A PRELIMINARY STUDY ON THE ROTATIONAL MOLDING PROCESS

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Abstract: *The rotational molding is a manufacturing method that allows obtaining parts with hollow form by rotating a mold around two perpendicular axes with the part material in the liquid state. Although the manufacturing method was proposed more than one century ago, there are yet aspects less investigated and the emergence of new materials that can be processed by rotational molding also generate interesting problems for the researchers. The paper presents some theoretical considerations concerning the conditions for the liquid flow during the rotational molding process. The coordinates of a point belonging to the mold were derived, even for the case where the mold rotates around two perpendicular axes. By knowing the relations specific to the point motion, the motion speed can be expressed. The main forces acting on a small volume of liquid material, i.e., gravitational, viscous, and centrifugal forces, were taken into consideration. The resultant force ensures conditions for the penetration of the liquid material in the narrow spaces of the mold cavity. A systemic analysis was used to highlight the main input and output factors specific to the process.*

Key words: *rotational molding, liquid flow, motion trajectory, forces, systemic analysis, input factors, output factors.*

1. INTRODUCTION

In the last decades, the evolution of the human society has determined an intense use of parts made of plastics. Along the time, a large set of machining methods able to ensure the manufacturing pieces of plastic was developed. Indeed, nowadays, the plastic parts could be made by extrusion, injection molding, compression and transfer molding, casting etc. Most of such manufacturing methods are based on the use of expensive manufacturing systems. A manufacturing method appeared more than 50 years ago and which seems to find a more extended use is the so-called *rotational molding* or, in a short form, the *rotomolding*. Essentially, this method allows obtaining parts with hollow form by using the gravity [5]; a rotation of the mold around two perpendicular axes ensures the flow of the melted plastic so that finally a part with hollow form can be obtained.

An inconvenient in using the rotational molding could be considered its relatively reduced productivity (generally, the duration of the mold rotation is longer than 10 minutes); in order to diminish this inconvenient, the systems for rotational molding could include many work stations, where various stages develop simultaneously (unload-load station, heating station, cooling station etc.). Inside the mold, the temperature must be of about 375^0 C; as parts materials, the polyethylene, polypropylene, ABS, high impact polystyrene can be used. A wide variety of parts are made by rotational molding (car and truck body parts - up to 226 kg car bodies, industrial containers – up to 2 273 l, telephone booths, playing balls, canoe hulls, storage tanks, garbage cans, light globes etc.); some of the main advantages of this manufacturing process concern the possibility to obtain large hollow products, including complicated curved surfaces, a good finish and stress-free strength [11].

For melting the plastics, various heating sources are used, but in the last years, some of the new solutions were based on the mixing of two or more components, one of these components being in a liquid state; during the rotation, a hardening process develops so that finally the desired part is obtained at opening of the mold. For such a version, the manufacturing system is not so expensive or it can be relatively easy designed and materialized; in this way, the equipment for rotational molding could be accessible inclusively to the small enterprises.

One has also to mention that the rotational molding could be applied in the case of big parts of plastic including hollows, when significant difficulties could appear at applying other methods for plastic parts manufacturing.

The first mention concerning the use of heat and biaxial rotation in order to produce a hollow part was included in 1 855 British patent and applied in forming of hollow metal artillery projectiles. Equipment involving a

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rotational molding was mentioned in a 1935 patent. The equipment was used for production of hollow latex objects; this patent is considered as the basis for the modern rotational molding equipments [3].

A group of researchers from New Zeeland and Northem Ireland took into consideration some ways to reduce cycle time of the rotational molding process [1]. They proposed some various techniques (combination of surface-enhanced molds, higher oven flow rates, internal mold pressure, water spray cooling) able to better exploit the advantages of the rotational molding process.

Banerjee et al. [2] proposed a heat transfer model by considering that the heat transfer to the powder at the mold-powder interface is through convection. The model was used in order to calculate the cycle time for particulate composites; a decrease of the cycle time was remarked in the case of reinforced composites, which are characterized by an increased thermal conductivity. The experiments proved the validity of the proposed model.

G. Gogos [4] described some solutions able remove the bubbles in rotational molding of polymer products. He also showed that a pressure increase imposed on a nearly saturated polymer melt could contribute to fast bubble shrinkage, this allowing a significant cycle-time shortening through elimination or reduction of the excessive heating.

Liu and Tsai [6] investigated how blowing agents could influence the rotational molding process and the product quality; they noticed that the blowing agents improve the impact properties of the foamed polyethylene products, but they can also generate longer cycle times, uneven surfaces, increase of shrinkage and decrease of the warpage.

Liu and Peng [7] showed that higher cooling rates applied in the rotational molding of polycarbonate reinforced polyethylene composites allow the obtaining products characterized by higher impact strengths, but lower tensile strengths. They analyzed various mathematical models, in order to predict the tensile properties of molded composites.

Olinek et al. [8] studied the flow characteristics of polymer particles during the rotational molding process; they noticed that certain segregation occurs when particles had smooth surfaces and regular shapes. They proposed to improve the product quality by acting on the heating rate and rotation sped.

In a paper published in 2008, Pethrick and Hudson [10] showed that the influence of temperature on the viscosity could be appreciated as a significant factor in bubble release and maintenance of wall thickness in thick-walled mouldings. They proposed a simplified model of the rotational mouldings process, in order to highlight the appropriate relationships describing the processing cycle.

Perot et al. investigated the relationship among the material structure, the process and the final properties in the case of using a polymer powder; afterwards, they proposed a heat transfer model during the process [10].

2. THEORETICAL CONSIDERATIONS

As above mentioned, the rotational molding process is based on the rotation of the mold including the plastic in a liquid state around two perpendicular axes (Fig. 1).

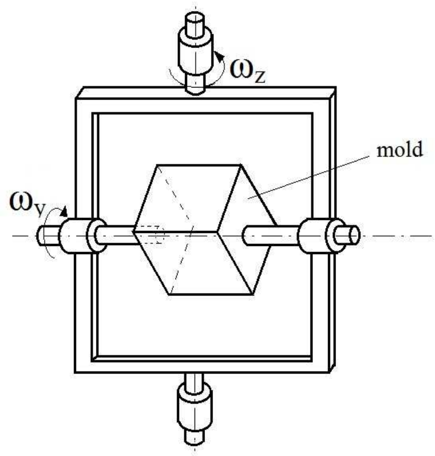

Fig. 1. Rotation of the mold around two axes perpendicular each other.

Due to the rotational motions, the liquid flows into the mold coating the internal surfaces. As one can see, the liquid flow along the internal walls of the mold is essentially determined by the gravity and not by the centrifugal force. Due to the two rotation motions, the trajectory of a point belonging to the mold is complex. Let us take into consideration a coordinate system *Oxyz* (Fig. 2) and a point *M* that belongs to the mold and whose projections are M_x, M_y, M_z, on the semi axes *Ox*, *Oy* and *Oz*, M_h – on the horizontal plane *Oxy*, M_v on the vertical plane *Oyz* and M_l on the lateral plane *Oxz*. The position of the point *M* is characterized (fig. 2) by the radius *R*, the angle λ between the plane *Oxz* and the semi axis *Oz* (colatitude) and the angle α between the plane *Ozx* and the plane defined by the points *O*, *M* and M_h.

The Cartesian coordinates of the point *M* are the following:

$$\begin{cases} x_M = R \cdot \sin\lambda \cdot \cos\alpha \\ y_M = R \cdot \sin\lambda \cdot \sin\alpha \\ z_M = R \cdot \cos\lambda \end{cases} . \qquad (1)$$

In Fig. 2, the angle β was also included; this angle is formed by the segment OM_x and OM_l and it is necessary when characterizing the rotation of the mold round of the semi axes *Oy* and *Oz*. The writing of the angle λ as a function of the angles α and β is therefore necessary. From the triangle OMM_z, one can write:

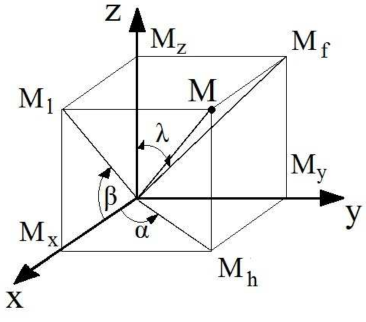

Fig. 2. Position of a point belonging to the mold.

$$\cos\lambda = \frac{OM_z}{R}. \quad (2)$$

But $OM_z=M_lM_x$; form the triangle OM_xM_l, the following relation can be written:

$$\tan\beta = \frac{M_lM_x}{x_M}, \quad (3)$$

or:

$$\tan\beta = \frac{M_lM_x}{R\sin\lambda\cos\alpha}. \quad (4)$$

In this way, one can write:

$$M_lM_x = R\sin\lambda\cos\alpha\tan\beta. \quad (5)$$

Taking into consideration the last equality, the relation (2) becomes:

$$\cos\lambda = \frac{R\sin\lambda\cos\alpha\tan\beta}{R} \quad (6)$$

or

$$\cos\lambda = \sin\lambda\cos\alpha\tan\beta. \quad (7)$$

From the last relation, one can write:

$$\tan\lambda = \frac{1}{\cos\alpha\tan\beta}. \quad (8)$$

or

$$\lambda = \arctan\frac{1}{\cos\alpha\tan\beta}. \quad (9)$$

The Cartesian coordinates of the point *M* become:

$$\begin{cases} x_M = R\cdot\sin\left(\arctan\dfrac{1}{\cos\alpha\tan\beta}\right)\cdot\cos\alpha \\ y_M = R\sin\left(\arctan\dfrac{1}{\cos\alpha\tan\beta}\right)\cdot\sin\alpha \\ z_M = R\cdot\cos\left(\arctan\dfrac{1}{\cos\alpha\tan\beta}\right) \end{cases}. \quad (10)$$

As consequence of the mold rotations around the semi axes *Oy* and *Oz*, with the angular speed ω_y,…, ω_z, instead of the angle α, the angle $\alpha+\omega_z t$ and instead of the angle β, the angle $\beta + \omega_y t$ could be considered, *t* being the time.

The equations system becomes:

$$\begin{cases} x_M = R\cdot\sin\left[\arctan\dfrac{1}{\cos(\alpha+\omega_z t)\cdot\tan(\beta+\omega_y t)}\right]\cdot \\ \cdot\cos(\alpha+\omega_z t) \\ y_M = R\cdot\sin\left[\arctan\dfrac{1}{\cos(\alpha+\omega_z t)\cdot\tan(\beta+\omega_y t)}\right]\cdot \\ \cdot\sin(\alpha+\omega_z t) \\ z_M = R\cdot\cos\left(\arctan\dfrac{1}{\cos(\alpha+\omega_z t)\cdot\tan(\beta+\omega_y t)}\right) \end{cases}. \quad (11)$$

It is known that the angular speed ω could be put in connection with the rotation speed *n* (rotations per minute) by means of the relation:

$$\omega = \frac{\pi n}{30}. \quad (12)$$

Of course, there is the possibility to use distinct rotation speeds around two considered axes.

The viscosity refers to resistance of a fluid which is being deformed by either shear or tensile stress and it characterizes the internal resistance to flow; sometimes, the viscosity is considered as *a fluid friction*.

One can take into consideration the dynamic viscosity, the cinematic viscosity and the Engler conventional viscosity, respectively.

The dynamic viscosity η is a coefficient of proportionality included in the relation of the tangential tension τ: (shearing stress between two planes parallel with the direction of flow):

$$\eta = \frac{\tau}{\dfrac{dv}{dr}}, \quad (13)$$

where $\dfrac{dv}{dr}$ is the velocity gradient at right angles to the direction of flow.

The kinematic viscosity υ corresponds to the ratio between the dynamic viscosity η and the fluid density ρ:

$$\nu = \frac{\eta}{\rho}. \quad (14)$$

The fluidity refers to the capacity of a fluid to flow and this propriety is considered as a reciprocal of the viscosity.

The force of viscosity (or *force of internal friction*) is tangentially directed to the surface of neighboring layers and has an opposite direction to the motion direction.

In the case of laminar flow, this force is given by the Newton's relation:

$$F_{cv} = -\eta\cdot S\cdot\frac{dv}{dz}, \quad (15)$$

where η is the coefficient of dynamic viscosity, *S* – the common surface of two neighboring surfaces, and d*v*/dz is the gradient of speed (the speed variation on the length unit). In the case of the liquids, the viscosity could be explained by taking into consideration the additional forces appeared between molecules; these forces generate an additional contribution to the shear stress, but the relation between flow and viscosity is not completely known and explained. The viscosity could be measured by means of various *viscometers* and *rheometers*; the last type of apparata is used when the liquid cannot be characterized by a single value of viscosity.

During the rotational molding process, the fluid viscosity has to be high enough to ensure conditions of fulfilling the internal small cavities existing in the mold walls.

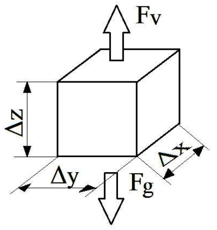

Fig. 3. Main forces acting on a small volume of liquid material.

The centrifugal force is usually defined as opposite to the centripetal force; the last concept (centripetal force) concerns the force which must be applied to a body in order to ensure to it a circular motion. In accordance with the third principle of dynamics, the centrifugal force acts simultaneously with the centripetal force and it could be determined by means of the relation:

$$F_{cf} = \frac{m \cdot v^2}{R}, \tag{16}$$

where v is the body speeds along the circular trajectory and R is the distance from the rotation center to the mass center of the rotating body.

In our case, if one considers (Fig. 3) the small volume $V = \Delta x \cdot \Delta y \cdot \Delta z$, the mass of this volume is given by:

$$m = \Delta x \cdot \Delta y \cdot \Delta z \cdot \rho, \tag{17}$$

ρ being the liquid material density.

By taking into consideration the last relation, the centrifugal force becomes:

$$F_c = \frac{(\Delta x \cdot \Delta y \cdot \Delta z \cdot \rho) \cdot v^2}{R}. \tag{18}$$

In order to write the expression of the motion speed v, the coordinate x_M, y_M, z_M of the point M could be taken into consideration.

The speed of the point motion can be written as a derivative of the functions (relation (11)) corresponding to the coordinates of the point M:

$$\begin{cases} v_x = \dfrac{dx}{dt} \\ v_y = \dfrac{dy}{dt} \\ v_z = \dfrac{dz}{dt} \end{cases}. \tag{19}$$

The derivative of the coordinates x, y and z have a complex aspect:

$$v_x = \frac{\partial x_M}{\partial t} = \frac{-R}{\tan^2(\beta+\omega_y t)} \cdot \frac{1}{\sqrt{1+\dfrac{1}{\cos^2(\alpha+\omega_z t)\cdot\tan^2(\beta+\omega_y t)}}} \cdot (1+\tan^2(\beta+\omega_y t))\cdot\omega_y - \frac{R}{\tan(\beta+\omega_y t)} \cdot \frac{1}{\sqrt{\left(1+\dfrac{1}{\cos^2(\alpha+\omega_z t)\cdot\tan^2(\beta+\omega_y t)}\right)^3}} \cdot \left(\frac{\sin(\alpha+\omega_z t)\cdot\omega_z}{\cos^3(\alpha+\omega_z t)\cdot\tan^2(\beta+\omega_y t)} + -\frac{(1+\tan^2(\beta+\omega_y t))\cdot\omega_y}{\cos^2(\alpha+\omega_z t)\cdot\tan^3(\beta+\omega_y t)}\right) \tag{20}$$

$$v_y = \frac{\partial y_M}{\partial t} = \frac{R}{\cos^2(\alpha+\omega_z t)\cdot\tan(\beta+\omega_y t)} \cdot \frac{1}{\sqrt{1+\dfrac{1}{\cos^2(\alpha+\omega_z t)\cdot\tan^2(\beta+\omega_y t)}}} \cdot \sin^2(\alpha+\omega_z t)\cdot\omega_z - \frac{R}{\cos(\alpha+\omega_z t)\cdot\tan^2(\beta+\omega_y t)} \cdot \frac{1}{\sqrt{1+\dfrac{1}{\cos^2(\alpha+\omega_z t)\cdot\tan^2(\beta+\omega_y t)}}} \cdot \sin(\alpha+\omega_z t) \cdot (1+\tan^2(\beta+\omega_y t))\cdot\omega_y - -\frac{1}{2}\frac{R}{\cos(\alpha+\omega_z t)\cdot\tan(\beta+\omega_y t)} \cdot \frac{1}{\sqrt{\left(1+\dfrac{1}{\cos^2(\alpha+\omega_z t)\cdot\tan^2(\beta+\omega_y t)}\right)^3}} \cdot \frac{2\cdot\sin^2(\alpha+\omega_z t)\cdot\omega_z}{\cos^3(\alpha+\omega_z t)\cdot\tan^2(\beta+\omega_y t)} + -\frac{2\cdot(1+\tan^2(\beta+\omega_y t))\cdot\omega_y}{\cos^2(\alpha+\omega_z t)\cdot\tan^3(\beta+\omega_y t)} + +\frac{R}{\tan(\beta+\omega_y t)} \frac{\omega_z}{\sqrt{1+\dfrac{1}{\cos^2(\alpha+\omega_z t)\cdot\tan^2(\beta+\omega_y t)}}} \tag{21}$$

$$v_z = \frac{\partial z_M}{\partial t} = = -\frac{R}{\sqrt{\left(1+\dfrac{1}{\cos^2(\alpha+\omega_z t)\cdot\tan^2(\beta+\omega_y t)}\right)^3}} \cdot \left(\frac{\sin(\alpha+\omega_z t)\cdot\omega_z}{\cos^3(\alpha+\omega_z t)\cdot\tan^2(\beta+\omega_y t)} + -\frac{1+\tan^2(\beta+\omega_y t)\cdot\omega_y}{\cos^2(\alpha+\omega_z t)\cdot\tan^3(\beta+\omega_y t)}\right) \tag{22}$$

The speed modulus is given by the relation:

$$v = \frac{ds}{dt} = \sqrt{v_x^2 + v_y^2 + v_z^2}, \tag{23}$$

where s corresponds to the relation of the point motion in the given coordinate system.

In such conditions, the centrifugal force F_c can be written by considering the relations established for the mass m and speed v:

$$F_c = \frac{(\Delta x \cdot \Delta y \cdot \Delta z \cdot \rho) \cdot \left(v_x^2 + v_y^2 + v_z^2\right)}{R_M}. \quad (24)$$

The gravity force F_g for the small volume having the dimensions Δx, Δy, and Δz can be written as:

$$F_g = m \cdot g\ , \quad (25)$$

where m is the mass of the small volume of liquid material and g – the gravitational acceleration.

If the relation (16) for the mass m is considered, the following relation can be written for the gravity force:

$$F_g = \Delta x \cdot \Delta y \cdot \Delta z \cdot \rho \cdot g\ . \quad (26)$$

Due to the rotation motions, the centrifugal force changes continuously the direction in which it acts; when the centrifugal force has a vertical direction to the Earth centre, it helps the liquid flow and the fluid penetration in the cavity placed in the bottom zone of the mold in that position.

If it necessary to ensure the liquid flow even in the position when the point M is found in a superior position (over the horizontal axis), the centrifugal force must exceed the sum of the forces corresponding to the gravity and viscosity force:

$$F_c > F_g + F_v\ . \quad (24)$$

Meeting of this condition allows to the fluid to flow and thus to penetrate in the small cavities from the mold, inclusively when the considered point is found over the horizontal rotation axis.

3. SYSTEMIC ANALYSIS

A more complex image concerning the rotational molding process could be obtained by using the systemic analysis. It is known that the systemic analysis takes into consideration an assembly or a process as a system, including input factors, output factors, disturbing and eventually intermediary factors.

In the case of the rotational molding process, one can appreciate that the main *input factors* are the following:

- physical and chemical properties of the material found in a liquid stated and introduced in the mold cavity (viscosity, capacity to adhere to the mold walls, density etc.);
- particle characteristics;
- temperature of the liquid; one accepts that usually, the higher the temperature is, the lower and the more convenient the liquid viscosity is;
- the heating rate;
- the position (distance) of the considered point to the rotation axis of the mold;
- the rotation speeds around two perpendicular axes;
- the duration of the process; during the rotation, the liquid ought to cover all the internal walls of the cavity existing in the mold and, also, to solidify in contact with these walls.

The solidification can be generated by the cooling the mold, but certain versions of the rotational molding processes can be based on chemical reactions among two or more substances found in the liquid just during the rotational molding process etc.

As *output factors*, one can take into consideration:

- the solidity (the tensile strength) of the wall of the obtained part;

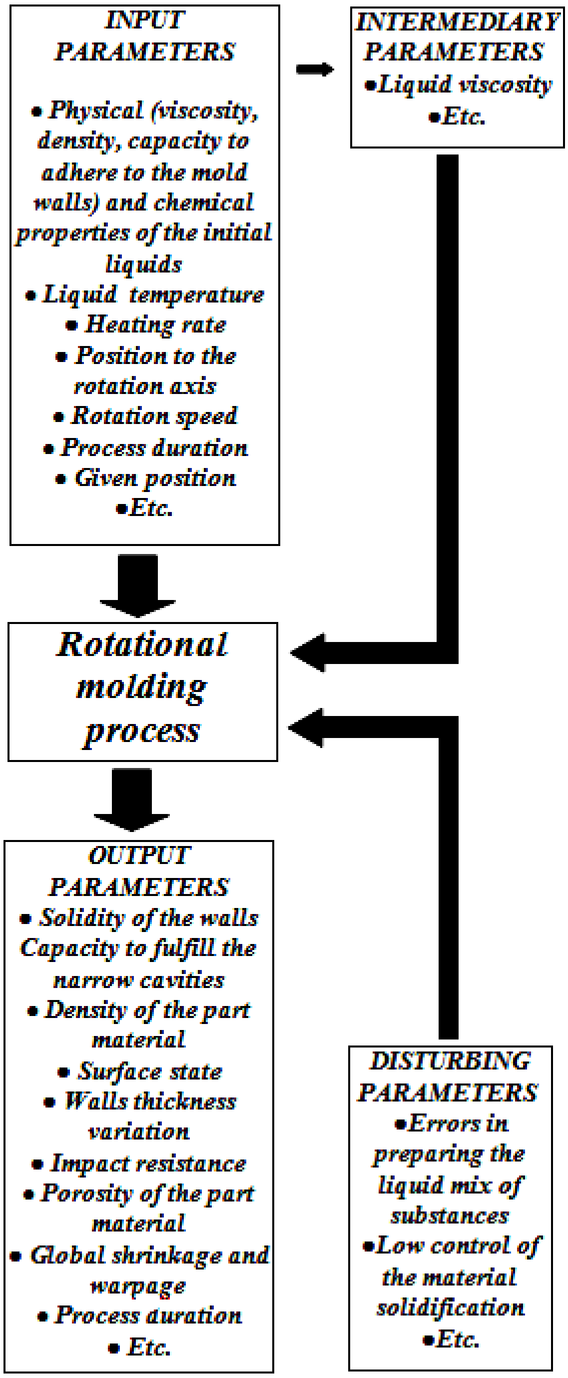

Fig. 4. Factors able to affect the rotational molding process.

- the fulfillment of the narrow cavities existing in the mold and which finally are found as narrow prominences on the obtained part;
- the density of the part material resulted by solidification;
- the surface state of the obtained part walls;
- the walls thickness variation;
- the impact properties;
- the porosity, which is a property in direct connection with the above mentioned output factor (density);
- the global shrinkage and warpage;
- even the process duration was mentioned as an input factor, one can consider also the process duration as an output factor.

Indeed, the chemical compositions of the substances mixed in order to obtain the liquid could influence the duration of the process and this means that one can take into consideration the duration of the rotational molding process also as an output factor.

In fact, the process duration offers an image about the process productivity, this being an important technological objective.

Of course, there are many *factors able to disturb* the rotational molding process:

- the errors in ensuring the specified quantities of materials used to obtain the initial liquid;
- a lower control of the material solidification in the mold; thus, if the solidification process begins too early, the premature increase of the viscosity could generate difficulties in the penetration of the liquid in the narrow cavities existing in the mold and finally the part could present shape errors etc.

Some of the above mentioned input factors and other work parameters could be also considered as *intermediary factors*; for example, the viscosity of the liquid could be put in connection with the liquid temperature.

4. CONCLUSIONS

The rotational molding is a manufacturing method based on the liquid material solidification within the mold, during the rotation of the mold around two axes perpendicular each other. Nowadays, the rotational molding is widely applied in order to obtain hollow parts of plastics. Even the productivity of the method is lower in comparison with other methods applied for obtaining plastic parts, the manufacturers prefer to use it due to the relative simplicity of the equipment and of the technology.

The new materials imposed the development of researches directed to the correct establishing of the work conditions or to improve the results of applying the rotational molding process. Some considerations were elaborated about the coordinates of a point belonging to the mold found in the motions specific to the rotational molding process.

A short examination was made in the direction of the forces which act on a small volume of liquid material and facilitate the contact of the liquid with the walls of the cavity existing in the mold.

A systemic analysis was also developed in order to highlight the main influence factors which could influence the parameters of technological interest. In the future, there is the intention to investigate the trajectory of a point belonging to the mold during the rotation motions around two perpendicular axes. There is also the intention to build a simple equipment able to be used for experimental research of the rotational molding process, in order to highlight the influence exerted by some input factors on the output parameters.

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