TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 61, Issue Special, September, 2018

SIMULATING THE THERMOFORMING PROCESS OF A BOX FOR UPHOLSTERED FURNITURE

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Abstract: *The current paper presents the finite element analysis (FEA) of the thermoforming process of a part made from natural fiber-based composite material. The analyzed part has the shape of a box and is considered to be relevant for the replacement of wood components from the resistance structure of the upholstered furniture. The results of the analysis are used in the integrated design process of the parts in order to produce the composite material and the molds. The results of the numerical simulation have been validated by means of experimental research.*

Key words: *Thermoforming, FEA, composite material, natural fibers, renewable resources.*

1. INTRODUCTION

1.1 The need to replace upholstered furniture wood structure by composite materials

The majority of the upholstered products contain a reinforcement structure, generally made as a timber frame. Wood is an excellent material in terms of functional, environmental and aesthetic purposes, but its overexploitation has an impact on the environment, and most of the countries have adopted legislation regarding the forestry exploitation.

For this reason, manufacturers of large quantities of upholstered furniture are looking for solutions to replace wood with other recyclable products that offer benefits in terms of productivity and the overall cost of the product.

TAPARO, a Romanian company of upholstered products, has completed theoretical and experimental research through its own R&D department. Research has led to the realization of a composite material and a technology for its completion. The material and the technology were the object of a patent application entitled "Composite Textile Material for the Manufacturing of Thermoformed Products, Method and Machinery for its Manufacturing" (Patent application: Romania - a2016 00160/ 07.03.2016; WIPO: PCT/IB2017/051209). The problem solved by the above-mentioned invention consists in the realization of a composite material meant to enable the production of articles by thermoforming at low cost, 100% recyclable and which requires a low usage of hydrocarbon-based synthetic materials, being obtained to a large extent from natural raw material of fast growth (hemp fibers). The composite material for thermoforming is made, according to the TAPARO invention, from a fiber thermoplastic component that consists of polypropylene fibers of 40-60 mm length and linear mass density of 7-16 DEN, in a percentage of 8% to 20% of the total weight of the mixture, and a vegetal fiber component that can be made of fibers of hemp, flax, coconut, etc. There can be used a mixture of natural fibers, with a degree of defibration at a fineness of the fiber of about Tden = 70-80, and a length of the fiber of 5 to 100 mm, in a percentage that ranges from 80% to 92% of the total amount of the mixture.

The physical and mechanical properties of this material have been presented in [1].

Using this composite material, TAPARO manufactured some components for furniture: armchair shells, sofa sides, chairs, 90° brackets, etc. [2].

The authors of the present paper analyzed the possibility of replacing wood with composite materials and developed a new design method for replacing the wooden parts of furniture [3]. Based on the research completed [1-4], the authors found out that many elements can be replaced by parts made of box-shaped composite material.

In order to achieve high-quality products with minimal waste of reinforced material, there was needed a close analysis of the thermoforming process. The main aim of this paper is the numerical simulation of the thermoforming of a parallelepiped-shaped box (Fig. 1).

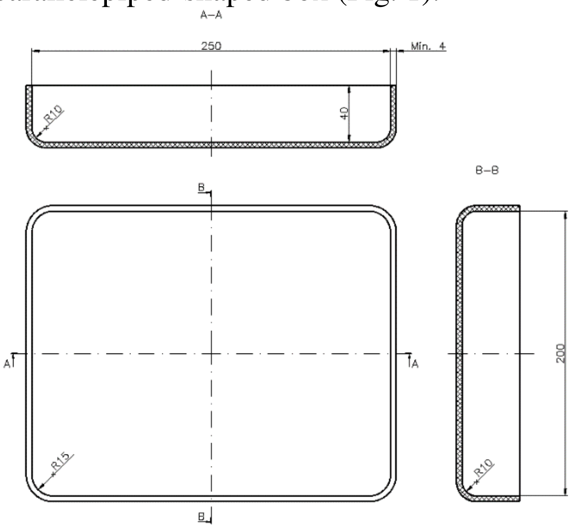

Fig 1: Characteristics of the box-shaped part

1.2 Thermoforming process

The parts of composite material made from natural fiber are obtained by thermoforming. This procedure consists of the following stages:

1. Obtaining the composite material as an unreinforced fiber layer, an unwoven material consisting of a mixture of natural fibers and thermoplastic fibers (polypropylene)
2. Cutting out the material, by overlapping different layers of fiber material and cutting them according to the outline of the desired shape
3. Warming the material cut between the heated platens of a press at a temperature that ranges from 220 to 230ºC, at which polypropylene, as shown by previously conducted studies [1], has an extremely low mechanical strength
4. Thermoforming in the mold, which consists in the transfer of the material to a mold, pressing the material and cooling it in view of its hardening
5. Cutting the outline of the finished part
6. Grinding the waste resulted for reusing it.

Replacing wood by composite materials involves redesigning the furniture components. This stage is strongly influenced by the thermoforming process, in the sense that it ensures the achievement of the desired curvatures, while limiting the phenomenon of wrinkle formation and the excessive thinning of the walls, or the tearing of the material during thermoforming.

2 MATERIALS AND METHODS

2.1 Hypotheses

The semi-finished product does not cool too much before it reaches its final configuration, given the fact that the thermoforming process lasts only a couple of seconds, and that the thermal conductivity of its components (mostly polypropylene) is low. Under these circumstances, the following working hypotheses have been adopted:

a) The thermal transfer between the semi-finished product and the components of the mold does not influence significantly the thermoforming process. Thus, the numerical simulation can be performed using a purely mechanical model which describes a quasi-isothermal process.
b) The polypropylene has the most significant influence on the mechanical properties of the semi-finished product to be thermoformed (Fig. 2), meaning that the contribution of the natural fiber to the overall strength of the thermoformed material is negligible.

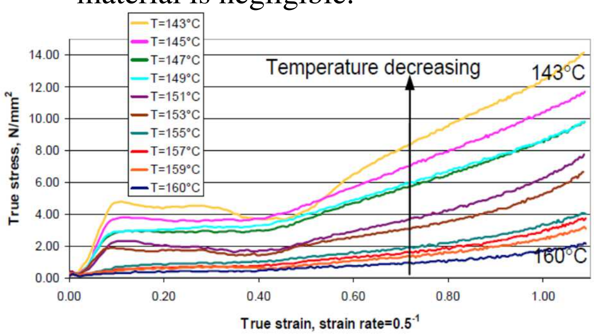

Fig 2: Isothermal stress-strain curves obtained by testing polypropylene (temperature range 143 ÷ 160ºC, constant velocity) [5]

As illustrated in Fig. 2, the polypropylene reduces to a great extent its strength as it is heated. It is important to highlight that, at a temperature of 160ºC, the stress that corresponds to the unit strain does not exceed 2 N/mm2. Fig. 2 also shows a continuous decrease of the stress-strain curves when the polypropylene is heated. Actually, the stress-strain curve determined at a temperature of 160ºC is almost similar to the characteristic curve of a continuous medium exhibiting an elastoplastic behavior. One may assume that this similarity is kept at temperatures above 160ºC as well. Moreover, one may notice the stabilization of the mechanical characteristics at ever increasing temperatures. By exploring this behavioral particularity of the polypropylene, the authors of the current paper extended the validity of the stress-strain curve determined at 160ºC to greater temperatures.

2.2 Selection of the constitutive model that describes the material behavior in the temperature range specific to thermoforming

The above-mentioned reasons explain the choice of an isotropic elastoplastic description of the mechanical behavior of the polypropylene in the temperature range specific to the analyzed thermoforming process. The elastic part of this model is defined by Hooke's law which involves two material constants: Young's modulus and Poisson's ratio. As concerns the plastic component of the constitutive model, this is based on the model proposed by von Mises, in combination with a tabular representation of the hardening law [5]. The tabular representation of the hardening law was obtained by digitizing the experimental stress-strain curve corresponding to the temperature of 160ºC (Fig. 2).

Table 1: Values of material constants describing the elastoplastic behavior of polypropylene in the temperature range characteristic to the thermoforming process

Mass density	$9\cdot10^{-10}$ ton/mm^3					
Young's modulus	12.5 N/mm^2					
Poisson's Ratio	0.45					
Tabular representation of the hardening law						
Plastic strain [-]	0	0.2	0.4	0.6	0.8	1
Yield stress [N/mm^2]	0.2	0.35	0.43	0.71	1.10	1.73

Table 1 lists the values of the material constants that describe the elastoplastic behavior of the polypropylene in the temperature range that is characteristic to the analyzed thermoforming process.

2.3 Characteristics of the mold and semi-finished product

The thermoforming is performed on a single-action press using a mold whose main components are the punch fixed on the bolster and the molding plate attached to the slider (fig. 3). By comparing the dimensions presented in the diagrams shown in Figures 1 and 3, it can be easily noticed that the work surface of the punch copies the internal surface of the box. As for the work surface of the molding plate, this has been generated by offsetting the corresponding regions of the punch at a distance j = 1,1 • s = 1,1 • 8 = 8,8 mm (s = 8 mm is the nominal thickness of the semi-finished product).

In the stage that precedes the thermoforming, when the press slider is withdrawn to the superior dead end of its trajectory, the human operator places the preheated semi-finished product onto the surface of the punch. Obviously, for the vertical walls of the box to be completed at the corresponding height, the margins of the semi-finished product have to exceed the limits of the upper surface of the punch. Given the extremely low mechanical strength of the polypropylene layers, the semi-finished product will deform gravitationally, by folding onto the upper fillet areas of the punch and making folds.

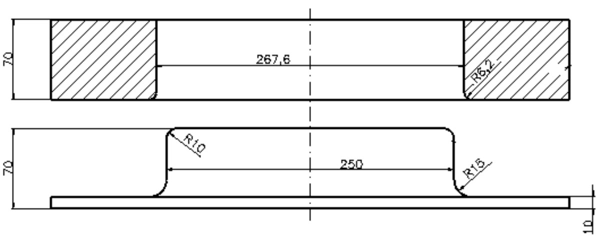

Fig 3: Characteristics of the thermoforming mold

(upper part: mold plate; lower part: punch)

The thickness of the semi-finished product (8 mm) has been established by repeated simulations of the thermoforming process, having in mind to meet the condition that the wall of the box does not decrease below 4 mm. The numerical tests have been performed for thickness values of 6, 7 and 8 mm. At the end of the tests, the authors have concluded that only the last value ensures an appropriate quality of the finished product.

3. SIMULATION OF THE THERMOFORMING PROCESS

3.1 Selection of the simulation program

The finite element program DYNAFORM has been used for the numerical simulation of the thermoforming. This program has three main modules:

- eta/DYNAFORM graphical pre-processor [3];
- LS-DYNA solver [4];
- eta/POST graphical post-processor [5].

Some of the most important features of these modules are the following ones:

- Possibility of importing the geometrical models of the semi-finished product and tools prepared by means of the most commonly used CAD programs (SolidWorks, CATIA, AutoCAD, etc.)
- Automatic meshing of the semi-finished product and tools
- Possibility of simulating a wide range of manufacturing processes (forming on single, double or triple action presses, etc.)
- Possibility of analyzing a sequence of stages involved in the manufacturing of the semi-finished product by continuing the computation
- Automatic positioning of the semi-finished product on tool surfaces
- Availability of constitutive models appropriate for thermoforming simulation
- Modeling of the friction contact between the semi-finished product and tool surfaces
- Graphical representation of the numerical results (configuration and distribution of the thickness of the deformed semi-finished product, variation of the pressing force, etc.).

The above-mentioned features, as well as the fact that the Department of Manufacturing Engineering at the Technical University of Cluj-Napoca holds a DYNAFORM license, determined the selection of this program for the numerical simulation of the thermoforming process.

The simulation has been performed using models of the tools and of the semi-finished product reduced to a quarter of their actual geometry, due to the symmetry of the given components with respect to two mutually perpendicular planes (Fig. 4). The 3D representations of the tools and of the semi-finished product have been generated using SolidWorks, and then transferred to the eta/DYNAFORM pre-processor as IGES files. The functional characteristics of the eta/DYNAFORM pre-processor imposed the reduction of all the geometrical models to collections of surfaces:

- Median surface of the semi-finished product
- Working surfaces of the molding plate and punch

3.2 Simulation of the gravitational deformation of the raw material on the surface of the punch

The extremely low strength of the semi-finished product allowed ignoring the deformation of the thermoforming plate and punch, the active surfaces of both tools being meshed with rigid facet elements [6]. The only deformable component of the model submitted to analysis was the semi-finished product. In order to discretize the latter, Belytschko-Lin-Tsai thick shell elements were used [6]. The thickness shear strength of these shell elements was diminished by adjusting the SHRF parameter from the standard level of 0.833 to 0.05.

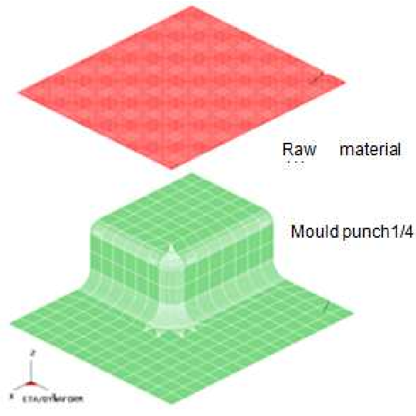

Fig 4: Finite element meshing of the components of the gravitational deformation process

Due to the relatively large area and of the reduced mechanical strength, when placed on the upper surface of the punch, the semi-finished product will deform gravitationally. The model of the process of gravitational deformation has therefore only two components (Fig. 4): semi-finished product (deformable body) and fixed punch (rigid body). As mentioned above, due to their double symmetry, the representations of both components can be reduced to a quarter of their actual geometry. Naturally, at the level of the sides that result from cutting with symmetry planes, there should be imposed appropriate boundary conditions to reflect the mechanical effect of the missing regions of the bodies.

As illustrated in Figure 5, the gravitational deformation is accompanied by the wrinkle formation and significant variations of the thickness of the semi-finished product. The most important thinning occurs at the level of the punch corners (up to about 4.54 mm).

3.3 Simulation of the thermoforming process through the combined action of the plate and the punch

The thermoforming model has three components: semi-finished product (deformable body), mobile plate and fixed punch (rigid bodies).

By means of the specialized application AutoSetup of the eta/DYNAFORM pre-processor, a finite element model of the thermoforming process on a single-action press was developed.

In the first stage of the model generation, AutoSetup requires the specification of some general characteristics of the forming process:

- Thickness of the semi-finished product (8 mm);
- Typology of the process (forming on a single-action press)
- Tools whose models are available in the database of the eta/DYNAFORM pre-processor (in the given case, both the thermoforming plate and punch).

The second stage involves the completion of different panels of a graphic interface, in which the user performs the following operations:

- Choice of a title of the model and the specification of the coordinate system to be used (in the given case, the global coordinate system, defined implicitly by the eta/DYNAFORM pre-processor)
- Selection of the finite element model of the semi-finished product, specification of its mechanical properties (Table 1), definition of the symmetry characteristics of the analyzed process (symmetry with respect to two mutually perpendicular planes) and the parameters associated to the interactions of friction contact between different areas of the semi-finished product
- Selection of the discretized models of the thermoforming plate and punch and definition of the parameters of the friction contact interaction on their surfaces.

The third stage consists in specifying the control parameters of the LS-DYNA solver and solving the finite element model of the thermoforming process. Once the calculations are completed, the eta/POST post-processor allows the graphical representation and the interpretation of the numerical results. In the case of a thermoforming process, the following aspects should be considered:

- Configuration of the completely formed semi-finished product
- Thickness distribution of the completely formed semi-finished product (Fig. 6);
- Variation of the force developed by the press slider during the thermoforming process (Fig. 7).

As shown by the diagram in Figure 6, the wrinkles do not disappear completely after the end of the thermoforming process. They remain not only in the marginal regions of the semi-finished product (where the wrinkles are quite visible), but also in the proximity of the corner areas of the upper part of the punch. Close to the corners, as shown by the diagram of the thickness distribution in Figure 6, there can be seen small spots of vivid blue in which, according to the legend, the thickness of the wall is of approximately 10.84 mm. Such a thickening is made possible solely through an intense tightening of the semi-finished product in the gap between the thermoforming plate and punch. At the other end, the lowest thickness level (approximately 4.06 mm) is recorded at the very level of the corner areas of the punch. It should be mentioned that the value obtained as a result of the simulation is in accordance with the dimensional prescription in Figure 2.

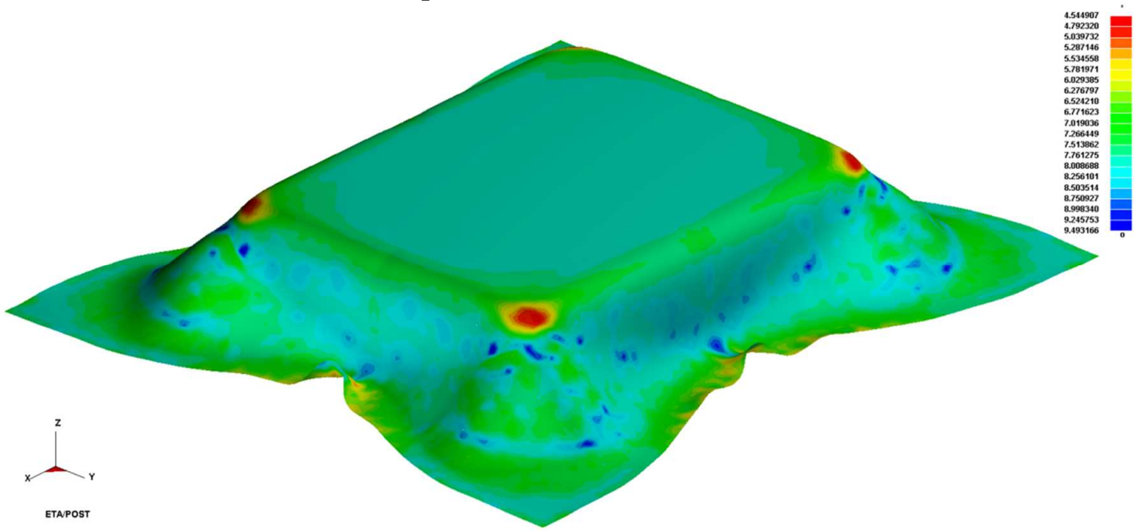

Fig 5: Thickness distribution at the end of the gravitational deformation process

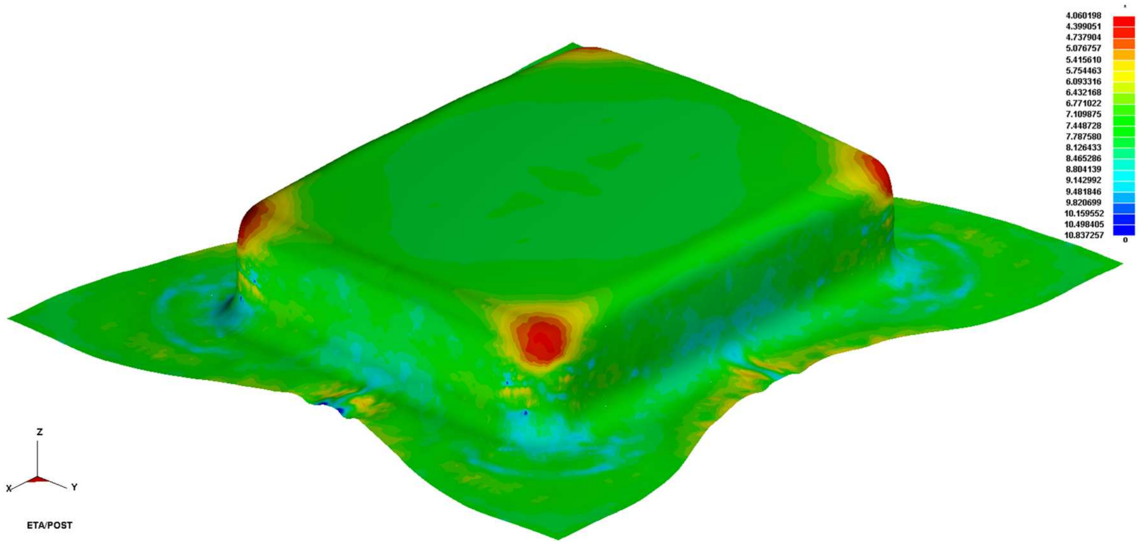

Fig 6: Thickness distribution at the end of the thermoforming process

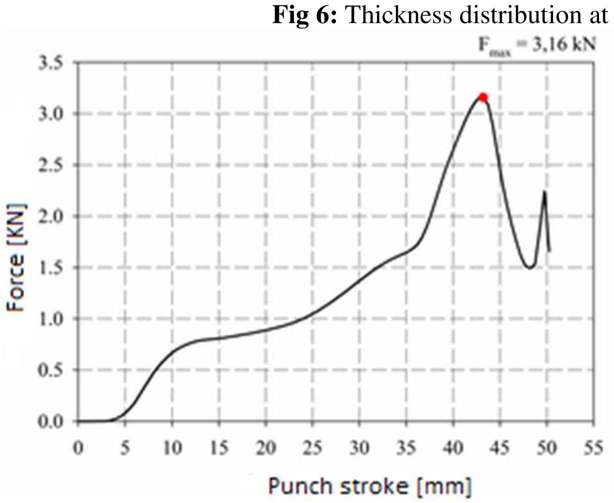

Fig 7: Variation of the pressing force

The diagram shown in Figure 7 presents the variation of the vertical force developed by the press slider during the thermoforming stage.

The maximum value of the force (3.16 kN corresponding to a slider stroke of 43.2 mm), the total stroke under load of the slider (50.3 mm), as well as the overall dimensions of the mold influence the selection of the pressing machine. Towards the end of the descending trajectory of the slider, puts into evidence a secondary maximum value of the pressing force. This sudden growth of the vertical force exerted by the slider is due to the compression of the wrinkles located in the border area of the semi-finished product.

The elimination of the technological addendum from the border area of the thermoformed part is achieved through shearing.

Figure 8 shows the thickness distribution of the box obtained after the removal of the additional material on the border.

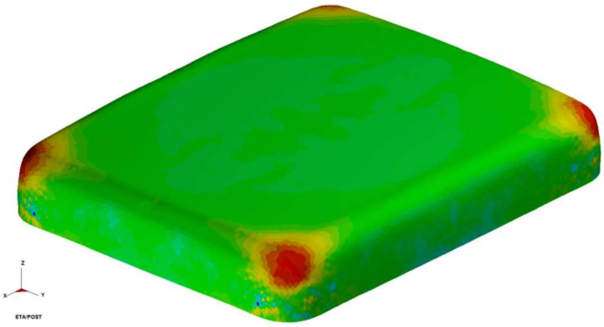

Fig 8: Thickness distribution of the finished product resulted after removing the technological addendum

4. EXPERIMENTAL RESULTS

The results of the simulation have been compared with experimental results obtained by thermoforming some box-type parts: sofa sides (Fig. 9) and chair seats (Fig.10).

Fig 9: Sofa side - 90º corner

Fig 10: Chair seat - 78º corner

5. CONCLUSIONS

The results presented in this paper prove the capability of the DYNAFORM finite element program to provide useful information on the mechanics of thermoforming processes.

The adoption of numerical simulation in the industrial practice is beneficial from several perspectives:

- The usage of this technique allows adjusting the geometry of the semi-finished product and thermoforming tools from the very initial stages of the technological design, without imposing the repeated completion of the adjustment steps typical to the traditional design strategy. As a consequence, the costs involved by the preparatory stages of the manufacturing process are reduced.
- The technician has access to detailed information regarding the quality of the thermoformed parts (e.g. amplitude and position of wrinkles and thickness distribution of the part).
- The simulation also provides information regarding the evolution of the forces developed by the active elements of the mold, which enables the best selection of the pressing machine.

From a qualitative point of view, the numerical simulation of the thermoforming process has been validated experimentally by manufacturing some typical components of upholstered furniture.

The results obtained from experiments have shown that the thickness distribution of thermoformed parts is more uniform than the distribution predicted by simulation programs. In the same time, the amplitude of the wrinkles occurred during the thermoforming process is smaller than the one predicted by programs. These discrepancies are explainable by the fact that human operators always adjust the distribution of the gravitationally deformed semi-finished part in the corner areas before closing the thermoforming mold.

The quality of the thermoformed parts can be improved if the gravitational deformation is

immediately followed by a manual molding of the semi-finished part on the punch surface.
If the semi-finished part is not manually molded in the corner areas before closing the thermoforming tool, one may notice a wrenching tendency of the reinforcing fibers (Fig. 9 and 10).

6 ACKNOWLEDGMENTS

This work was supported by a grant of the Romanian National Authority for Scientific Research and Innovation, CNCS/CCCDI – UEFISCDI, project number PN-III-P2-2.1-PTE-2016-0179, within PNCDI III.

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Simularea procesului de termoformare a unei cutii pentru mobilier tapiţat

Rezumat: Lucrarea prezintă analiza cu elemente finite a procesului de termoformare a unei piese de mobilier executată din material compozit pe bază de fibre naturale. Piesa analizată are forma unei cutii și este considerată a fi relevantă pentru înlocuirea componentelor din lemn din structura de rezistență a mobilierului tapițat. Rezultatele analizei sunt utilizate în procesul de proiectare integrată a pieselor, pentru a produce materialul compozit și apoi matrițele. Rezultatele simulării numerice au fost validate prin cercetări experimentale.

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