injection temperatures – 180, 190, 200, 210 and 220°C – and at the following subsequent pressures – 800, 900, 1000, 1100 and 1200 bar. The PMMA samples were obtained at the following injection temperatures – 220, 230, 240, 250 and 260°C – and at the following subsequent pressures – 450, 550, 650, 750 and 850 bar. The PC+ABS samples were obtained at the following injection temperatures – 230, 240, 250, 260 and 270°C – and at the following subsequent pressures – 500 bar, 600 bar, 700 bar, 800 bar, and 900 bar. We have used the method of determining flexural properties, such as the flexural stress, flexural deformation, and flexural modulus. It was observed that in the case of HDPE, the highest values of flexural stress were registered at its lowest temperature (180°C) – the flexural stress recorded 28,3038 MPa – and at the highest value of subsequent pressure (1200 bar) – the flexural stress recorded 29.3380 MPa. PC+ABS acts in a similar manner to HDPE. In the case of PC+ABS, 240°C recorded the highest value for the flexural stress of 89.2246 MPa, while the highest subsequent pressure of 900 bar recorded the highest value of flexural stress of 88.5375 MPa. In the case of PMMA, the highest value for flexural stress (124.2563 MPa) was recorded at the lowest processing temperature (220°C) and at the subsequent pressure of 550 bar, where the value of the flexural stress was of 110.5376 MPa. In the case of HDPE and PC+ABS, the flexural deformation is barely influenced by the processing temperature and the subsequent pressure, whereas in the case of the PMMA, the processing temperature and the subsequent pressure influence the flexural deformation. The increase in the subsequent pressure leads to a slight increase of the flexural modulus in the case of the three studied polymers. The increase in the processing temperatures of HDPE and PC+ABS leads to a slight decrease of the flexural modulus, whereas in the case of the PMMA, the increase in the processing temperatures barely influences the flexural stress.

Keywords: high density polyethylene (HDPE), polymethyl methacrylate (PMMA), acrylonitrile butadiene styrene polycarbonate blend (PC+ABS, flexural stress, flexural deformation, flexural modulus

Injection together with extrusion, calendaring, and thermoforming are the main technologies of manufacturing thermoplastic objects. Through injection, a wide range of intricately-shaped objects of different sizes can be moulded, namely cellulose acetate, general-purpose polystyrene, shock-resistant polystyrene, acrylonitrile butadiene styrene, polyamides, low-density and high-density polyethylene, polypropylene, polyoxymethylenes, polycarbonates, polyvinyl chloride, fluoropolymers, thermoplastic polyesters, polysulphones, polyaryl-etherketones, thermoplastic polyurethanes, methyl polymethacrylate, and various blends of polymers [1]. The properties and uses of HDPE, PMMA, and PC+ABS blend are specified in a series of recently published series of papers [2-11].

Forming through injection is a cyclical process, every cycle is comprised of several operations, such as the dosage of the material, the heating and melting of the material in the cylinder of the machine, the closing of the mould, the introduction of the molten material under pressure in the mould, the solidification and cooling of the material in the mould, the support distance of the mould and the taking out of the injected piece from the mould [12]. The main factors which determine the process of forming are: chemical and physical properties, properties regarding the flow of the thermoplastic material in specific conditions of the injection process, the temperature regimen, the pressure regimen, and the duration necessary to the forming.

The temperature regimen consists of the temperature of the cylinder of the injection machine and the temperature of the mould. The melting the thermoplastic material is done through the transfer of heat from the wall of the cylinder to the material or through the transformation by friction of the mechanical energy into thermal energy. The more the temperature of the thermoplastic material is higher, the more it is more fluid, and the mould fills faster, and the injection times are reduced. The temperature of

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the mould is crucial in the cooling process and the solidification of the injected piece.

The pressure regimen consists of the external pressure (on the thermoplastic material in the cylinder of the injection machine), internal pressure (the pressure inside the mould cavity), subsequent pressure (the pressure done by the barrel–nozzle on the thermoplastic material in the mould cavity), sealing pressure (pressure done on the thermoplastic material in the mould cavity when the intake solidifies), and the internal remnant pressure (the pressure of the injected piece when the mould opens).

The duration of the forming depends on the characteristics of the polymer, the dimensions of injected piece, and the cooling system of the mould [9].

The characteristics of the products obtained through the injection of the thermoplastic materials are influenced by the aforementioned factors and were presented in recent papers [13-18]. In recent years, a series of research papers was published regarding the mechanical behaviour of different types of polymers in different conditions [19-30].

This paper proposes in the first part to analyze the variation of the flexural properties (flexural stress, flexural deformation, and the flexural modulus) dependent on the processing temperature by injection, when other factors that could influence the process remain unchanged, for the high-density polyethylene HDPE type CABELEC XS6114, for the polycarbonate and acrylonitrile butadiene styrene blend PC+ABS type CYCOLOY RESIN XCY620, and for the polymethyl methacrylate PMMA type PLEXIGLAS 8N CRYSTAL. The paper proposes in the second part to present the influence of the subsequent pressure in the forming by injection of the HDPE, PMMA, and PC+ABS blend on the mechanical properties of flexure, when other factors that could influence the forming remain unchanged.

Experimental part

The following materials have been used in manufacturing the specimens: high-density polyethylene HDPE type CABELEC XS6114, polymethyl methacrylate PMMA type PLEXIGLAS 8N CRYSTAL, and polycarbonate and acrylonitrile butadiene styrene blend PC+ABS type CYCOLOY RESIN XCY620, using a KRAUSS MAFFEI KM65-160C1 injection machine, made in 2001 (fig.1).

The first part of the experiment focuses on the influence of the injection temperature on flexural properties. Measuring the temperature of the material in its flow state was done with the help of thermocouples fixed on the plastification–injection cylinder. The HDPE samples were obtained at the following injection temperatures: 180, 190, 200, 210 and 220°C. The PMMA samples were obtained at the following injection temperatures: 220, 230, 240, 250 and 260°C, and the PC+ABS samples at the following injection temperatures: 230, 240, 250, 260, and 270°C. During the injection of the HDPE, PMMA and PC+ABS specimens, all parameters that influence the cycles of injection were kept constant, altering only the injection temperatures. Injection of HDPE specimens was done by keeping the following injection parameters constant: subsequent pressure of 850 bar, mould temperature of 20°C, cooling time of 10 s, injection speed of 12 mm/s, and injection cycle of 44 s. Injection of PMMA specimens was done by keeping the following injection parameters constant: subsequent pressure of 450 bar, mould temperature of 70°C, cooling time of 12 s, injection speed of 30 mm/s, and injection cycle of 35.8 s . Injection of PC+ABS specimens was done by keeping the following injection parameters constant: subsequent pressure of 600 bar, mould temperature of 60°C, cooling time of 10 s, injection speed of 25 mm/s, and injection cycle of 30.8 s.

Fig.1. KRAUSS MAFFEI KM65-160C1 injection machine

The second part of the experiment focuses on the influence of the subsequent pressure on the flexural properties. The HDPE samples were obtained at the following subsequent pressures: 800 bar, 900 bar, 1000, 1100 and 1200 bar. The PMMA samples were obtained at the following subsequent pressures: 450 bar, 550 bar, 650 bar, 750 bar, and 850 bar. The PC+ABS samples were obtained at the following subsequent pressures: 500, 600, 700, 800 and 900 bar. During the injection of HDPE, PMMA, and PC+ABS sample, all the other factors which could influence the injection process remain unchanged, changing only the subsequent pressures. Injection of HDPE specimens was done by keeping the following injection parameters constant: injection temperature 220°C, mould temperature of 20°C, cooling time of 10 s, injection speed of 12 mm/s, and injection cycle of 44 s. Injection of PMMA specimens was done by keeping the following injection parameters constant: injection temperature 260°C, mould temperature of 70°C, cooling time of 12 s , injection speed of 30 mm/s, and injection cycle of 35.8 seconds. Injection of PC+ABS specimens was done by keeping the following injection parameters constant: injection temperature 270°C, mould temperature of 60°C, cooling time of 10 s, injection speed of 25 mm/s, and injection cycle of 30.8 s.

All samples were injected at S.C. Plastor S.A, Oradea and were tested for flexural properties at room temperature in the Laboratory of Advanced Materials at the Institute of Research, Development, Innovation, and Technical and Natural Sciences under the aegis of the “Aurel Vlaicu” University of Arad. Determining the flexural properties was made on model specimens with the shape and size of the one presented in figure 2.

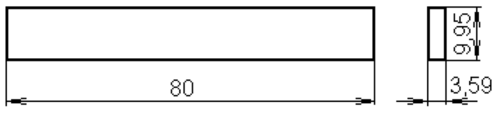

Fig.2. Model specimen for the testing of flexural properties

Testing was done in accordance with European norms SR EN ISO 178:2011 [31] using a MTS Criterion Model 43 trial machine made in USA in 2015 (fig.3).

The specimen has a right-angled transversal section leaning on two bolsters and it undergoes flexing with the help of a mandrel acting on the specimen at the middle distance between bolsters (fig.4).

The specimen is bent like this with a constant speed at the middle of the support distance, until the exterior of the specimen breaks or until there is a maximum deformation of 5% – whichever occurs first. During this trial, we

Fig.3. MTS Criterion Model 43 trial machine made in USA

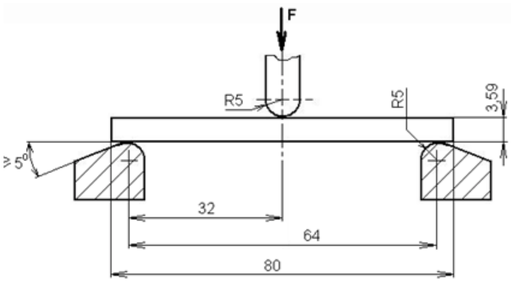

Fig.4. The position of the specimen at the start of the trial

measured the force applied at the middle distance to the specimen and the resulting arrow. The trial speed was of 6 mm/min.

We used the following equation for the flexural stress (σ_f):

$$\sigma_f = \frac{3FL}{2bh^2}, \qquad [MPa] \qquad (1)$$

where:

σ_f – flexural stress

F - the force, in N

L – the support distance, in mm

b – the width of the specimen, in mm

h – the thickness of the specimen, in mm

Testing was done in accordance with European norms SR EN ISO 178:2011 and the specimens had a 64 mm support distance. In the case of the MTS Criterion Model 43 trial machine, the computer software automatically displays the values of the forces applied in newtons and the value of the arrows in millimetres. For every injected probe at a certain temperature and subsequent pressure, 5 samples were tested and the result was conveyed as arithmetic mean.

We used the following equation for the flexural deformation (ε_f):

$$\varepsilon_f = \frac{600sh}{L^2}, \qquad [\%] \qquad (2)$$

where:

ε_f – the flexural deformation

s – the arrow, in millimetres

h – the thickness of the specimen, in mm

L – the support distance, in mm

To determine the flexural modulus, we calculated the arrows s_1 and s_2 according to the values of the flexural deformations ε_{f1} = 0,.005 and ε_{f2} = 0.0025, using the following equation:

$$s_i = \frac{\varepsilon_{fi} L^2}{6h}, \qquad (i = 1 \text{ or } 2) \qquad (3)$$

s_i – one of the arrows, in millimeters

ε_{fi} – the corresponding flexural deformation, whose values $[_{f1}$ and $[_{f2}$ are designated above

L – the support distance, in mm

h – the thickness of the specimen, in mm

We calculated the flexural modulus E_f (in megapascals) using the following equation:

$$E_f = \frac{\sigma_{f2} - \sigma_{f1}}{\varepsilon_{f2} - \varepsilon_{f1}}, \qquad [MPa] \qquad (4)$$

where:

σ_{f1} – flexural stress measured at arrow s_1, in megapascals

σ_{f2} - flexural stress measured at arrow s_2, in megapascals

Results and discussions

For every tested specimen with the MTS Criterion Model 43 trial machine, we obtained the value of the force applied (in newtons) and the value of the arrow (in millimetres). Figure 5 presents the variation of the arrow depending on the force applied for one of the 5 specimens of PC+ABS injected at 240°C.

The results that were centralized after having tested the HDPE samples regarding the influence of the processing temperature on the flexural stress, flexural deformation, and the flexural modulus are presented in table 1.

Increasing the processing temperature from 180°C to 220°C leads to a decrease in the applied force from 37.8082 N to 32.2838 N, and to a decrease in the flexural stress from 28.3038 MPa to 24.1682 MPa. Increasing the processing temperatures influences the HDPE CABELEC XS6114 behaviour in a similar manner to shock and tension, where the highest values of the Izod shock resistance and the highest values of the tensile strength at break were registered at the lowest processing temperatures [32].

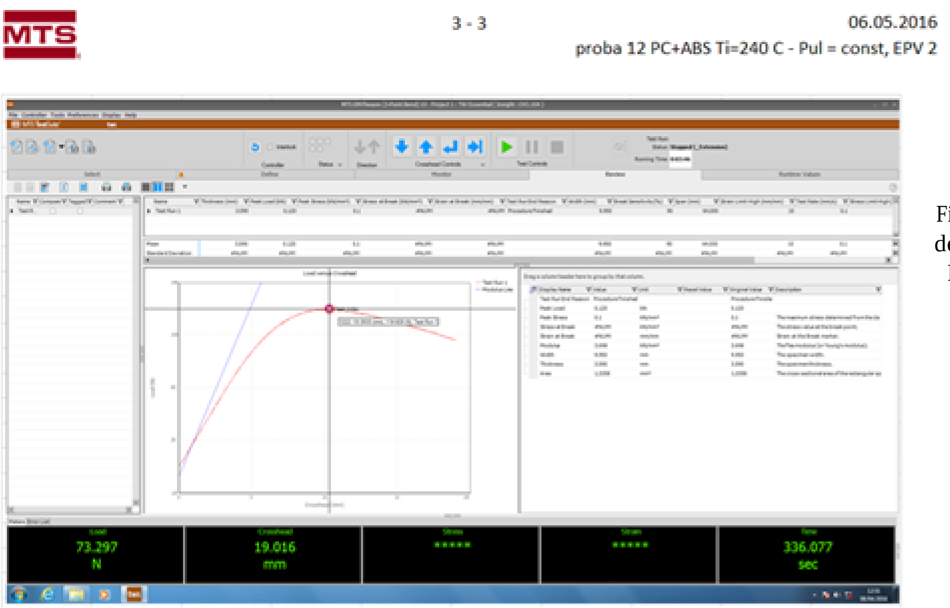

Fig.5. The variation graph of the arrow depending on the force applied on the PC+ABS specimen injected at 240°C

Table 1
THE FLEXURAL STRESS, THE FLEXURAL DEFORMATION, AND THE FLEXURAL MODULUS ON HDPE CABELEC XS6114, DEPENDING ON THE PROCESSING TEMPERATURE

Processing temperature [°C]	Applied force [N]	Arrow [mm]	Flexural stress [MPa]	Flexural deformation [%]	Flexural modulus [MPa]
180	37.8082	13.4272	28.3038	7.0611	1592
190	36.5514	13.0386	27.3630	7.0394	1376
200	34.9772	13.0443	26.1845	6.8597	1399
210	33.8546	12.8116	25.3441	6.7274	1379
220	32.2838	13.0684	24.1682	6.8724	1364

Tabelul 2
THE FLEXURAL STRESS, THE FLEXURAL DEFORMATION, AND THE FLEXURAL MODULUS ON PMMA PLEXIGLAS 8N CRYSTAL, DEPENDING ON THE PROCESSING TEMPERATURE

Processing temperature [°C]	Applied force [N]	Arrow [mm]	Flexural stress [MPa]	Flexural deformation [%]	Flexural modulus [MPa]
220	165.9813	11.8465	124.2563	6.2298	3742
230	161.2035	9.8284	120.6795	5.1685	3731
240	115.5647	5.0702	86.5136	2.6663	3837
250	113.8690	5.0570	85.2442	2.6594	3824
260	133.5555	6.7042	99.9818	3.5256	3789

Flexural deformation is barely influenced by the processing temperature. The highest value of the flexural modulus (1592 MPa) was recorded at the lowest processing temperature (180°C), and the lowest value of the flexural modulus (1364 MPa) was recorded at the highest processing temperature (220°C). The results that were centralized after having tested the PMMA samples regarding the influence of the processing temperature on the flexural stress, flexural deformation, and the flexural modulus are presented in table 2.

Increasing the processing temperature from 220°C to 250°C leads to a decrease in the applied force from 165.9813 N to 113.8690 N, and to a decrease in the flexural stress from 124.2563 MPa to 85.2442 MPa. The further increase in temperature to 260°C leads to a slight increase in both the applied force (133.5555 N) and the flexural stress (99.9818 MPa). Increasing the processing temperatures influences the PMMA PLEXIGLAS 8N CRYSTAL behaviour in a similar manner to shock and tension [32]. Flexural deformation is influenced by the processing temperature and presents the highest value (6.2298%) at the lowest processing temperature (220°C) and the lowest value (2.6594%) at the processing temperature of 250°C. Flexural modulus is barely influenced by the processing temperature and has the highest value of 3837 MPa at the processing temperature of 240°C. The results that were centralized after having tested the PC+ABS samples regarding the influence of the processing temperature on the flexural stress, flexural deformation, and the flexural modulus are presented in table 3.

Increasing the processing temperature from 230 to 240°C leads to a slight increase in the applied force from

Table 3
THE FLEXURAL STRESS, THE FLEXURAL DEFORMATION, AND THE FLEXURAL MODULUS ON PC+ABS CYCOLOY RESIN XCY620, DEPENDING ON THE PROCESSING TEMPERATURE

Processing temperature [°C]	Applied force [N]	Arrow [mm]	Flexural stress [MPa]	Flexural deformation [%]	Flexural modulus [MPa]
230	116.2280	10.1378	87.0102	5.3313	2721
240	119.1860	10.0975	89.2246	5.3101	2919
250	117.1210	10.2982	87.6787	5.4156	2868
260	114.4765	9.7943	85.6989	5.1506	2824
270	113.5127	10.2598	84.9774	5.3954	2705

Subsequent pressure [bar]	Applied force [N]	Arrow [mm]	Flexural stress [MPa]	Flexural deformation [%]	Flexural modulus [MPa]
800	34.3091	12.8879	25.6843	6.7775	1364
900	32.6011	12.4339	24.4057	6.5387	1466
1000	33.2684	13.4350	24.9052	7.0652	1597
1100	37.6054	12.9630	28.1520	6.8169	1828
1200	39.1897	13.1475	29.3380	6.9139	1719

Table 4
THE FLEXURAL STRESS, THE FLEXURAL DEFORMATION, AND THE FLEXURAL MODULUS ON HDPE CABELEC XS6114, DEPENDING ON THE SUBSEQUENT PRESSURE

Subsequent pressure [bar]	Applied force [N]	Arrow [mm]	Flexural stress [MPa]	Flexural deformation [%]	Flexural modulus [MPa]
450	133.5555	6.7042	99.9818	3.5256	3789
550	147.6560	8.0094	110.5376	4.2120	3851
650	127.7707	5.9181	95.6512	3.1122	3919
750	135.5925	6.4671	101.5067	3.4009	3978
850	135.5506	6.1942	101.4753	3.2574	3931

Table 5
THE FLEXURAL STRESS, THE FLEXURAL DEFORMATION, AND THE FLEXURAL MODULUS ON PMMA PLEXIGLAS 8N CRYSTAL, DEPENDING ON THE SUBSEQUENT PRESSURE

Table 6
THE FLEXURAL STRESS, THE FLEXURAL DEFORMATION, AND THE FLEXURAL MODULUS ON PC+ABS CYCOLOY RESIN XCY620, DEPENDING ON THE SUBSEQUENT PRESSURE

Subsequent pressure [bar]	Applied force [N]	Arrow [mm]	Flexural stress [MPa]	Flexural deformation [%]	Flexural modulus [MPa]
500	113.0050	10.2196	84.5973	5.3743	2683
600	113.5127	10.2598	84.9774	5.3954	2705
700	115.4713	9.7921	86.4436	5.1495	2788
800	117.5097	10.0797	87.9696	5.3007	2794
900	118.2682	10.2371	88.5375	5.3835	2802

116.2280 N to 119.1860 N, in the flexural stress from 87.0102 MPa to 89.2246 MPa, and in the flexural modulus from 2721 MPa to 2919 MPa, followed by a further increase in the processing temperature from la 240°C to 270°C which leads to a decrease in the applied force from 119.1860 N to 113.5127 N, to a decrease in the flexural stress from 89.2246 MPa to 84.9774 MPa, and to a decrease in the flexural modulus from 2919 MPa to 2705 MPa. Increasing the processing temperatures influences the PC+ABS CYCOLOY RESIN XCY620 behaviour in a similar manner as shock and tension [32]. The flexural modulus is barely influenced by the processing temperature. The results that were centralized after having tested the HDPE samples regarding the influence of the subsequent pressure on the flexural stress, flexural deformation, and the flexural modulus are presented in table 4.

Increasing the subsequent pressure from 800 bar to 900 bar leads to a slight decrease in the flexural stress from 25.6843 MPa to 24.4057 MPa. A further increase of the subsequent pressure from 900 bar to 1200 bar leads to an increase in the flexural stress from 24.4057 MPa to 29.3380 MPa. We observed that the highest value of the subsequent pressure (1200 bar) is recorded at the highest value of the flexural stress, namely 29.3380 MPa. HDPE CABELEC XS6114 presents almost the same behaviour to the variation of tensile strength at break and tension according to the subsequent pressure, in other words the increase in the subsequent pressure leads to an increase in the tensile strength at break and tension [33]. The flexural deformation is barely influenced by the subsequent pressure. Increasing the subsequent pressure from 800 bar to 1100 bar leads to an increase in the flexural modulus, from 1364 MPa to 1828

MPa. The results that were centralized after having tested the PMMA samples regarding the influence of the subsequent pressure on the flexural stress, flexural deformation, and the flexural modulus are presented in table 5.

We observed that the flexural stress is influenced by the subsequent pressure and also that the highest value of the flexural stress of 110,5376 MPa was recorded at the subsequent pressure of 550 bar. The flexural deformation is also influenced by the subsequent pressure – its highest value of 4,2120% is recorded at the same subsequent pressure of 550 bar. Increasing the subsequent pressure leads to a slight increase in the flexural modulus and its highest value of 3978 MPa is recorded at a subsequent pressure of 750 bar. The results that were centralized after having tested the PC+ABS samples regarding the influence of the subsequent pressure on the flexural stress, flexural deformation, and the flexural modulus are presented in table 6.

Increasing the subsequent pressure from 500 to 900 bar leads to a increase in the flexural stress from 84,5973 MPa to 88,5375 MPa. It also has almost the same behaviour to the variation of tensile strength at break and tension according to the subsequent pressure [33]. The flexural deformation is barely influenced by the subsequent pressure. Increasing the subsequent pressure from 500 bar to 900 bar leads to a slight increase in the flexural modulus, from 2683 MPa to 2802 MPa.

Conclusions

The variation of the flexural properties (flexural stress, deformation, and modulus) were studied in first part according to the processing injection temperature, when other factors which could influence the process remain unchanged for the high-density polyethylene HDPE CABELEC XS6114, for the polymethyl methacrylate PMMA PLEXIGLAS 8N CRYSTAL, and acrylonitrile butadiene styrene polycarbonate blend PC+ABS CYCOLOY RESIN XCY620. In the second part of the paper, we studied the influence of the subsequent pressure in the injection process of HDPE, PMMA, and PC+ABS blend on the flexural properties, when the other factors which could influence the process remain unchanged. The HDPE samples were obtained at the following injection temperatures – 180, 190, 200, 210 and 220°C – and at the following subsequent pressures – 800 bar, 900 bar, 1000 bar, 1100 bar, and 1200 bar. The PMMA samples were obtained at the following injection temperatures – 220, 230, 240, 250 and 260°C – and at the following subsequent pressures – 450, 550, 650, 750 and 850 bar. The PC+ABS samples were obtained at the following injection temperatures – 230, 240, 250, 260 and 270°C – and at the following subsequent pressures – 500, 600, 700, 800 and 900 bar. The samples were injected with the help of a KRAUSS MAFFEI KM65-160C1 injection machine. The flexural properties were determined on model samples according to SR EN ISO 178:2011 with the help of a MTS Criterion Model 43 trial machine made in the USA in 2015.

We observed that the highest values of the flexural stress for HDPE CABELEC XS6114 and PC+ABS CYCOLOY RESIN XCY620 were obtained at low temperatures and at the highest subsequent pressures. In the case of PMMA PLEXIGLAS 8N CRYSTAL, the highest value of flexural stress was recorded at the lowest processing temperature (220°C) and at subsequent pressure of 550 bar. In the case of HDPE CABELEC XS6114 and PC+ABS CYCOLOY RESIN XCY620, the flexural deformations are barely influenced by the processing temperature and subsequent pressure, whereas in the case of PMMA PLEXIGLAS 8N CRYSTAL, the processing temperature and subsequent pressure influence the flexural deformation. Increasing the subsequent pressure leads to a slight increase in the flexural modulus in the case of the three studied polymers. Increasing the processing temperatures of HDPE and PC+ABS leads to a slight decrease in the flexural modulus, whereas in the case of PMMA the increase in processing temperatures barely influences the flexural modulus.

The obtained results are fully accordant with the data pertaining to the literature, which states that in order to obtain high-quality injected pieces with minimal contraction in volume, the filling of the mould cavity is done at a high pressure [1, 6, 12].

We recommend the manufactured pieces of HDPE CABELEC XS6114, PC+ABS CYCOLOY RESIN XCY620, and PMMA PLEXIGLAS 8N CRYSTAL which require high resistance to flexure be made by injection at low processing temperatures and high subsequent pressures.

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