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DESIGNING A LINE FOR THE CONTINUOUS THERMOFORMING OF BOARDS MADE OF COMPOSITE MATERIALS

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Abstract: *The work presents technical solutions for the design of a continuous thermoforming line for thermoplastic composite materials. The line consists of a material heating unit above the melting temperature of the thermoplastic matrix and a cooling unit used for consolidation. In addition to the constructive solutions, a series of mathematical equations necessary for the design and optimization of the line are also presented.*

Key words: *continuous thermoforming, composite material boards, thermoplastic composite, vegetable fibers.*

1. INTRODUCTION

The authors of the current paper have identified the need to produce panels from composite materials in a collaboration with the company TAPARO SA from Târgu-Lăpuş, one of the largest producers of upholstered furniture in Romania and the only one that uses thermoplastic composite material from plant fibers, accepted by large retailers. A piece of upholstered furniture consists of a support structure generally made of wood, a comfort material and external fabric. In the last five years, the interest of companies in the development of composite materials intended to replace wood has increased. The company's motivation to look for new materials is related to the limited availability of wood exploitation and the significant increase in the purchase price. This increase is due either to the implementation of some legislative regulations that limit the intensive exploitation of some resources, or to other restrictive factors. Another important factor that led TAPARO to look for solutions to replace wood with composite materials is given by the reduced possibilities of re-introducing wood waste from manufacturing or from disassembling the products at the end of their life into the production process. Due to the reasons mentioned above the project "Creation of a center of excellence in the field of composite material at S.C. TAPARO S.A.", MySMIS no. 121434, developed new composite materials based on plant fibers together with adequate production technologies to transform them into products.

The paper [1] presents in detail the advantages of developing composite materials with plant fibers.

The composite materials developed by TAPARO are obtained from plant fibers mixed with polypropylene fibers or different natural adhesives. Details regarding the component and manufacturing process of a thermoplastic composite material with hemp fibers and polypropylene were patented by TAPARO (Patent EP 3426833). Other materials with natural fibers and natural adhesives (starch, lignin) were presented in paper [2].

A method of redesigning furniture parts for replacing wood with composite is presented in paper [3], and some aspects related to the thermoforming process were presented in papers [4, 5]. Other aspects related to the stages of the thermoforming process and the optimization of the parts were presented by the authors in papers [6, 7, 8].

Paper [9] deals with problems related to the influence of the mechanical properties of hemp and polypropylene thermoplastic composites.

An interesting approach regarding the determination of the mechanical properties of composites with neural networks is presented in paper [10].

In general, companies producing upholstered furniture work for retailers that operate on a global market and that issue orders for large series of products, to several suppliers, putting them in competition. That's why product cost estimation is particularly important, and a quick estimation and cost optimization method was presented in paper [11].

The papers [12, 13] analyzed the influence of the hemp/matrix ratio and the nature of the matrix on the properties of the composites.

Numerous solutions for obtaining plastic boards are known, but they are not suitable for forming profiled composite boards.

Wood plastic composites (WPC) are a type of composite made from wood particles or fibers and a polymer matrix. This material is similar to natural fiber reinforced composites and the manufacturing methods used for WPC sheets and boards can be a good indicator of how to process natural fiber composites.

The main method for manufacturing WPC profiles is extrusion. It melts the matrix and pushes the material through a die to shape it. Paper [14] presents four variations of this process among which are the single screw and the co-rotating twin screw. Extrusion provides good productivity, but can have a high purchase cost and requires a fine adjustment of the process parameters to avoid for example polymer or wood thermal damage and the required quality of the finished product: homogeneous constituent mix, satisfactory mechanical properties and surface finish.

Injection molding is an alternative to extrusion and, even though much slower, it can produce parts of complex geometry. It is typically used for parts which can’t be manufactured using extrusion. The cost per part increases, but as an advantage it offers products that do not require further finishing.

Both compression molding and thermoforming can be applied to WPC materials. They have slower productivity than the previous two types of processes, but have found many applications with automotive parts [14]. They have the advantage of using low cost equipment such as presses and simple molds and can be used to produce large parts with intricate geometries of very good quality. Similarly to the particleboard industry there are continuous belt presses which can produce continuous WPC boards at high speeds, but with a flat surface. These types of presses are also very complex machinery and come with high capital costs.

The need for a line for continuous thermoforming of boards appeared due to the need to increase the productivity of the thermoforming process.

2. GENERAL SPECIFICATIONS FOR LINE DESIGN

Before the design of the technological line, a series of aspects related to the process itself must be taken into account. The line will be supplied with composite material in the form of a fibrous layer mechanically reinforced by interweaving and delivered as a roll. The fibrous layer is well consolidated and offers tensile strength so that it can be unrolled and transferred between the line’s equipment. The process of transforming the fibrous layer into boards involves the following steps:

- supplying the material continuously;
- heating the material above the melting temperature;
- forming profiled boards and consolidating them by cooling;
- trimming and cutting them.

Taking into account the phases of the process and the authors' experience gained during the formation by static thermopressing of a range of parts for the upholstered furniture industry, the following general requirements are formulated:

- the temperature of the heating equipment of the line cannot be raised above 220 °C, because the plant fiber is affected;
- reducing the heating time can be done by reducing the thickness of the fibrous layer of composite material, this being possible by feeding several strips of material in parallel.
- the thermoplastic composite material adheres to the hot elements it comes into contact with, which requires some technical solutions to avoid adhesion.

Considering the phases of the process, the following functional requirements of the component equipment of the line can be formulated.

A. Feeding equipment:

- to offer the possibility of continuous feeding, with adjustable speed;
- to allow the quick change of material rolls and the connection of a new fibrous layer at the end of a roll.

B. Heating equipment:

- to offer the possibility of temperature regulation;
- to be able to adjust the transfer speed of the material through the equipment to ensure the time required for the mass heating of the composite material;
- the heating should be efficient;
- to avoid damage to the material during heating, through overheating or the formation of folds or other defects.

C. Forming and cooling equipment:

- the pressing force necessary for forming;
- elements should be adjustable to ensure a pressure on the active surface between 3 and 10 daN/cm^2;
- to work for boards with different thicknesses and models.

D. The transfer equipment must offer possibilities for automation of the line, with the maneuvering and stacking of boards.

The line must meet the following operational requirements:

- Safety in operation;
- Programming options;
- Adjustment of process parameters specific to each consolidated part.

3. CONCEPTUAL SOLUTIONS FOR THE CONSTRUCTION OF THE LINE

Taking into account the equipment specific to each phase of the process, we will use morphological analysis to generate conceptual solutions. Since its conception and development in the late 1940's by Fritz Zwicky at the California Institute of Technology (Caltech), the "morphological approach" - or General Morphological Analysis (GMA) - has been applied to many diverse areas of study, from engineering design and technological forecasting to policy analysis, organizational development and creative writing [15].

For each of the equipment of the line, we analyze the possible variants, and the general solution will result as a combination of the possible variants.

Table 1 shows the component assemblies A-D and their solutions. From the analysis of the components in table 1 there are a number of 3x7x5x4=420 possible solutions to choose from.

For each of the variants presented in table 1, there are also sub-variants, these being taken into account only in the actual design of the line.

Table 1.

Zwicky Diagram

A. Feeding equipment	B. Heating equipment	C. Forming and cooling equipment	D. Transfer equipment
A1. A single fibrous layer	**B1.** In-line rollers	**C1.** A single mold	**D1.** Metal belts
A2. Two parallel fibrous layers	**B2.** Zig-zag rollers	**C2.** A forming and calibration mold	**D2.** Textile belts with teflon covering
A3. Several parallel fibrous layers	**B3.** In-line boards	**C3.** Succesion of profile rollers for forming and calibration	**D3.** Rollers
	B4. Parallel boards	**C4.** Profiled rollers-calibration mold	**D4.** Belts and rollers combination
	B5. Parallel boards and in line rollers	**C5.** Preforming mold -profiled rollers-calibration mold	
	B6. Parallel boards and zig-zag rollers		
	B7. Plates mounted on a chain		

Figure 1 shows the conceptual diagram of a continuous thermoforming line obtained by combining variants A2-B5-C3-D4 consisting of a heating system 1 and a forming system 2. The heating system is of mixed type, having a heating zone between plates and a heating zone between rollers.

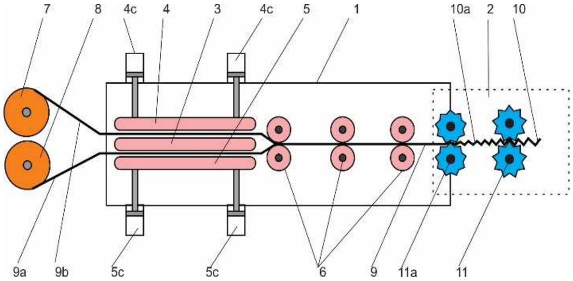

Fig. 1. Conceptual diagram of the continuous thermoforming line

The material is unrolled from the drums 7 and 8 in the form of two strips 9a and 9b. Each strip is passed between the fixed plate 3 and the pressing plates 4 and 5. The feeding of the material is discontinuous. During heating, the plates 4 and 5 are pressed on the fixed plate 3 with the help of the hydraulic cylinders 4c and 5c.

After the material is kept pressed between the plates 3,4,5 for a long enough time so that the polypropylene in the superficial layers melts and avoids the expansion of the material, the cylinders 4c and 5c remove the plates 4 and 5 from the plate 3.

At this moment , the material advances until near the profiled rollers 11a, and the two strips 9a, 9b will form a single strip 9.

Using two strips of material leads to a reduction in heating time because the material is thinner and has a larger contact surface with the hot plates.

At the same time, the material between the hot rolls 6 passes between the profiled forming rolls 11a and calibration 11, forming a profiled plate 10.

Rolls 11a and 11 have different profiles. Thus, roller 11a will create an initial profile of the plate 10, and roller 11 will calibrate the profile.

Obviously, several profiled rollers can be used, depending on the dimensions and the final profile of the board.

Figure 2 shows another variant of the thermoforming line obtained by combining variants A2-B2-C3-D4. The line consists of two material advance systems 1a and 1b, mounted in parallel, with interspersed material strips.

By arranging the system 1b in the mirror to a horizontal plane compared to 1a, a reduction of the total volume of the oven was obtained.

The two strips of material 2a and 2b unfold from drums 3, pass over the rollers related to paths 1a and 1b, and finally overlap between pressing rollers 4, forming a single strip 2. From here the material 2 is passed between forming rollers 5 and results in a continuous profiled plate 6 that is cut to the desired length.

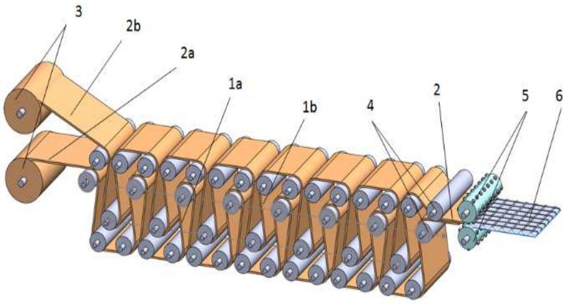

Fig. 2. 3D model of the continuous thermoforming system of profiled plates

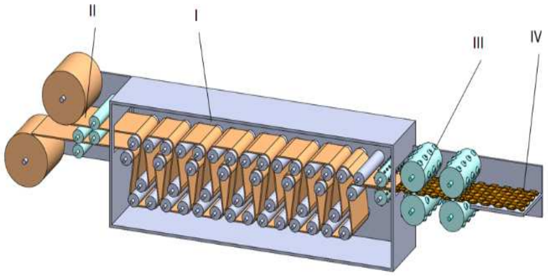

Fig. 3. Continuous thermoforming line of profiled boards– isometric view

Figure 3 represents an isometric view of the transfer line with the overlapping of two layers of material and continuous forming with profiled rolls.

The following areas are distinguished:

I – heating oven;

II – feeding of mechanically reinforced composite material;

III – forming with profiled rollers;

IV – cutting of the formed plates.

4. CALCULATION OF THE TECHNOLOGICAL PARAMETERS OF THE LINE

For the design of the line, the assumption is made that the heating time is directly proportional to the thickness of the material. The following values are considered to be known:

- t_h, heating time of the material to reach the working temperature;
- t_c, cooling time.

The length of the heating zones L1, L2, of the cooling zone L3 and the transport speed v will be determined.

For the line in figure 1, the conceptual diagram in figure 5 is considered. Based on the adopted hypothesis, in the first part of the heating zone of length L1, since it is about two layers, the contact length is 2L1.

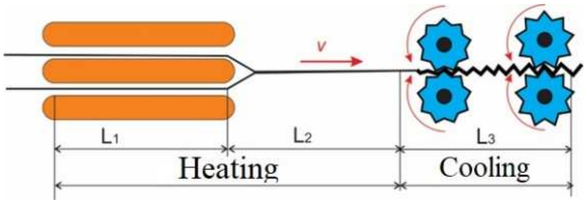

Fig. 5. Conceptual diagram of the line in figure 1

The length of the heating zones L1, L2, of the cooling zone L3 and the transport speed v will be determined.

The equations can be written:

$$v = \frac{2L_1 + L_2}{t_h} \qquad (1)$$

$$v = \frac{L_3}{t_c} \qquad (2)$$

$$L_1 = cL_2; c = 1 \dots 5 \qquad (3).$$

From equation (1), the equivalent length (Le) of the material strip in the heating zone is obtained:

$$L_e = 2L_1 + L_2 = v \cdot t_h \qquad (4).$$

From equations (3) and (4) the length of the oven (Lo) is obtained:

$$L_o = L_1 + L_2 = \frac{L_e}{2c+1}(c+1) \quad (5).$$

The research conducted so far shows that the heating time t_h will be between 3-6 min, and the cooling time 0.5-1 min. Equation (2) determines that the advance speed can be adjusted between 2 and 6 m/min. The equivalent length Le and the length of the oven Lo for c=1/3 are presented in figures 6 and 7.

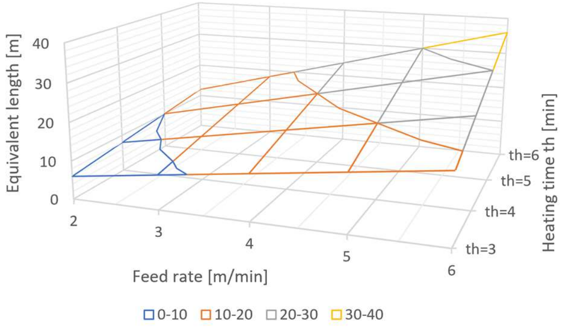

Fig. 6. Equivalent length

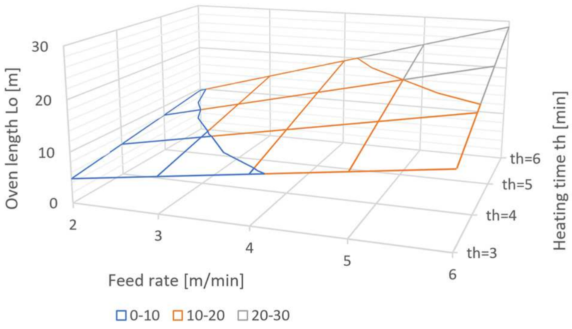

Fig. 7. Oven length

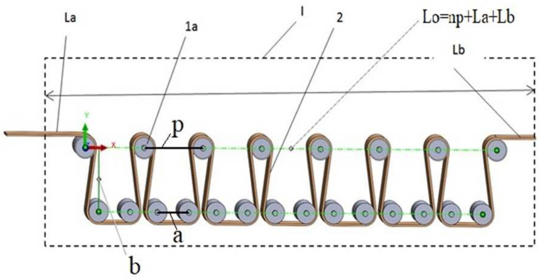

Fig. 8. Conceptual diagram of the oven with zig-zag path

The pitch p, the diameter d and the distances a and b for the layout of the rolls are considered known. With the notations in figure 8, the length of the material corresponding to a step p (denoted by Lp) and the equivalent length Le, are determined with the equations:

$$L_p = a + \pi d + 2\sqrt{b^2 + (\frac{d}{2})^2} \qquad (6)$$

$$L_e = n \cdot L_p + L_a + L_b \tag{7}$$

Figures 9 and 10 show the length of the oven for a single zig-zag layer of material, and for two parallel layers.

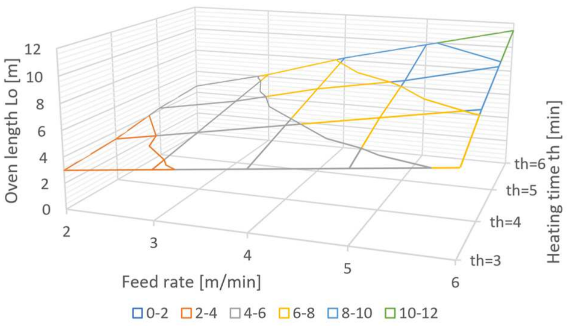

Fig. 9. The length of the oven with one zig-zag path

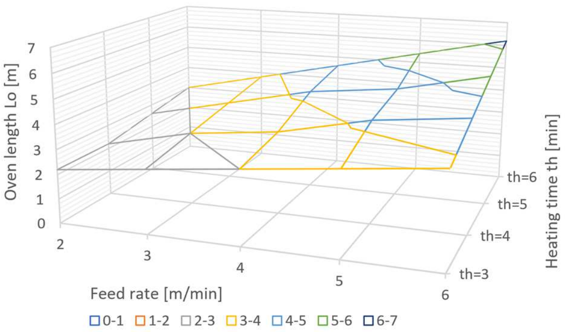

Fig. 10. The length of the oven with two zig-zag paths

5. FEA ANALYSIS OF A PROFILED BOARD OBTAINED BY CONTINUOUS THERMOFORMING

Figure 11 shows a board obtained by rolling between profiled rollers. The board has the dimensions of 400x600x20 mm and the mass of 1.65 kg and will be compared with a smooth board having the same weight.

To analyze the performance of the board in figure 11, a static study was carried out using the finite element method. Two lateral bands with a width of 50 mm were considered as supporting surfaces, and as a loading surface, a circle with a radius of 350 mm, placed in the center of the board (figure 12). The request is similar to the test for sitting on a chair and a force of 1300 N was applied.

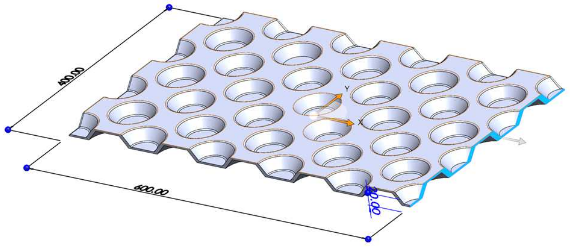

Fig. 11. Profiled board made by continuous thermoforming

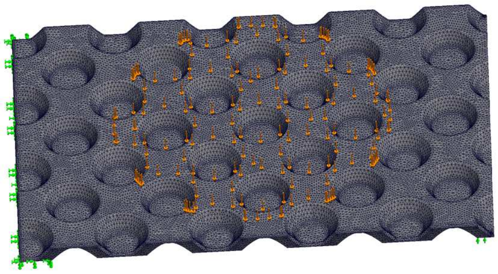

Fig. 12. Fixtures and loads

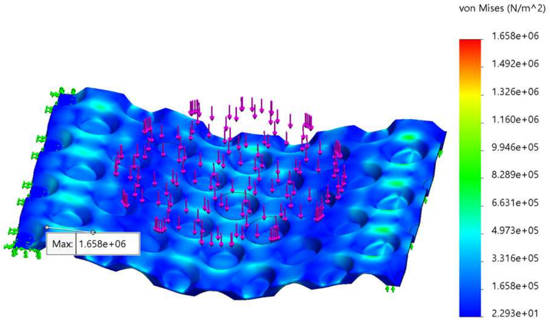

Fig. 13. Von Mises diagram

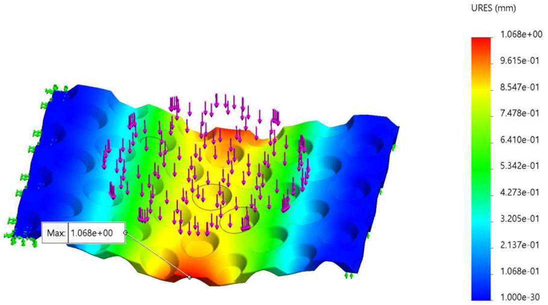

Fig. 14. Profiled board displacement

The results of the FEA study show (Fig. 13, 14) that the maximum stress is obtained at the edge of the fixed area (1.68 MPa), and the maximum deformation in the center of the board (1.06 mm).

In contrast, a board made of the same material of the same size, but flat and with a thickness of 7.5 mm, having the same weight as the profiled board, deforms about 20 times more (Fig. 15.).

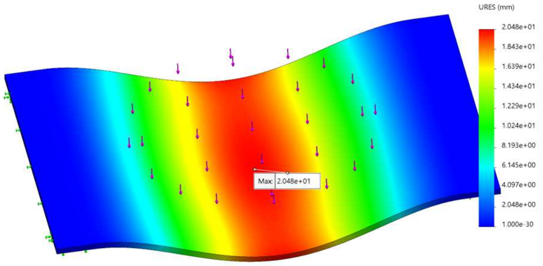

Fig. 15. Flat board displacement

6. CONCLUSIONS

Unlike static thermoforming, continuous thermoforming has advantages regarding process automation and productivity. Analyzing the possible combinations from table 1, it turns out that a range of thermoforming line variants can be designed depending on the choice of heating and cooling systems.

The material heating equipment will give the speed of the line considering the fact that the composite material contains dry plant fibers, which behave as a thermal insulator, and the fact that the temperature of the heating equipment cannot be raised above 220° C due to the damage to the plant fibers.

In order to reduce the heating time and the equivalent length of the material strip in the heating area, we recommend an oven that uses all types of heat transfer: conduction, convection, radiation. The heating elements will be located on the side walls, on the top and on the base. The heat transfer will mainly be done by forced convection. Oil heating of the rollers is also possible, which would improve operation and allow better temperature control.

Technical solutions are needed to keep the dimensions of the heating equipment to a minimum, due to the following drawbacks:

- the large space occupied and the large contact surface with the environment;
- high heat losses due to high exchange with the exterior;
- difficulty of intervention in case of malfunctions, etc.

Reducing the dimensions of the oven can be done by:

- efficient use of all types of heat transfer: conduction, convection, radiation;
- optimization of the route of the material strip in the oven to maximize the equivalent length of the strip inside the oven;
- parallel heating of several strips of material.

Solving the problem of avoiding the adhesion of the material to the heating elements (boards or rollers) is necessary for any conceptual variant of the line. This can be done by choosing materials to which the composite does not adhere or by covering them with a non-stick material (Teflon, ceramic, etc.).

Another option to avoid the adhesion of the composite to the heating elements is to use a demolding agent that forms a wax film on the contact surfaces. This agent must form a strong non-stick layer with high resistance to the working temperature (approx. 200° C.)

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PROIECTAREA UNEI LINII PENTRU TERMOFORMAREA CONTINUĂ A PLĂCILOR DIN MATERIALE COMPOZITE

Rezumat: Lucrarea prezintă soluții tehnice pentru proiectarea unei linii de termoformare continuă a materialelor compozite termoplaste. Linia se compune dintr-o unitate de încălzire a materialului peste temperatura de topire a matricei termoplaste și o unitate de consolidare prin răcire. Pe lângă soluțiile constructive se prezintă și o serie de relații matematice necesare proiectării și optimizării liniei.

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