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OPTIMIZATION OF THE GEOMETRIC PARAMETERS OF THERMOFORMED PARTS

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Abstract: *The paper aims to optimize geometric parameters for thermoforming box-type parts made of composite materials based on vegetable fibers. The defects that appear at the thermoforming of these parts are formation of folds, excessive thinning or rupture of the material. In order to study the influence of geometric parameters, such as the corner radius and the inclination angles on the variation of the wall thickness and the formation of folds, finite element simulations were performed using Dynaform software. The force developed by the press ram in relation to the radius corners at different inclination angles was also analyzed. The simulation highlighted that the thinning of the material at the corners is reduced with the increase of the radius and the inclination angle and the strength of the ram decreases with increasing radius at the corners.*

Key words: *thermoforming, composite materials, Dynaform, finite element simulation.*

1. INTRODUCTION

Thermoplastic composite materials consist of a thermoplastic matrix and reinforcing fibers. This paper deals with problems related to thermoplastic materials reinforced with vegetable fibers (hemp, flax, poplar, willow, etc.). These materials are recyclable because by heating above the melting temperature of the thermoplastic matrix, it becomes plasticized and can be remodelled, which offers a major advantage over carbon fiber or glass composites, whose recycling is very difficult.

Most companies, especially those in the automotive and upholstered furniture industry, are looking for solutions to replace wood with recyclable composite materials that offer similar qualities. [1]

The composite material with thermoplastic matrix is made in the form of a nonwoven fibrous layer consisting of a mixture of vegetable fibers and thermoplastic fibers (polypropylene). The transformation of the composite into parts involves performing the following operations:

- Spaning - overlapping several layers of composite depending on the final thickness of the piece;
- Cutting according to a contour to ensure obtaining the finished part
- Heating over melting temperatures of the thermoplastic fiber
- Pressing in the mold in order to obtain the shape of the piece and to consolidate by cooling.

The process of obtaining the composite material by thermoforming [2] is a simple and relatively inexpensive process compared to other processes such as injection or extrusion of materials. In order to obtain the desired shape, it is necessary to heat the material on a press with heated plates at a temperature of approximately 200 ° C, following which the heated material is pressed into the mold to take its shape. The main disadvantage of this process is that it is not possible to obtain complex shaped parts or cylindrical shaped parts.

Today, Taparo [3] uses polypropylene composite materials reinforced with hemp fibers to replace the wood in the resistance structure of upholstered furniture (sofas, armchairs, chairs, etc.). [4]

The problems appeared in the thermoforming process are the defects as folds or envelopes of the material in the corner area, especially for the parts with more complex shapes. The folds leads to large variations in part thickness, resulting in surfaces with large deviations from the designed shape. Another defect that must be avoided, consists in the appearance of cracks or even ruptures of material, especially in parts with hollow shapes, with pronounced corners and sharp angles. Although these parts are later covered with sponge and textile material, which can hide the defect from thermoforming, the problem persists because the defects affect the mechanical strength or even the aesthetics of the product.

This paper aims to optimize the thermoforming process taking into account the design of a part in the form of a rectangular box made by thermoplastic composite material, with a final thickness of 4 mm. The optimization consists in performing numerical simulations having as variable parameters the corner radius R and the inclination angle α. Following the simulation, the folding, the variation of thickness and the maximum force during pressing will be analysed. The obtained results will contribute to the improvement of the quality of the thermoforming process of the prismatic parts made of natural fiber composite materials.

2. PROCESS SIMULATION USING DYNAFORM

The numerical simulation was performed using DYNAFORM software version 5.6.1. This software contains 3 modules:

- eta / DYNAFORM graphic preprocessor - is the module where data on thermoforming simulation are entered such as material characteristics (Young's modulus, Poisson's ratio, stress-strain curve data), surface to be thermoformed, material thickness, travel speed of the press ram. In this module is also introduced the mold as well as the semi-finished product in the form of a surface under the .IGS extension. [5]
- LS-DYNA solver - is the module that solves finite element analysis. [6]
- eta / POST graphic postprocessor - is the module where the obtained results are displayed regarding the obtained shape, the thickness of the part, the tensions appeared. [7]

In the case of simulating the thermoforming process, two simulations are needed for each piece. The first simulation is the gravitational placement of the blank on the core of the mold. The second simulation is the pressing of the blank placed on the mold obtaining a shape of the part according to the core and the mold.

Due to the shape of the prismatic piece, it was decided to divide it into 4 parts and use 1/4 of the piece for numerical simulation in Dynaform, in this way the time for simulation is shorter and the results are similar.

The prismatic part for which the optimization is performed is 300 x 400 x 60 mm according to figure 1 below. The 3D model was developed using SolidWorks software. In the Extrude function, the degrees 0°, 3 and 6° were introduced, and with the fillet function, the corners were rounded to 2, 4, 6, 8, and 10 mm.

The characteristics of the material as well as the methodology of numerical simulation by Dynaform was also discussed in the paper [8] where the problem of thinning the material in the area of the corners of the prismatic piece was discovered. In general, these problems appear when thermoforming the parts in the shape of a box, which was found during the application of the process at TAPARO SA.

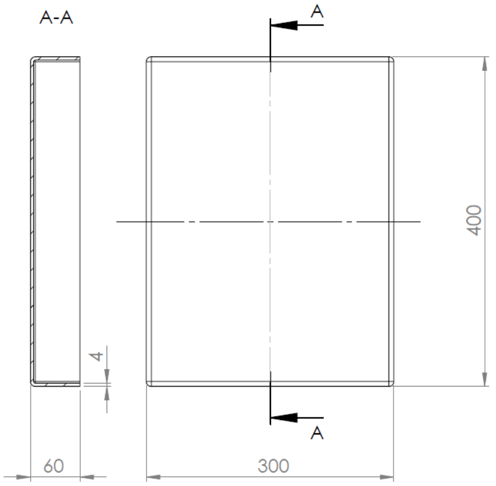

Fig. 1. Shape and dimensions of the piece

In the first stage regarding the simulation, a gravitational placement of the prismatic part will be performed, and then in another numerical simulation we will move on the Z axis of the mold press to obtain the shape between the core and the mold.

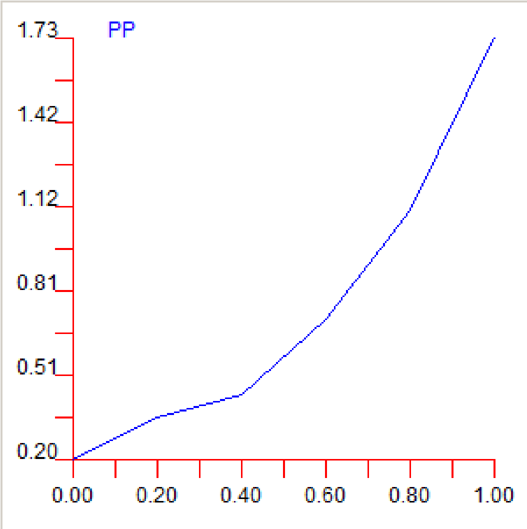

Fig. 2. Stress-strain curve

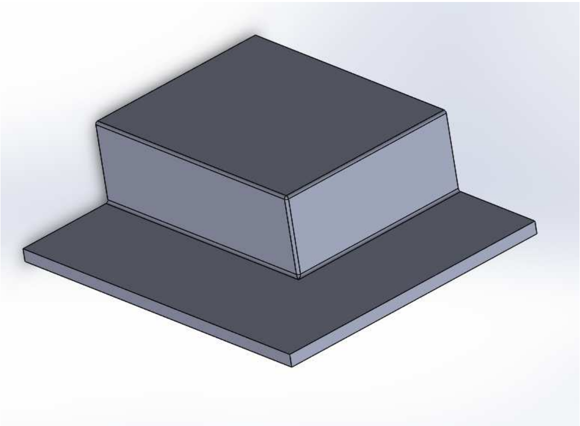

Fig. 3. The ¼ of the prismatic piece

For the finite element analysis, a size of 3.5 mm of the finite element discretization network was used.

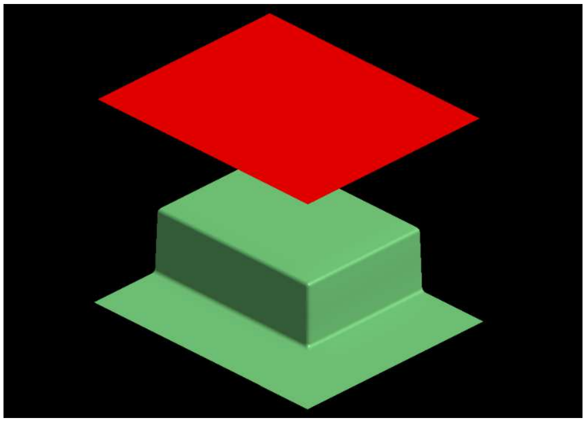

Fig. 4. Gravitational deformation

The gravitational placement of the semi-finished product can be seen in figure 4. This simulation is static and only the semi-finished product moves on the Z axis.

Fig. 5. Semi-finished product after gravitational deformation

Figure 5 shows our semi-finished composite material formed after gravitational placement. This simulated semi-finished product is introduced in the following simulation which represents the thermoforming itself.

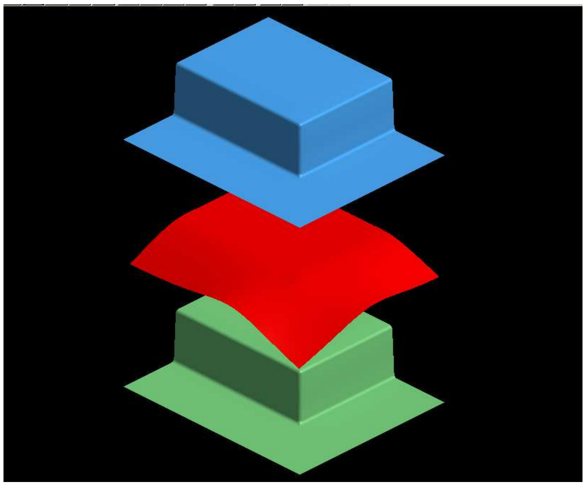

Fig. 6. Pressing into the mold

Figure 6 shows the core of the mold, the blank and the mold that makes a movement on the z axis. The moving speed of the mold on the Z axis is 500mm / s.

After obtaining the thermoformed part, it was necessary to cut the excess material so as to obtain the prismatic part. For the final evaluation, the entire model of the piece was used, considering all the four parts into which it was divided for the simulation, accordind to figure 8.

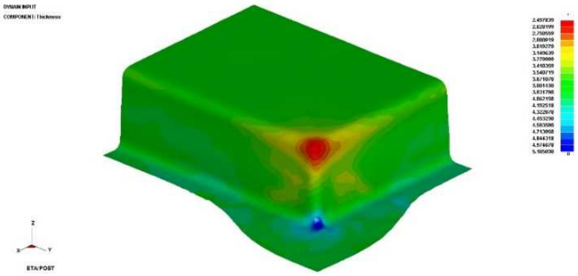

Fig. 7. Thermoformed part

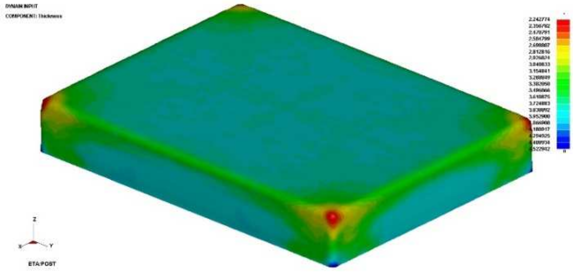

Fig. 8. Finished part

A research program was established by simulating the influence of different geometric parameters of the punch and the mold on the wall thickness of the final part and the pressing force.

In this regard, simulations were performed considering the following variable parameters (Figure 9):

1. Variable corner radius in the range 2 - 10 mm, with a pitch of 2 mm
2. The angle β of the core and the mold resulting in a finished part with an inclination of 0°, 3° and 6°.

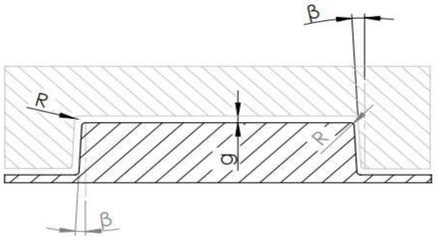

Fig. 9. Mold and core section

For all the simulations it was considered that the initial thickness (g) of the semi-finished product is 4 mm, equal to the design part thickness of the wall.

Following the study, the results were classified in table 1, resulting for each finished part: minimum thickness, maximum thickness, thickness variation and force developed by the press ram.

Table 1

Results obtained from numerical simulations

Nr. Crt	Tilt angle of the piece β [grade]	Radius at the corners [mm]	Minimum thickness g^{min} [mm]	Maximum thickness g^{max} [mm]	Variation of thicknesses Δg [mm]	The force developed by the press ram [N]
1	0°	2	1.38	3.47	2.09	1,216
2	0°	4	2.24	4.52	2.28	656
3	0°	6	2.53	4.80	2.27	695
4	0°	8	2.64	4.66	2.02	724
5	0°	10	2.81	4.76	1.95	658
6	3°	2	2.18	3.85	1.67	811
7	3°	4	2.49	4.62	2.13	677
8	3°	6	2.56	4.71	2.15	701
9	3°	8	2.72	4.71	1.99	653
10	3°	10	2.85	4.63	1.78	632
11	6°	2	2.32	4.04	1.72	666
12	6°	4	2.61	4.66	2.05	620
13	6°	6	2.62	4.69	2.07	682
14	6°	8	2.74	4.68	1.94	655
15	6°	10	2.88	5.05	2.17	605

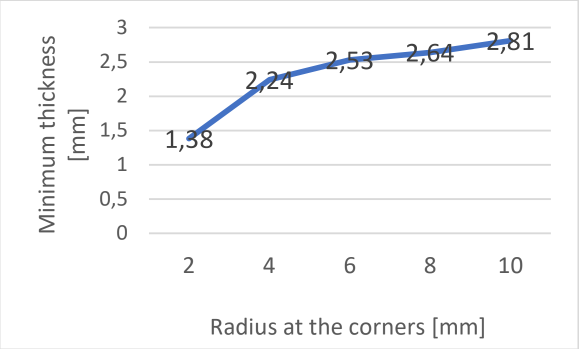

Fig. 10. Minimum thickness relative to the corner radius for the angle of part inclination of 0 °

According to the figure above, in the case of parts with an inclination angle of 0°, the increase of the minimum thickness is observed depending on the corners radius of the part. The minimum thickness is for the part with an inclination angle of 0° and a corner radius of 2 mm.

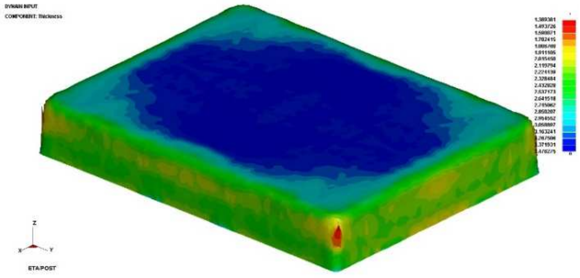

Fig. 11. Finished part with inclination angle β=0° and corner radius R=2 mm

In figure 11 we can see that the part has the maximum thickness on the top surface and the minimum thickness is in the area of the intersection between the sides.

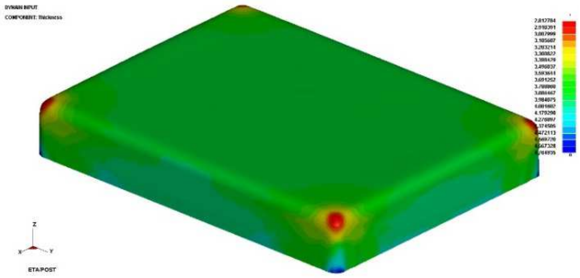

Fig. 12. Finished piece with β=0° inclination angle and corners radius R=10 mm

The piece in figure 12 is more uniform than the piece with radius R2 mm at the corners and has a minimum thickness of 2.81 mm only in the area of the intersection between the sides, being a relatively small surface.

Parts with an inclination angle of 3° show a slower increase of the minimum thickness in relation to the corner radius R according to the figure below.

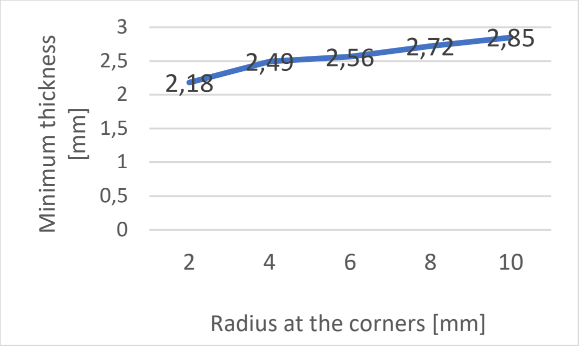

Fig. 13. Minimum thickness relative to the radius of the corners for the inclination angle of the part β of 3°

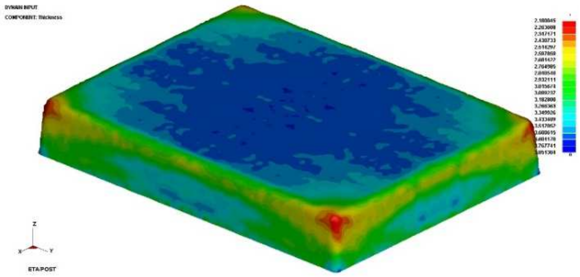

Fig. 14. Finished piece with inclination angle of β=3 ° and corners radius R=2 mm

Compared to the part with the inclination angle of 0 ° and R2 mm, the part with the inclination angle of 3 ° and R2 mm has a more distributed maximum thickness surface, instead the surface of the maximum thickness (highlighted in red) has increased.

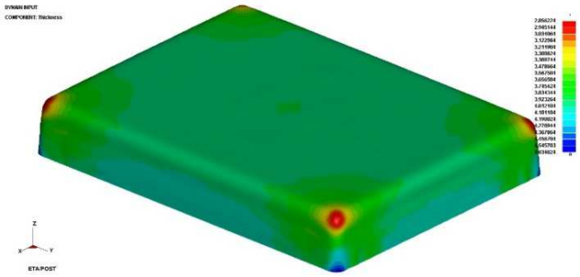

Fig. 15. Finished piece with inclination angle β=3° and radius at corners R=10 mm

Finished parts with R10 and with an inclination angle of 0° and 3° have approximately equal results in terms of shape and surfaces of minimum and maximum thickness.

The finished part with a radius at the corners of R2 mm and an inclination angle of 6 ° is better in terms of minimum thickness compared to parts with a smaller angle of inclination. According to the figure above we can see that the thickness distribution is more uniform.

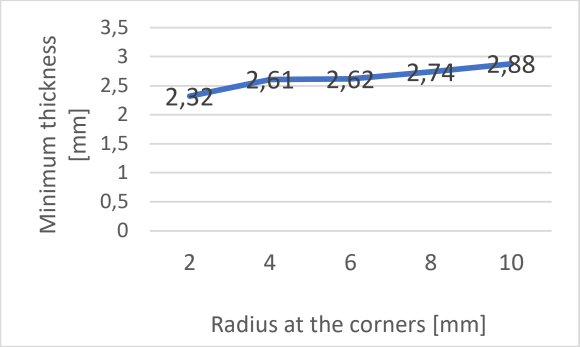

Fig. 16. Minimum thickness relative to the radius of the corners for the inclination angle β of 6°

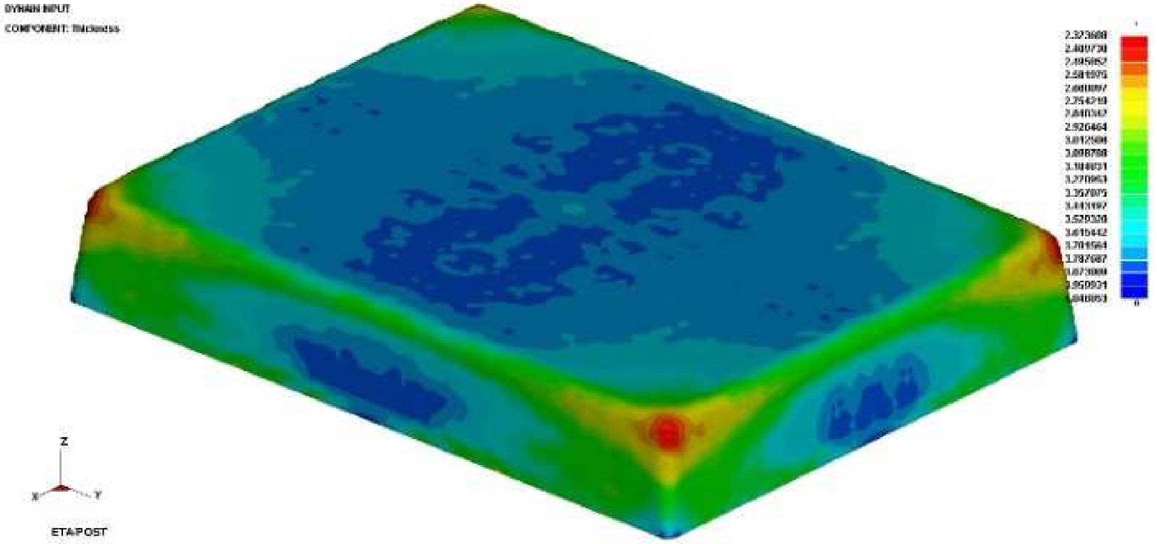

Fig. 17. Finished piece with inclination angle β=6 ° and radius at corners R=2 mm

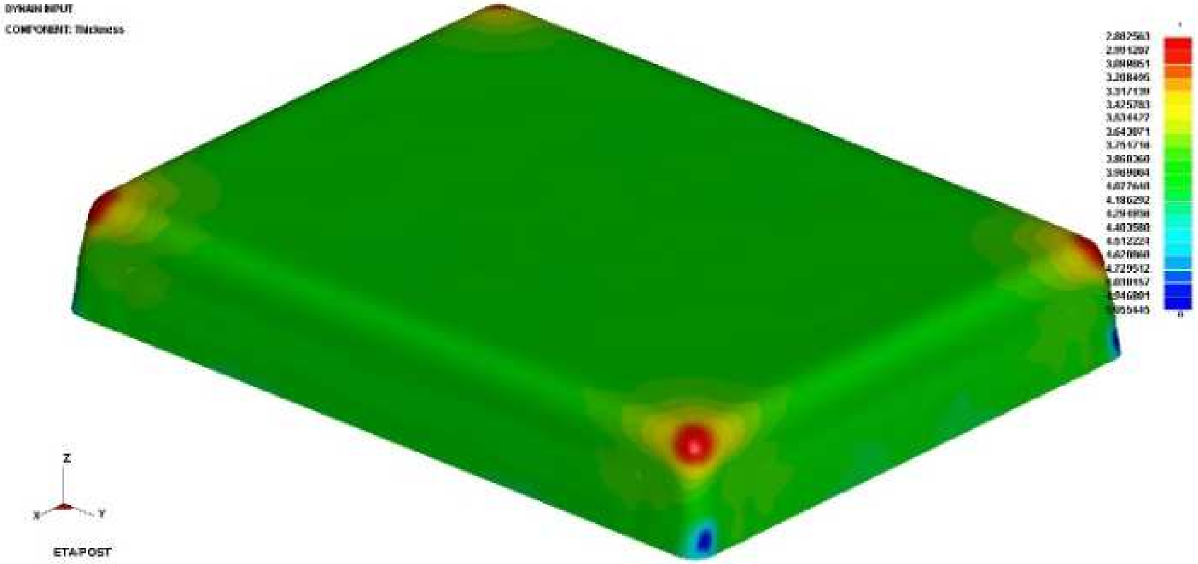

Fig. 18. Finished piece with inclination angle β =6 ° and radius at corners R=10 mm

In most cases, for parts with a radius at corners of R10 mm regardless of the inclination angle, approximately similar results are obtained in terms of minimum and maximum surface thickness.

The force developed by the press ram according to the simulations performed in relation to the radius at the corners can be seen in figure 12. It can be seen that the part with rounded corners at R2 mm needs a greater force, and in the case of R4, R6, R8 and R10 mm radius, the obtained force values are closer.

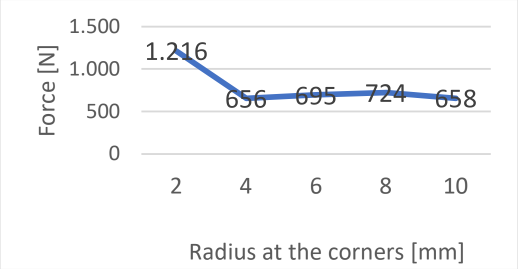

Fig. 19. The force developed by the press ram in relation to the corners radius for the inclination angle β of 0°

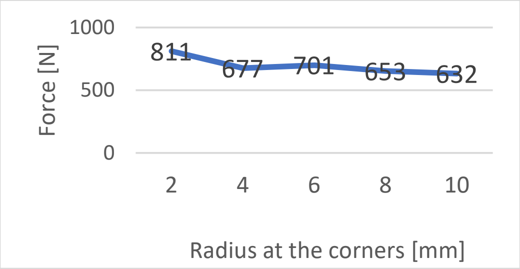

Fig. 20. The force developed by the press ram in relation to the corners radius for the inclination angle β of 3°

As in the previous case, when the inclination angle of the part is 3°, the effort made in the case of parts with a corner radius of R2 mm is higher in these cases as well.

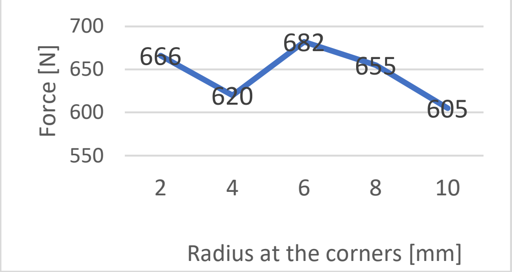

Fig. 21. The force developed by the press ram in relation to the corners radius for the inclination angle β of 6°

Figure 21 shows that the finished parts with an angle of inclination of 6° have a relative developed force around 650 N regardless of the corners radius of the part.

3. CONCLUSION

Following the simulations, it was found that:

- The thinning of the material at the corners is reduced with the increase of the radius and the inclination angle;
- The increase of the radius at the corners has the greatest influence on the minimum thickness, at small angles of inclination (Fig. 10). For β = 0° by passing from R = 2 mm to R = 4 mm, the minimum thickness increases from 1.38 mm to 2.24 mm (63%);
- Increasing the angle of inclination β has a positive effect on the thinning of the material in the corner area. At a radius of 2mm, with increasing angle β = 3° the minimum thickness increases from 1.38 mm to 2.18 mm;
- The strength of the ram decreases with increasing radius at the corners;
- Changing the angle of inclination β has little influence on the force of the ram for cases where the radius R is greater than the thickness of the wall. If R is less than the wall thickness is (R = 2 mm), the force decreases significantly with the application of an inclination angle of β = 3°.

The finished parts with an inclination angle of 0° and corners radius R=2 mm is an non-compliant part because it has a minimum thickness less than 60% compared to the initial thickness.

In the case of parts with a corner radius of R=10 mm, regardless of the inclination angle, approximately similar results were obtained.

Following the simulations, it is recommended to use corners radius larger than the thickness of the material and to use angles of wall inclination up to 6°, if they do not affect the aesthetics and functionality of the final product.

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Optimizarea parametrilor geometrici ai pieselor termoformate

Rezumat: *Lucrarea își propune să optimizeze parametrii geometrici pentru termoformarea pieselor de tip cutie din materiale compozite pe bază de fibre vegetale. Defectele care apar la termoformarea acestor piese sunt formarea de pliuri, subțierea excesivă sau ruperea materialului. Pentru a studia influența parametrilor geometrici, precum raza colțului și unghiurile de înclinare, asupra variației grosimii peretelui și a formării pliurilor, au fost efectuate simulări cu elemente finite cu ajutorul software-ului Dynaform. A fost analizată și forța dezvoltată de șurubul de presare în raport cu colțurile razei la diferite unghiuri de înclinare. Simularea a evidențiat că subțierea materialului la colțuri este redusă odată cu creșterea razei și a unghiului de înclinare, iar forța șurubului scade odată cu creșterea razei la colțuri.*

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