MILLING A LARGE MOLD FOR THE THERMOFORMING OF A PLANT FIBER COMPOSITE CHAIR

Mihai Ciupan[1,2], Ioan Cionca[3], Vasile Hereş[4], Claudiu Rusan[5,6]
[1] Technical University of Cluj-Napoca, Faculty of Machine Building, Dept. of Design Engineering and Robotics, mihai.ciupan@gmail.com
[2] Taparo SA, Research and Development Department
[3] Taparo SA, Research and Development Department, ioan.cionca@taparo.ro
[4] Taparo SA, Research and Development Department, vasile.heres@taparo.ro
[5] Technical University of Cluj-Napoca, Faculty of Machine Building, Dept. of Design Engineering and Robotics
[6] Comelf SA, rusan.claudiu@comelf.ro

ABSTRACT: The paper presents the design, manufacturing and testing of an innovative and low-cost mold used for the thermoforming of an armchair shell. The shell of the chair is made of a proprietary blend of plant and thermoplastic fibers which target the replacement of conventional wood products in order to improve the environmental sustainability of the furniture industry. The armchair was initially made of a welded steel frame and injected polyurethane foam and the task was to redesign it and develop the technology for prototyping a small run of 20 pieces. The mold was designed to be made of laminated wood sheets. The sheets were contour milled, assembled together using threaded bars and finally both the core and cavity of the mold were finish milled. All the milling was carried out using a Kuka KR210 L150-2 2000 industrial robot with a KRC2 control system and the programming and simulation of the process were done with SprutCAM Robot. The mold was tested and successfully produced the required armchair shells.

KEYWORDS: mold design, industrial robot milling, robot CAM software, plant fiber composite material, composite thermoforming

1. INTRODUCTION

Even large companies which are focused towards series manufacturing often have the need to prototype, test and analyze new products or changes made to existing ones. Taparo SA is a large Romanian furniture making company that specializes in manufacturing large volumes of chairs and sofas for global retailers.

It frequently receives requests for the development of new products which include design, prototyping, manufacturing technologies and pricing. This implies the actual making of a small batch of products which are sent to the customer for evaluation.

The last few years have shown an increased focus of the global furniture retailers on using recyclable or natural materials for their products and this, in the case of Taparo, has meant switching part of their production towards plant fiber and thermoplastic composites.

2. THE MANUFACTURING PROCESS

Taparo makes its own raw material by mixing and weaving hemp and polypropylene fibers into a textile sheet. It then stores the material as rolls until it is needed. When manufacturing of the chairs begins, material is unwound from the rolls, laid in multiple layers, depending on the required thickness of the final product, and cut into the shape of the armchair. The cut layers are put into a hot press and heated in order to melt the matrix of the composite, namely the polypropylene. The press is necessary to prevent the material from shrinking and warping under heat.

After the layers are heated, they are taken out of the press and set in a mould of the armchair. They are then pressed and the mold is held closed until the polypropylene cools enough so that the product holds its shape. Next the thermoformed shell is taken out of the mold and has its edges trimmed.

The next steps are common to many armchair construction methods and involve gluing foam layers intended for the comfort of the users over the shell and covering it with a fabric cover.

3. THE TASK

The current paper presents one of the tasks of the R&D department of the company. The R&D department received a request from one of the company's clients to make a prototype of a chair that was already on sale, but was made of classic materials. Its original construction comprised a welded steel frame and injected polyurethane foam. Even though steel is recyclable, polyurethane foam is not and the client wished to turn towards environmentally friendly products.

The objective was to redesign the armchair so it could be made of plant fiber composite and manufacture a small run of 20 pieces.

The chair's initial CAD model is presented in figure 1. The version that would be redesigned by Taparo had to maintain the look and feel of the original piece of furniture. This meant keeping the same outside surfaces and the same curvatures, but also maintaining similar stiffness so that a regular consumer could hardly tell the difference between the two types of chairs.

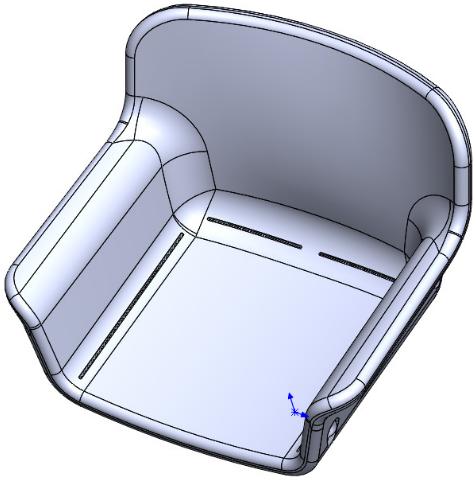

Figure 1. Initial CAD model of the chair

4. REDESIGN OF THE CHAIR

The chair was redesigned in order to conform to Taparo's manufacturing requirements. This meant picking the outer surfaces from the initial CAD model, the one made of steel and polyurethane foam, which are the most representative of the armchair's shape, and making an offset towards the interior part on which the user sits. The thickness of the offset was based on finite element analysis (FEA) and previous experience with similarly shaped pieces of furniture.

Besides this initial shape, steps were taken to modify and reinforce the areas where the legs supported the composite shell.

5. MOLD DESIGN

A simple two part mold was designed for the thermoforming of the chair's shell. The chair was set in a certain position inside the mold so that the mold would have a smaller height and the mold surfaces would have a draft angle of at least 3°, which ensured adequate demolding of the thermoformed part. The press available at Taparo onto which the mold would be mounted had a short stroke, respectively the maximum opening was small, therefore the height of the mold had to be kept small. In order to obtain the 3° draft angle, minor adjustments were made to the chair and to the mold. These resulted in unnoticeable cosmetic changes to the composite shell, but improved the demolding of the part significantly. Due to the fact that the mold has some surfaces close to vertical and it was made of laminated wood which had a rough surface and the material being pressed contained a large percentage of hemp fibers, there was a risk of the textile sheet becoming wedged between the two parts of the mold. Opening the mold would have become a very labor-intensive task in this case and would have probably resulted in damage to the mold surfaces, so trying to prevent this by using walls which were less vertical was an important optimization.

After talks with the design team, a decision was taken to make the mold core and cavity out of laminated sheets of wood which would be held together using long threaded bars and tightened with nuts at the end. For previous molds all the sheets were glued together, but this meant that if any of them got damaged during the thermoforming process, repairs would be very difficult since they couldn't be taken apart.

The CAD model was sectioned into sheets 15 mm thick that corresponded to the thickness of the laminated wood sheets. A total of 75 sheets were necessary for the core and another 75 were needed for the cavity. Because the profile of the sheet that went into the core was nearly identical to the corresponding one in the cavity, both profiles were cut from the same laminated wood sheet.

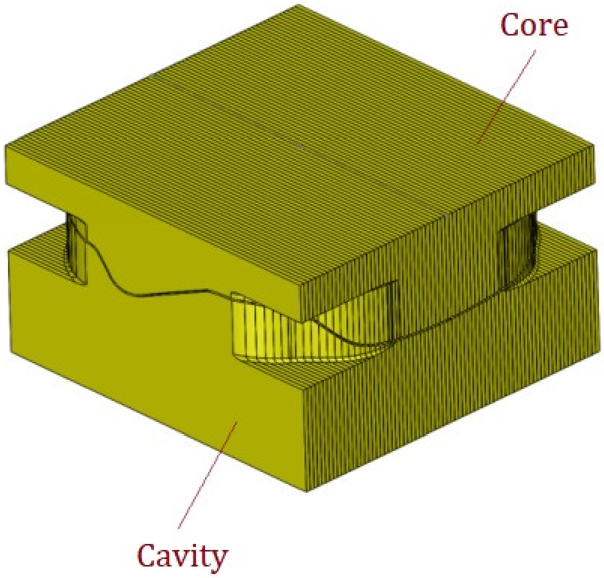

Figure 2. Assembled mold

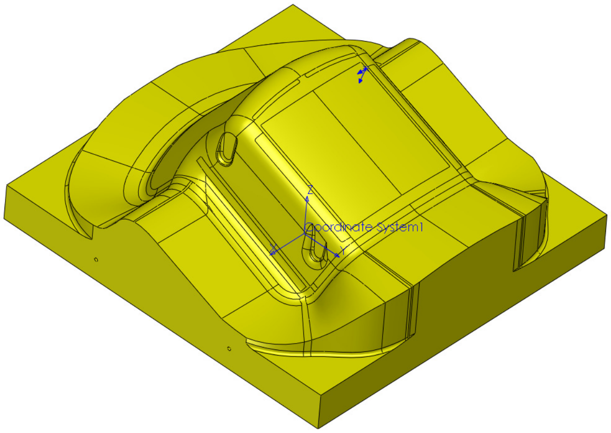

Figure 3. Mold core

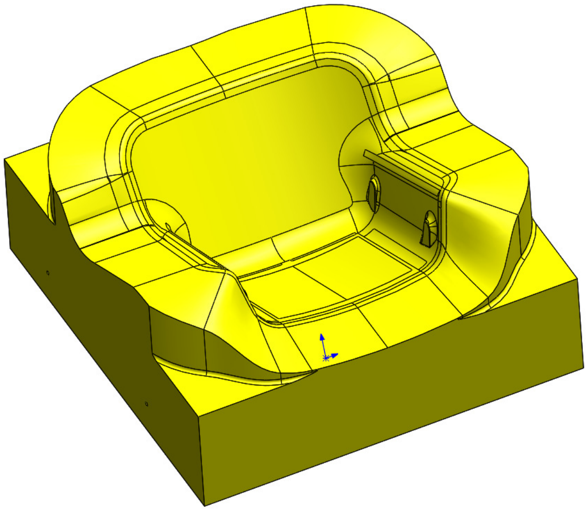

Figure 4. Mold cavity

6. CHOOSING THE MILLING MACHINE

It was clear from the start of the design phase that because of the large size of the mold and its complex surfaces it would need to be manufactured using a CNC machine. The closed mold would measure 1180x1125x650 mm and would weigh approximately 500 kg. However, a CNC milling machine that has such large travels is an expensive machine which the company doesn't own. This meant that normally the mold milling would have had to be outsourced to another company and because of the size of the parts it would have been a costly operation.

Fortunately, the company owns several large industrial robots, including a Kuka KR210 L150-2 2000 equipped with a high speed milling spindle and a large rotary table. The robot has large travels and can handle moving up to 210 kg at a maximum speed of 3 m/s.

Even though an industrial robot doesn't have the accuracy of a conventional milling machine, it can mill soft material parts to within a tolerance of ±0.5mm, which is sufficient for the thermoforming mold. A robot's accuracy is lower than that of machine-tools due to the fact that is has much lower stiffness and can encounter tool chatter due to its low natural vibrations [1].

The robotic arm has 6 rotary axes which allow it to work as a simultaneous 5 axis milling machine. The rotary table is represented as an external axis in the robot controller and can be moved independently or simultaneously with the other 6 axes. The table offers the possibility to turn the workpiece towards the robotic arm and makes access easier to different areas. There are examples of using similar machine setups for manufacturing architectural freeform shapes with good results [2].

The spindle is rated at 5.5kW at the maximum speed of 24000 rpm and has an ER32 collet chuck for fixing end mills. The speed is adjusted from a variable frequency drive (VFD) in 0.1Hz increments. This corresponds to 6 rpm increments at the spindle. The speed cannot be adjusted dynamically from a program running on the robot's controller, but has to be adjusted from the VFD manually.

Just as a normal machine-tool, the robot is capable of executing non-interpolated movements and also interpolated ones such as lines and arcs. Any move is programmed for the tool center point (TCP) in relation to the part origin, called the base. Any point used for the interpolated movements is defined by 6 coordinates: X, Y, Z, A, B and C. The values of X, Y and Z describe the position in millimeters in 3D space and A, B and C represent the rotations in degrees about axes Z, Y and X [3]. The rotations are executed sequentially in this order: first A, then B and last C. During an interpolated movement both the position and the orientation can change. When running a program the robot will always align the the X, Y and Z axes of the tool with the base when no other rotations are specified.

All the instructions are grouped in the main program which can address functions or subprograms. The programs conform to a language proprietary to Kuka that is similar to Pascal and is called Kuka Robotic Language (KRL).

There are some additional parameters that can be programmed. The speed of the movement and the accelerations can be set and the path on which the TCP moves can be approximated by parabolic segments so as to make the movements smoother and to use the motors' resources better. The user chooses how large this approximation is.

However, due to the fact that the robot has only rotary axes instead of some of them being linear such as for milling machines, programming is a bit more difficult. Singularities arise from the fact that the robot can have multiple axis angles for the same position and orientation of the TCP. These can be addressed either by including two additional parameters when specifying points or by positioning each axis at a certain angle that specifies the ranges of the rotary axes at the beginning of the program before using cartesian coordinates for the following movements.

Also the fact that the robotic arm is comprised only of rotary axes makes it more prone to collisions. This is why special attention needs to be paid to collision detection before running the program on the actual robot.

There is another difficulty associated with machining using the robot: the rotary table's surface isn't very precise and additionally the robot controller doesn't automatically move the workpiece origin with the turning of the table. This means that before a workpiece is rotated, small alignment surfaces need to be machined on its surface, which are used as a reference to remeasure the part origin once the rotation has taken place.

All these special requirements combined with the complexity of the surfaces to be generated led to choosing a specialized CAM software which is capable of calculating tool paths, detecting collisions and simulating the entire manufacturing process for robots: SprutCAM Robot.

7. PROGRAMMING USING SPRUTCAM

The SprutCAM Robot software was used to simplify programming and simulate the machining process. SprutCAM is a general purpose CAM software designed for programming machine-tools such as mills and lathes. It has numerous strategy packages for milling: 2.5 axes, 3 axes and even 4 and sequential or simultaneous 5 axes [4]. The robot version is developed specifically for serial robots and has some specialized features for controlling them. It has the possibility of changing the orientation of some of the robot's axes so that it adopts a certain configuration of the arm for the work to be done. It can also map the movements of the axes in order to see and correct abnormal or jerky movement. But most importantly it has a library of many makes and models of robot post processors. The post processor is one of the main differentiating feature compared to the standard SprutCAM software. It tells the software how to translate the TCP movements which are written using its own instruction set to the KRL format.

The programming was divided into two main sections: cutting the sheets of layered wood to a specific profile (fig. 5) and finish milling of the core and cavity of the mold (fig. 6).

The programming started with cutting each of the 75 layered wood sheets in pairs of profiled sheets that belonged to both the core and the cavity of the mold. Because the left and right sides of the mold were symmetric, a total of 38 programs were created, simulated and optimized using SprutCAM. The strategy used was "2D Contouring".

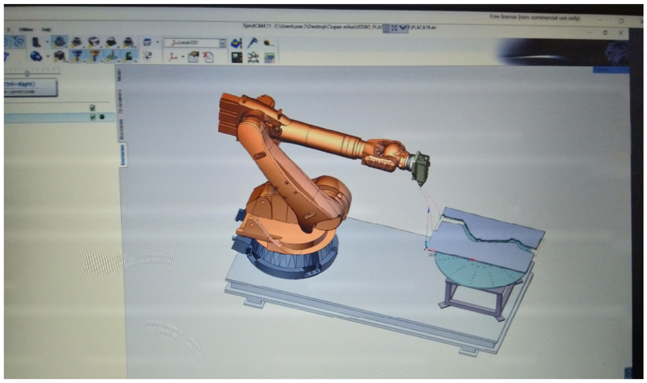

Figure 5. SprutCAM profile contouring

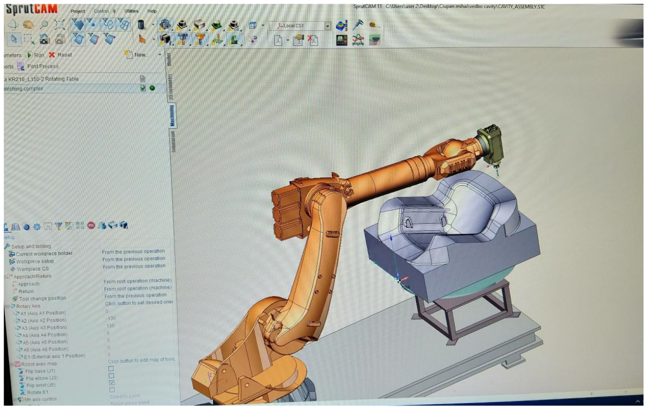

Figure 6. SprutCAM cavity finishing

Following this step, multiple programs were created for the finish milling of both the core and cavity. Each of the two mold parts had multiple programs because they needed to be rotated on the rotary table so the robot would have access to different areas.

The strategies used for the finishing of the core and cavity were a mix of 3+2 and simultaneous 5 axes. Even though from a technological perspective it is advantageous to use mostly simultaneous 5 axes milling for complex surfaces so as to keep cutting conditions close to constant, this was seldom possible since the CAM software could not control the position of the robotic arm very well. The arm either moved in such a fashion that it collided with the part or the robot's base or it simply went over its axis limits and the controller would issue an error and stop the movement. So most of the finishing was carried out by splitting the mold into areas, orienting the TCP so that the robot could reach them and machining them one by one using standard 3D strategies for complex surfaces.

The 3D strategies were “Waterline finishing” and “Plane finishing” and can be seen in figures 7 and 8. The “Waterline finishing” strategy is a constant Z-level milling operation which is suited for vertical and closer to vertical surfaces. “Plane finishing” is created by projecting a set of equidistant lines that lie in a horizontal plane onto the surface and offers the best results for horizontal and closer to horizontal surfaces. The strategies were combined by limiting the angle of the surfaces they could machine in order to take advantage of their capabilities.

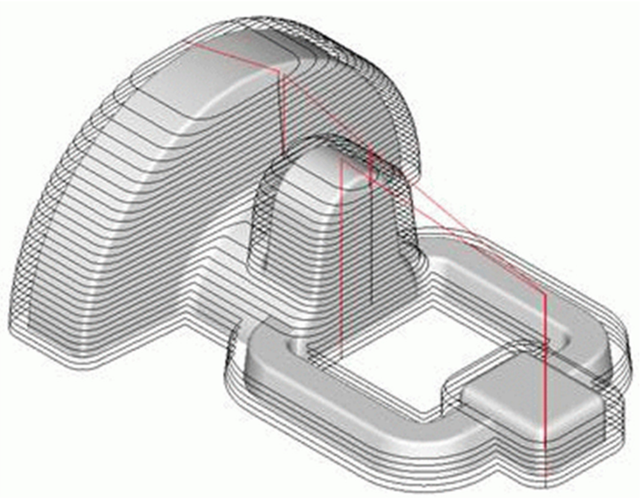

Figure 7. Waterline finishing

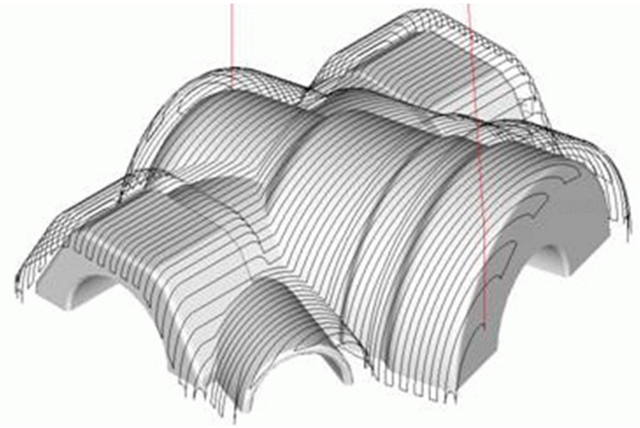

Figure 8. Plane finishing

Some of the milling parameters used for the finish milling were:

- tool: 12 mm solid carbide ball end mill;
- speed: 12000 rpm;
- feed: 5000 mm/min;
- depth: 5 mm;
- step between adjacent passes: 1.2 mm.

8. ACTUAL MANUFACTURING OF THE MOLD

Cutting the 75 pairs of mold profiles from the sheets (fig. 9) went relatively smoothly and was completed in approximately 20 work hours. In order to avoid milling the robot’s table, each sheet of wood was set on wooden blocks and screwed to them. The wood blocks lifted the sheet from the table so that the end mill wouldn’t damage it.

Figure 9. Actual profile contouring

The 150 profiles were each numbered at cutting time and were later assembled using threaded rods and tightened with nuts (fig. 10, 11). Large wooden handles were built and fixed using the same threaded rods for moving the mold. Care was taken when aligning the profiled sheets so that they would each fit in their proper place. However, while assembling the mold parts, it became clear that the laminated wood sheets had very large thickness tolerances: the 15 mm dimension varied by ±1.5 mm. This was corrected by the finish milling.

Then came the time to mill the cavity and with it a significant setback: the KRL program occupied over 6 MB of memory, and even though the robot’s computer was configured to accept up to a total of 12 MB of programs, the controller kept issuing an error saying it didn't have enough space. After some searching it was possible to access the registries of the Microsoft XP Embedded OS running on the industrial PC of the robot and change a memory setting which allowed copying large programs.

Figure 10. Cavity assembly

Figure 11. Assembled core

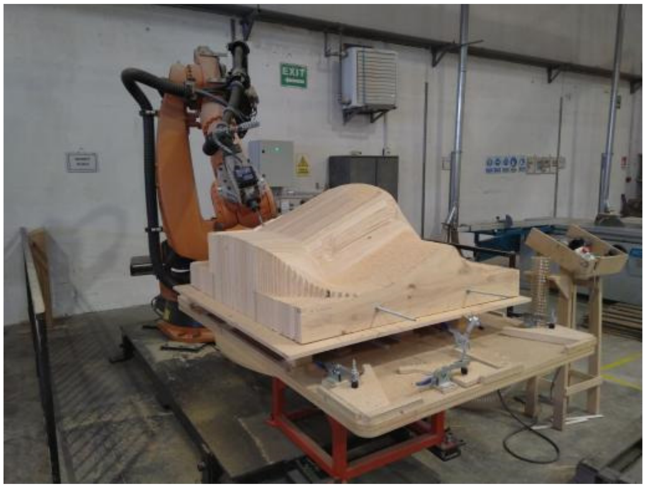

Figure 12. Core finish milling

This didn't prove to have a negative effect on the robot's operation and fortunately made it possible to run the whole finishing program without splitting it into more programs which would have been harder and more time-consuming to manage.

Figure 13. Cavity finish milling

Each new position of the rotary table used for either the cavity or the core required remeasuring the part origin, because the robot was not configured to compensate for this type of movement.

Because of the technical difficulties associated with working on large molds and substituting the milling machine with a robot (fig. 12, 13), the parts were completed in a total of around 60 work hours.

9. MOLD TESTING

The mold was tested by producing several thermoformed hemp and polypropylene composite chairs. It performed as expected and didn't exhibit wear following the small number of tries. This doesn't mean that it is a substitute for a steel or aluminum alloy mold, which can handle tens or hundreds of thousands of cycles.

Figure 14. Thermoformed chair shell

But it proves that it can be used successfully to prototype plant fiber composite furniture and make quick adjustments on a low budget that is a necessity in many pre-production runs.

10. CONCLUSIONS

The process that was developed for the manufacturing of thermoforming molds for small runs of plant fiber composite furniture offers satisfactory results. It shows a way to prototype large parts in a relatively short time all while keeping costs down and using materials readily available at the furniture factory. Care has to be taken when using laminated wood sheets since their thickness tends to vary a lot. If this is the case, then it's probably simpler to glue them together instead of using threaded rods and apply the same finish milling operations for obtaining a more accurate mold surface.

An industrial robot is a good alternative to a milling machine when the part finish and accuracy aren't very important. It is however more difficult to program and to get to work correctly, but the results are better than what is usually required in the furniture industry.

11. REFERENCES

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