Advances in Science and Technology
Research Journal
Volume 7, No. 19, Sept. 2013, pp. 79–87
DOI: 10.5604/20804075.1062380

Research Article

INVESTIGATION OF THE INFLUENCE OF MOLD ROTATIONAL SPEED ON THE CAST WALL THICKNESS IN THE ROTATIONAL MOLDING PROCESS

Tomasz Jachowicz[1], Janusz W. Sikora[1]

[1] Department of Polymer Processing, Mechanical Engineering Faculty, Lublin University of Technology, 36 Nadbystrzycka Str., 20-618 Lublin, Poland e-mail: t.jachowicz@pollub.pl; janusz.sikora@pollub.pl

Received: 2013.06.20
Accepted: 2013.08.07
Published: 2013.09.06

ABSTRACT
This paper presents the rotational molding process. The general principles of this polymer processing technology have been described. The main applications have been introduced and leading advantages and typical disadvantages of rotational molding process have been discussed. Based on the conducted experimental tests, the influence of changing one selected technological parameter, which characterized rotational molding process, on selected geometrical features of the polymer cast has been determined. Rotational mold's speed around axes was changed and a thickness of cast walls has been measured. Laboratory test stand, processing properties of polymer, also test program and experimental test methodology have been described.

Keywords: rotational molding process, mold rotational speed, polymer cast.

INTRODUCTION

The technological process of polymer molding can be divided into normal and rotational molding as well as slush molding and casting [3, 6]. In the rotational molding process, material in a liquid or plasticized state is placed in a mold form and subjected to centrifugal action or, additionally, to external pressure. In rotational molding, the mold is rotated around two or more axes at the same time, sometimes with an auxiliary circular motion [2, 7]. In centrifugal casting, which is a type of rotational molding, the mold is rotated around one axis only [4, 14].

Rotational molding is predominantly used to produce tanks, tubes, collar tubes, containers, lids, cases, canoes, and other axially symmetric parts, especially those which cannot be produced using other methods of polymer processing due to their exceptionally large external dimensions [3, 7]. Other from the advantages of the rotational molding technology, in contrast to different methods of production of hollow elements such as blow molding [17], there is the profitable influence of the processing shrink on removing the cast from the casting mold. The material applied to rotational molding has to have the shape of the powder or microgranules, what it gets the special methods of extruding the most often [16] using special extruder machines with the diverse construction [15].

The rotational molding process consists of a correct relation between rotational speeds around the axes, as it fundamentally affects both material flow direction and its even distribution in the mold [2, 6, 7]. Adequate technological parameters for the rotational molding process, such as an appropriate ratio of rotational speed around the main axis and auxiliary one, is fundamental to produce casts with the required wall thickness. The adequate parameter selection also entails good mixing, which ensures appropriate polymer homogenization in the mold; in effect, the polymer mechanical strength is adequate and its other properties are satisfactory. Hence, the cast meets the expected functional properties and high quality [4, 6]. Most often, the speed ratio is determined in manufacturing conditions for particular cast types only by means of experimental tests and is a business secret.

The available literature offers descriptions of studies in the rotational molding process dealing with melt polymer motion in the mold [1, 8], heat exchange between mold and polymer [18], and the behavior of various polymers in this process [5, 10, 19]. A development of modern calculation methods in recent years has led to developing programs which allow for the simulation of phenomena occurring during the rotational molding process [11, 12, 13, 20], mainly phenomena such as polymer heating [18], flow [1] and cooling [11], thanks to which the production preparation period is less time consuming and errors can be eliminated at the stage of developing cast design (examples of such special software are Rotolog and RotoSim as well as COMSOL, a multi-purpose computer program which allows for modeling and simulating various physical phenomena, including some aspects of rotational molding).

The present paper describes the experimental tests undertaken to examine the influence of rotational speeds of two axes of the mold on wall thickness of casts produced in the rotational molding process.

EXPERIMENTAL

Test stand

To determine the influence of the ratio between main axis speed and auxiliary axis speed of the mold in rotational molding on wall thickness of produced casts, experimental tests were performed using a laboratory machine for rotational molding available in the Department of Polymer Processing at Lublin University of Technology. The cast shape resembled a rectangular cube, and some of its edges were rounded (to facilitate the removal of the cast).

The machine control system allows for gearless speed change of both the main and auxiliary axes. The main axis speed can be adjusted within the range from 0 to 33 rpm, whereas the auxiliary axis speed is changed within the range from 100 to 0% of the main axis speed. This means that at 100%, the auxiliary axis makes as many rotations as the main axis, while at 0% the mold rotation around the auxiliary axis is stopped, as a result of which it is possible to realize the centrifugal molding process (in which the mold rotates around the main axis only) instead of rotational molding. Changing the rotational speeds of the main and auxiliary axes is done independently, which therefore makes it possible to adjust the reciprocal ratio of the main axis speed to the auxiliary axis speed. Such a possibility is vital for adequate selection of both rotational speeds, which will ensure that casts with adjustable wall thicknesses can be produced. Figure 1 shows this laboratory machine for rotational molding.

The rotational molding machine consists of the following systems:

- a rotational system,
- a heating system,
- a base equipped with a casing and a fan for cooling the mold,
- a control and regulation system.

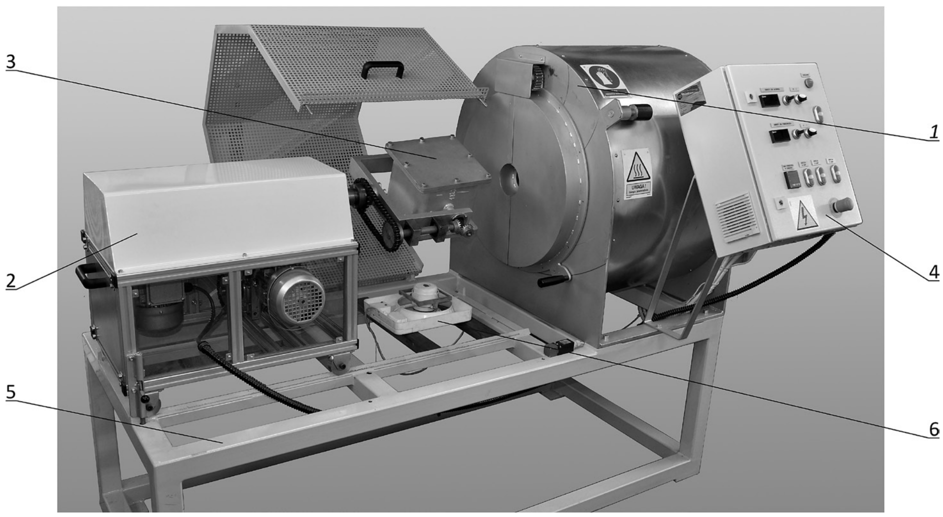

Fig. 1. Laboratory machine for rotational molding: 1 – heating system, 2 – rotational system, 3 – mold, 4 – control and regulation system, 5 – base, 6 – fan

The rotational system of the machine consists of the following elements: a main axis rotation unit, an auxiliary axis rotation unit, a mold, a support structure, a main axis rotation power unit, and an auxiliary axis rotation power unit. The support structure of the machine is in a form of a spatial frame made of aluminum angles. On the frame, the power units of arm and mold rotation as well as bearing casings are mounted. The road wheels make it possible for the rotational system to move along the rails in the machine base so that the mold can be placed in the heating chamber [9].

The heating system consists of a heating chamber and temperature sensors that transmit signals to the control and regulation system. The chamber consists of a chamber jacket, heaters, insulation, a chamber plate and a chamber door.

The rotational and heating systems as well as the rotational system casing and the fan for cooling the mold are mounted on the base.

The control and regulation system ensures that the rotational speed of the mold around the main and auxiliary axes can be changed; the system also allows for adjusting and stabilizing temperature inside the heating chamber (using resistance heaters and thermostats) [9].

Technical data of the rotational molding machine are given in Table 1.

Table 1. Technical data of rotational molding machine [20]

Technical parameter	Value
Mold maximum dimensions, mm	200 x 200 x 200
Main axis maximum speed, rpm	33
Auxiliary axis maximum speed, rpm	33
Rotation unit weight, kg	80
Heating unit with base weight, kg	300
Machine total weight, kg	400
Mold form dimensions, mm	180 x180 x 180
Mold rotation power, kW	0.25
Arm rotation power, kW	0.25
Heating chamber power, kW	12

Tools used

The mold shown in Figure 2 is made of steel plates. Their surface, which makes the internal walls of the mold, is polished to facilitate removal of the molded cast. The mold is closed from the top and bottom by means of heads which are screwed to the collars. There are journals welded to the two mold plates; the journals are at the same time mounted to the bearings located in the arm. On the longer journals there is a bevel gear which communicates rotational motion [9].

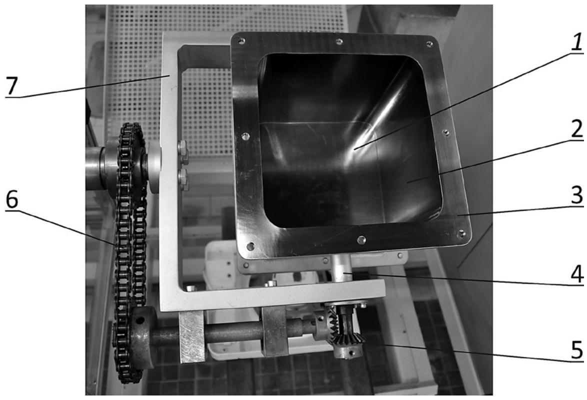

Fig. 2. Auxiliary axis rotation unit and mold for rotational molding: 1 – bottom head of mold, 2 – mold plate, 3 – collar for fastening upper head, 4 – journal bearing, 5 – bevel gear, 6 – chain transmission, 7 – arm

Polymer used in the experiment

The polymer used in the experiment was LUPOLEN 3621 M RM, a medium-density polyethylene PE-MD in a powder form, produced by LyondellBasell Industries. This polyethylene kind is used particularly in the rotational molding process due to its good flow rate to density ratio, as well as its good tensile impact strength and thermal stability. The melt flow rate of this polymer is 7.5 g/10 min (at a temperature of 190 °C and load of 2.16 kg) and its density is 935.5 kg/m^3 [9]. Its Vicat softening temperature is 113 °C, and the recommended processing temperature range is 180–210 °C. Its mechanical properties are as follows: tensile modulus – 700 MPa, tensile stress at yield – 17 MPa, tensile strain at yield – 10%, tensile impact strength at a temperature of –30 °C – 104 kJ/m^2, tensile impact strength at a temperature of 23 °C – 213kJ/m^2 [9].

Experimental test program

In the experimental tests, auxiliary axis speed was considered a variable factor. Given the capabilities of the control and regulation system of the rotational molding machine, it was assumed that auxiliary axis speed n_{sa} was 100, 80 and 60% respectively of the main axis speed n_{pa}. Table 2 shows values of coefficient R_{oR}, or the ratio of main axis speed n_{pa} to auxiliary axis speed n_{sa}, calculated with the formula [6]:

$$R_{oR} = \frac{n_{pa}}{n_{sa}} \tag{1}$$

Table 2. Values of n_{pa}, n_{sa} and R_{oR}

No.	Axis speed		Coefficient
	main axis speed n_{pa}, rpm	auxiliary axis speed n_{sa}, rpm	R_{oR}
1	30	30	1
2		24	1.25
3		18	1.67

The factor examined directly was the thickness of wall b of the produced cast. In order to describe changes in thickness of particular walls of the cast depending on the ratio between main axis speed n_{pa} and auxiliary axis speed n_{sa}, the coefficient of cast wall thickness, $W_{bs,}$ was determined; it was calculated as the ratio of wall thickness in a given measuring point of the cross section to average wall thickness in a given section. If the value of W_{bs} is greater than 1, it means that the cast walls are thicker, especially in the corners and on the edges of the rectangular cast, whereas W_{bs} lower than 1 means that the cast walls are thinner, what can be particularly noticed in their geometric center.

The constant factors included such technological parameters of rotational molding as: main axis speed of 30 rpm and polymer weight of 300 g. The dwell time of the mold in the heating chamber was 20 minutes, while the cooling time of the mold was 25 minutes. The temperature inside the heating chamber was 230 °C and cooling air flow rate was 300 m^3/h.

The disturbing factors included changes in ambient temperature, polymer humidity, air relative humidity and voltage fluctuations in the mains supply. It has been observed that these disturbing factors have no significant effect on the experiment results.

Experimental test methodology

In order to produce casts, 30 g batches of LUPOLEN 3621 MRM were prepared using a laboratory scales. After checking if the bottom head was installed accurately, the mold was filled with the prepared polymer. Next, the upper head of the mold was installed and tight fixed. After starting the rotational motion around the main and auxiliary axes and setting appropriate speed values of n_{pa} and n_{sa}, the rotating mold was placed in the heating chamber of the rotational molding machine heated to a temperature of 230 °C. After 20 minutes, the mold was removed from the chamber and then cooled for 25 minutes. The rotating mold was cooled in an airflow generated by a fan. After cooling the mold and stopping its rotational motion, the upper and bottom heads of the mold were unscrewed and the produced cast was hand removed.

The process of rotational molding was performed three times; each time the mold speed around the auxiliary axis was decreased according to the adopted experimental test program. Figure 3 shows one of the produced casts.

The wall thickness of the produced casts was measured using a slide caliper equipped with a digital measuring device. In order to make the measurements, the casts were cut in three reciprocally perpendicular planes S1, S2 and S3 shown in Figure 4. The cast walls were denoted in the following way: C denote the walls adjacent to the mold walls connected to the journal bearings, W denote the walls perpendicular to the main axis of rotation, while P denote the walls which are adjacent to the upper and bottom heads closing the mold. The measuring points in which the thickness of the sides of the cast was measured were disposed in even spaces, measuring approx. 10 mm.

Fig. 3. Cast produced in rotational molding

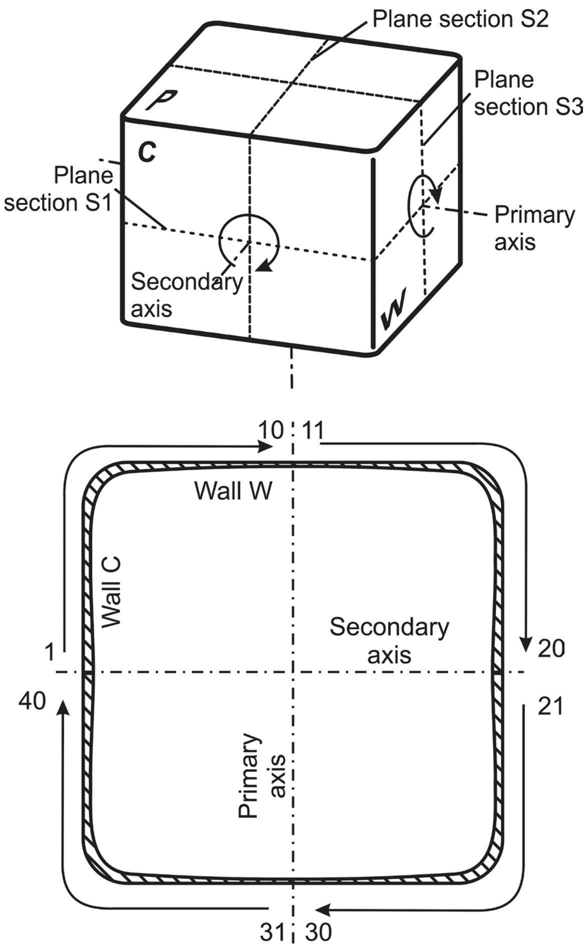

Fig. 4. a) positions of plane sections S1, S2 and S3 relative to main and auxiliary axes of rotation, b) example of position of measurement points at plane section S1

EXPERIMENT RESULTS

Figures 5, 6 and 7 present changes in average wall thickness depending on a quarter of the cross section shape obtained after cutting the cast by planes S1, S2 and S3. Increasing R_{oR} caused a clear change in the melt polymer movement and the forming of walls *C* and *W* of the cast. At R_{oR} = 1, in the geometric centre of walls *C* in the thermal centre resulting from the mass concentration of the journal bearings, average wall thickness was 2.81 mm and as R_{oR} was increasing, average wall thickness was decreasing to 2.46 mm and 2.36 mm respectively, which corresponds to a decrease in wall thickness by 12% and 16%. An increase in R_{oR} led to a decrease in cast wall thickness in the rounded corners (in plane section S1) from 3.36 mm at R_{oR} = 1 to 2.66 mm at R_{oR} = 1.25 and 2.11 mm at R_{oR} = 1.67, which corresponds to a decrease in the rounded corner thickness by 20 and 37%. The highest value of wall thickness, over 5 mm, was measured in the acute corners (of plane sections S2 and S3), which is shown in Figures 6 and 7. In the plane perpendicular to the main axis of rotation, the wall thickness on the cast edges changed from 5.32 mm to 4.60 mm, together with an increase in R_{oR}, whereas in the plane perpendicular to the auxiliary axis of rotation, a change in the value of R_{oR} had no significant effect on changing the wall thickness on the cast edge – it changed from 5.30 mm to 5.18 mm together with an increase in R_{oR} (Fig. 7).

Figure 8 shows the effect of speed ratio R_{oR} values on average thickness of walls *C*, *P* and *W*, determined in the geometric centre of these walls. The highest value of average thickness can be noted in the case of walls *C*, which resulted from an unfavorable distribution of the mold material mass, that is – the journal bearings connected to the relevant mold walls. An increase in R_{oR} led to a proportional decrease in average wall thickness, the most considerable decrease was observed in the case of walls *C* (from 2.68 mm to 2.27 mm, which corresponds to 15%). In the case of *P* walls, a decrease in thickness was smaller, by 12%, from 0.92 mm to 0.81 mm, yet it occurred already at R_{oR} = 1.25. Average thickness of walls *W*, determined in their geometric centre (hence on the main axis of rotation) decreased the least, by 10% (from 0.87 mm to 0.78 mm), and it did not occur until R_{oR} was of 1.67.

In order to describe the extent of changes in the thickness of particular walls, depending on the ratio between the main axis speeds n_{pa} and auxiliary axis speeds n_{sa}, wall thickness coefficient W_{bs} was calculated. In the areas where cast walls were thicker, W_{bs} was greater than 1, which could especially be observed in the corners and on the edges of the cast, whereas when W_{bs} was smaller than 1, it meant that the cast walls had a decreased thickness, which was especially noticeable in the central area of the cast walls. Figure 9 illustrates changes in the values of coefficient W_{bs} depending on the ratio of main axis speed to auxiliary axis speed, determined in plane section S1. The higher the difference between the mold speed around the main axis and its rotational speed around the auxiliary axis, the more evident the change in cast wall thickness, especially on the walls parallel to the mold axis of rotation. At R_{oR} = 1, the changes in W_{bs} ranged approx. from 0.60 to 1.3, while at the maximum difference between main axis speed n_{pa} and auxiliary axis speed n_{sa}, at

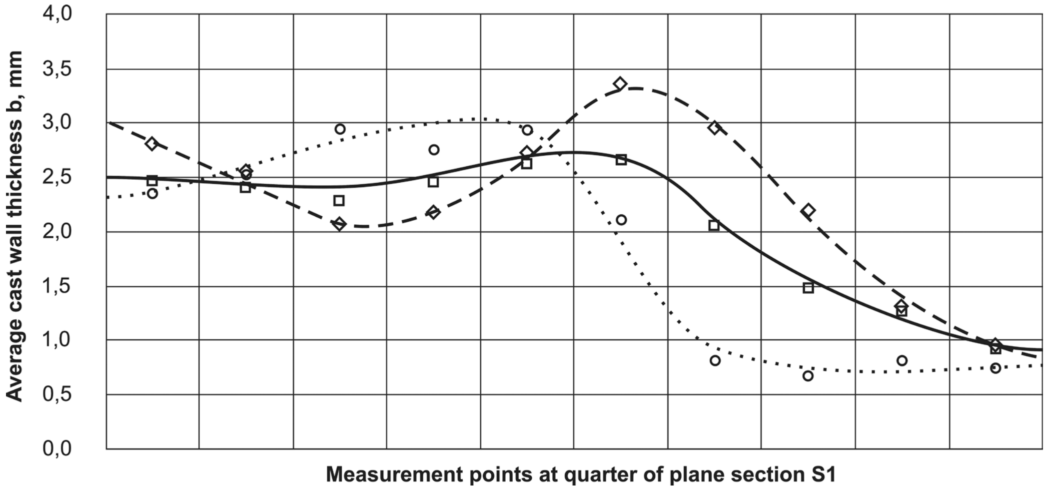

Fig. 5. Changes in average cast wall thickness *b* in plane section S1: $R_{oR} = 1$ (full line), $R_{oR} = 1.25$ (dashed line), $R_{oR} = 1.67$ (dotted line)

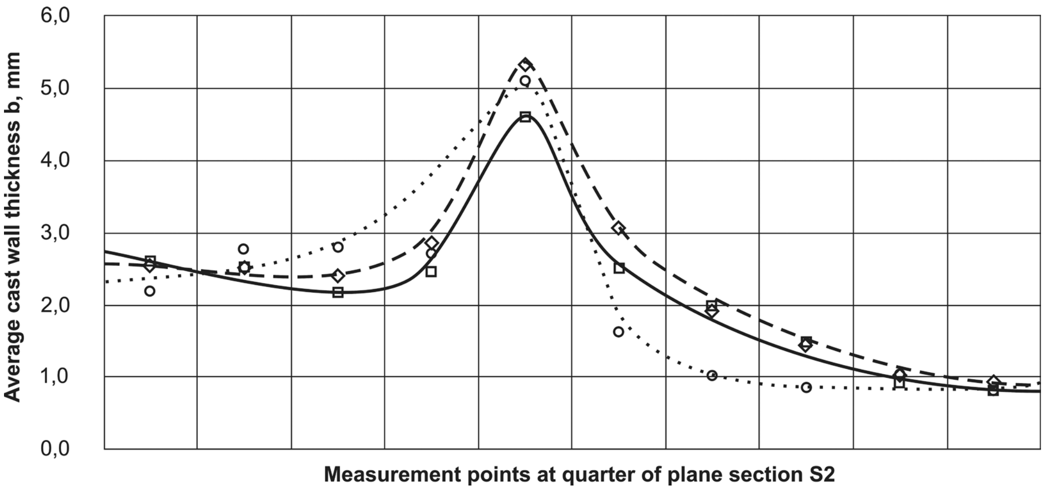

Fig. 6. Changes in average wall thickness *b* in plane section S2: $R_{oR} = 1$ (full line), $R_{oR} = 1.25$ (dashed line), $R_{oR} = 1.67$ (dotted line)

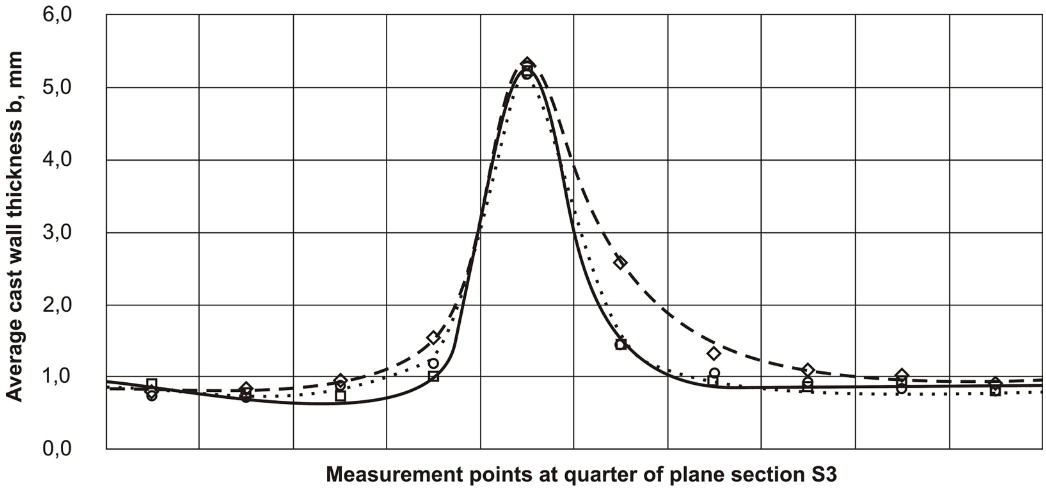

Fig. 7. Changes in average wall thickness *b* in plane section S3: $R_{oR} = 1$ (full line), $R_{oR} = 1.25$ (dashed line), $R_{oR} = 1.67$ (dotted line)

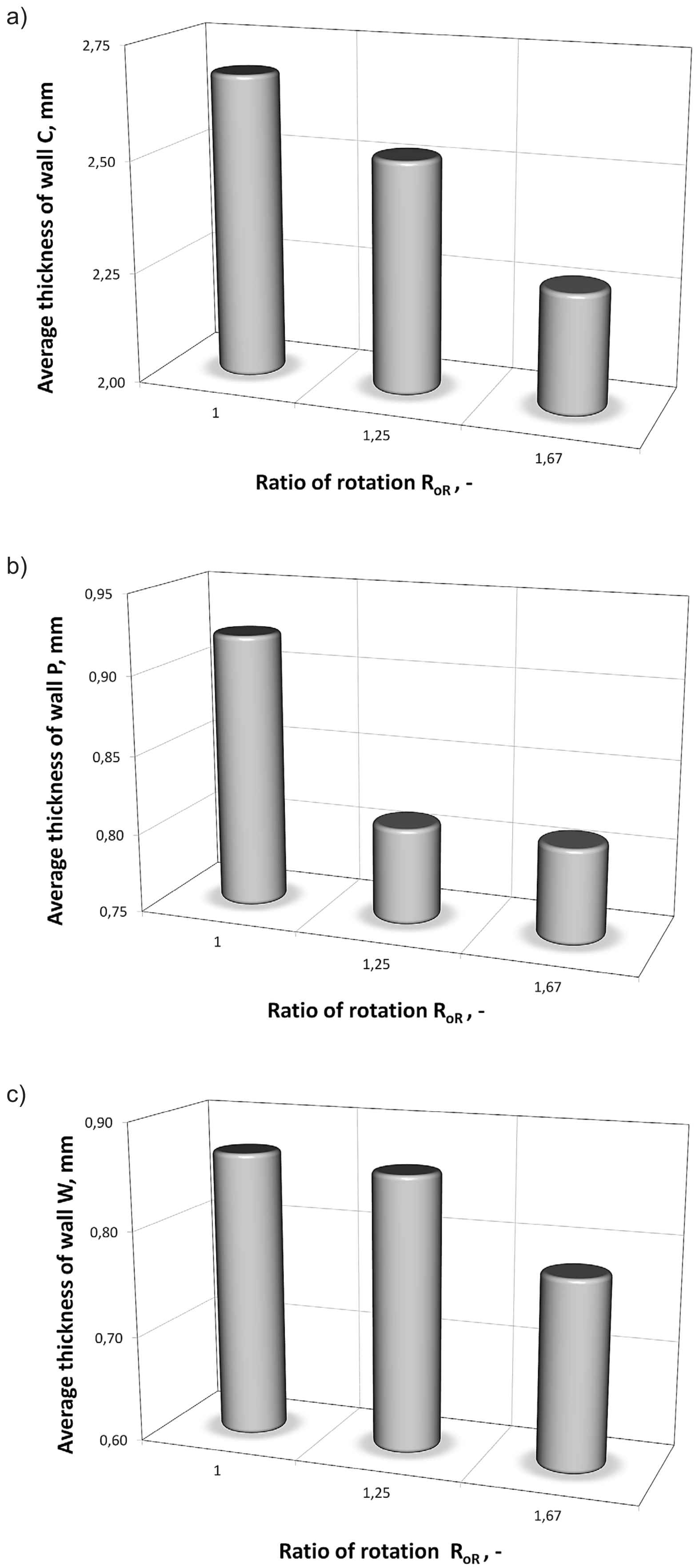

Fig. 8. Dependence of average wall thickness determined in geometric centre of cast on speed ratio R_{oR}: a) wall *C*, b) wall *P*, c) wall *W*

$R_{oR} = 1.67$, differences in the value of W_{bs} ranged from approx. 0.20 up to 1.6.

The results obtained in the experimental tests undertaken to investigate the influence of the changing speed ratio R_{oR} on wall thickness of casts produced by rotational molding, allowed for evaluating the unevenness of wall thickness of the produced casts. An increase in the value of R_{oR} meant a clear difference in wall thicknesses, which resulted in decreased thickness in their geometric centre, while the walls were thicker in the corners and on the edges. Owing to this, the casts in a form of rectangular cubes with varying rigidity were produced; the more rigid the casts were, the greater amount of polymer moved towards the cast edges, yet the wall strength was relatively small, which results in worse functional properties of these casts. Decreasing the auxiliary axis speed led to a change in the movement of the plasticized polymer along the walls parallel to this axis, while a relative increase in the main axis speed caused that the melt polymer moved away from walls W which were the least thick. Moreover, it was observed that walls *C* were clearly thicker in their geometric centre, which is the area where, in terms of the design, the mold was connected to the journal bearings. This metal mass concentration whose thickness was higher than on walls *W* and *P* leads to the occurrence of a thermal centre that keeps the polymer in the plasticized state in this area longer and leads to uneven cast cooling. As a result, particles of the melt polymer can adhere to this increased temperature area more easily, creating in this way a thicker layer. Compared to the other walls, wall *C* is nearly twice as thick at $R_{oR} = 1$. The unfavorable wall thickness distribution in plane section S3 was corrected by setting the ratio R_{oR} to a value of 1.25, which is illustrated by the dotted line in Figure 9. However, it should be noticed that such a solution is not optimum – the wall thickness is partially uniform near the journal bearings where the thermal centres occur, yet the thickness of the other walls is decreased because the melt polymer is affected by the centrifugal forces of varying values, which results from a difference between the main axis speed and auxiliary axis speed.

CONCLUSIONS

Based on the conducted experimental tests undertaken to investigate the influence of the speed ratio R_{oR} of two axes of rotation on wall thickness of casts in form of rectangular cubes produced in the rotational molding process, the following has been observed:

- an increase in R_{oR} leads to a decrease in average thickness of all cast walls in their geometric centre, which proves that the polymer mass moves towards the corners of the mold form; the largest decrease in average wall thickness has been observed on walls *C* perpendicular to the auxiliary axis of rotation,
- changing values of R_{oR} results in the smallest differences in wall thickness in plane section S3 parallel to the main axis of rotation and perpendicular to the auxiliary axis of rotation; the curves illustrating changes in wall thickness in particular measuring points in these cutting planes are similar,

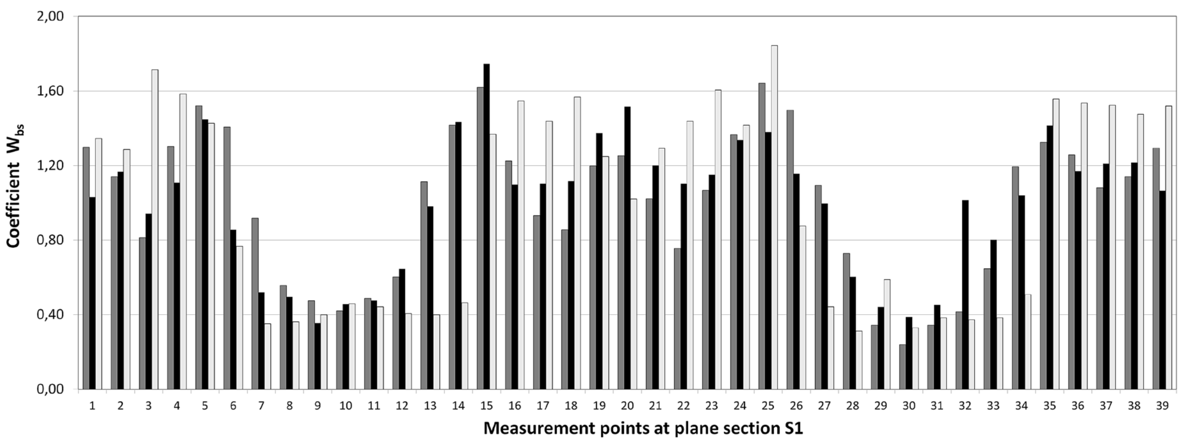

Fig. 9. Changes in values of W_{bs} depending on speed ratio R_{oR} determined in plane section S1: $R_{oR} = 1$ (grey bar), $R_{oR} = 1.25$ (black bar), $R_{oR} = 1.67$ (white bar)

- changing values of R_{oR} result in clear differences in wall thickness in plane section S1 that overlaps with the main and auxiliary axes of rotation of the mold,
- increasing values of R_{oR} in plane section S1 causes a gradual increase in wall thickness in the direction from the auxiliary axis of rotation to the cast corner (of wall C) and a decrease in wall thickness in the direction from the cast corner to the main axis of rotation (of wall W), and the most favorable change in wall thickness has been observed at $R_{oR} = 1.25$,
- differences of several percent in speeds of both axes entail a clear change in wall thickness which equals tens of percent. In the experiments it was found that decreasing the speed of one axis by 20% leads to a several percent difference between the thickness of the thickest wall and the narrowest one in the pointwise symmetric cast, which allows for formulating a speculation that it may have a negative effect on strength properties of such cast, for example its rigidity,
- as for the mold used to produce casts for the experimental tests, an unfavorable effect of extensive mold material mass concentration has been observed (in the area where the journal bearings were located and where the thermal centers occurred), which leads to unevenness of mold cooling and affects negatively wall thickness uniformity.

REFERENCES

1. Aissa A.A., Duchesne C., Rodrigue D.: Characterization of polymer powder motion in a spherical mold in biaxial rotation. Polymer Engineering & Science, 52, 2012. 953-963.
2. Anandha Rao M., Throne J. M.: Principles of rotational molding. Polymer Engineering and Science, 12, 4, 2004, 237-264.
3. Beall G., Throne J.: Hollow Plastic Parts: Design and Manufacture. Hanser Gardner Publications, USA, Cincinnati 2004.
4. Beall G.: Rotational Molding. Design, Materials, Tooling and Processing. Hanser Gardner Publications, USA, Cincinnati 1998.
5. Calò E., Massaro C., Terzi R.: Rotational Molding of Polyamide-6 Nanocomposites with Improved Flame Retardancy. International Polymer Processing, 27, 2012, 370-377.
6. Crawford R., Kearns M.: Practical Guide to Rotational Moulding. Rapra Technology Limited, UK, Shawbury 1998.
7. Crawford R., Throne J.: Rotational Moulding Technology. William Andrew Inc., USA, New York 2002.
8. Gogos G.: Bubble removal in rotational molding. Polymer Engineering & Science, 44, 3 2004, 88-394.
9. Information taken from the following websites: Clips Poly Engineering, Fixopan, Metalchem Toruń, Naroto, Persico, Plastigi, Rotoline, Rotomachinery Group, Roto Plastic International, Roto Plastics, R.S. Engineers, LyondellBasell Industries, and others.
10. Kulikov O., Hornung K., Wagner M.: Novel Processing Additives for Rotational Molding of Polyethylene. International Polymer Processing, 05, 2009, 452-462.
11. Lim K.K., Ianakiev A.: Modeling of rotational molding process: Multi-layer slip-flow model, phase-change, and warpage. Polymer Engineering & Science, 46, 7, 2006, 960-969.
12. Olson L.G., Crawford R., Kearns M., Geiger N.: Rotational molding of plastics: Comparison of simulation and experimental results for an axisymmetric mold. Polymer Engineering & Science, 40, 8, 2000, 1758-1764.
13. Olson L. G., Gogos G., Pasham V.: Axisymmetric finite element models for rotational molding. International Journal of Numerical Methods for Heat & Fluid Flow, 9, 5, 1999, 515-542.
14. Rusu G., Rusu M., Rusu E., Stolieru A., Teaca C. A.: Direct centrifugal molding of nylon 6-based product from ϵ-caprolaktam. Polymer - Plastics Technology and Engineering, 39, 2000, 233-247.
15. Sikora J.W.: Chapter 5. Screw Extrusion. In Advances in Polymer Processing: From macro to nano scales, Eds. Sabu T., Yang W. Oxford - Cambrigde - New Delhi, Wodhead Publishing Limited 2009.
16. Sikora J. W.: Review: Increasing the Efficiency of the Extrusion Process. Polymer Engineering and Science, 48, 9, 2008, 1678-1682.
17. Sikora R., Jachowicz T.: Wpływ czasu ochładzania na skurcz przetwórczy wytworów otrzymanych metodą wytłaczania z rozdmuchiwaniem. Polimery, 45, 2000, 713-719.
18. Sobotka V., Perot E., Maazouz A., Delaunay D.: Experimental Analysis of Heat Transfer in Rotational Molding Process. International Polymer Processing, 01, 2008, 93-102.
19. Szostak M.: Wpływ recyklatów PE na właściwości wyrobów odlewanych rotacyjnie. Inżynieria i Aparatura Chemiczna, 5, 47, 2008, 47-48.
20. Wang F., Yao W.G., Qiao C.D., Jia Y.X.: Finite element analysis of the physical gelation process of PVC plastisol during rotational molding. Acta Polymerica Sinica, 9, 2012, 1035-1041.