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Research article

Design and manufacturing of a fully automated thermoforming machine for the production of confectionary boxes

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Abstract

Thermoforming, a method in which thermoplastic sheets are heated and reshaped to generate the desired output, has found widespread use in the packaging industry and the manufacture of disposable containers. The main problem in this process is predicting the thickness distribution of the final product without using trial and error methods. In this research, by considering the material model as a hyper–viscoelastic combination and also presenting a comprehensive model of the heating and forming stages, as well as conducting experimental tests and studying the behavior of HIPS and PVC polymers during the thermoforming process, an attempt is made to conduct a comprehensive study and learning about the thermoforming process. The design and construction stages of the fully automatic thermoforming machine for the production of plastic boxes for sweets are presented. The results show that the parts produced with a masculine mold have thinner walls than the bottom of the container. While this is completely reversed for the female form. Another thing that was discovered during the experimental tests was that by reheating the shaped container, the shape changes are completely reversed and the piece returns to its original state. This issue indicates the dominance of the hyperelastic behavior of the material. Furthermore, suitable thickness distribution in production components suggests that a good material model was chosen and that the process was executed properly.

Keywords: Hyperplastic, Thickness distribution, Thermoforming, Viscoelastic

1- Introduction

In the last few decades, various methods have been invented to make polymer products as engineering materials. One of the most important methods used to make thin parts that usually have a large area is thermoforming. Thermoforming is the reshaping of hot plastic sheets with the help of molds and air pressure. This method, which is one of the old and common methods of working with plastic materials, was invented in the 1960 [1]. In this method, the plastic sheet that is heated until it becomes completely soft is placed on the mold and then it is pushed into the mold by applying air pressure or suction of the trapped air between the sheet and the mold or by moving the mandrel or a combination of them [2]. After cooling, the sheet takes the geometry of the mold and remains in the same state. This process is used to make a wide range of products such as trays or toys to covers or compact cockpit covers. Also, the smallest parts, such as watch battery covers, and the largest parts, such as garden ponds, which have dimensions of about 5x3 meters, can be made by thermoforming. Material distribution in the direction of thickness and in line with the cut profile of the products produced in this way is the most important issue discussed in the thermoforming process. The thermoforming process is used in various industries such as construction and interior decoration, boat building, computer, packaging, electronics, design, home appliance production, automobile manufacturing, and hospital and health cases. But the most important application of the thermoforming process is related to the production of disposable containers and packaging industries. Wherever the topic of packaging is discussed, if it is important to avoid packaging with paper materials, without a doubt, thermoforming is the best and least expensive process possible. For example, in some materials, there is no need to make a mold. Rather, packaging can be done by placing the product itself on the table of the thermoforming machine. Disposable containers made of amorphous or foam materials are produced by suction thermoforming (for parts with a shallow depth) or by thermoforming with an auxiliary mandrel (for deep parts). The body of the refrigerator is made of Acrylonitrile-Butadiene Styrene (ABS) material by the method of retraction thermoforming.

The thermoforming process has different methods, and the general steps are almost constant in all of these methods. The following general steps can be considered for thermoforming: Heating, Transporting and closing the sheet on the mold, Reverse pre-stretching (optional), Stretching with an auxiliary mandrel (optional), Applying air pressure with suction, Cooling, Final operations such as removal or drilling.

Today, there are various methods to recognize a phenomenon or a process, among which methods based on finite elements are one of the cheapest and most efficient. But methods based on experimental tests are more valid. Since the mid-1990s, in-depth studies have been conducted on the thermoforming process and the effective parameters in this process, both experimentally and in the form of finite elements. McEvoy et al. [3] in 1998 simulated the blow-stretch molding process of polyethylene terephthalate bottles. They defined creep constitutive model as UMAT subroutine in Abaqus software. They found that by considering the cubic element along with the high friction coefficient, a reasonable approximation of the predicted thickness has been made. The application of air pressure was in two stages, in the first stage, bar 10 air pressure along with the movement of a pre-tensioning rod formed the piece, and at the end of the rod movement, bar 40 air pressure was applied to complete the final shape of the piece. The use of the shell element in cases where the thickness change is one of the important output factors, seems to be inappropriate. The modeling was carried out isothermally and by comparing the simulation results with the experimental results, it was found that the simulation results are slightly larger. Nam et al. [4] simulated suction thermoforming and thermoforming with auxiliary mandrel using membrane element and hyperelastic material model. Also, in order to validate the simulation, they conducted experimental tests on Acrylonitrile-Butadiene-Styrene (ABS) materials. They extracted the properties of the materials by performing a hot tensile test. Three-dimensional modeling and considering temperature effects are good aspects of this research, but due to the assumption of the membrane element, the effects of bending and stress along the thickness have been removed, and the material model is not subject to strain rate. Lee et al. [5] also investigated the effects of rheological properties and the effects of process parameters on the final quality of the production part and chose the retraction forming process for this purpose. Wagner's nonlinear viscoelastic model was chosen for simulation, and the rheological properties of the material were included in the problem by changing the parameters of the material model. The focus of Marckmann et al. [6] is on the development of an explicit dynamic method for solving and numerically simulating the thermoforming process. In this work, the Mooney-Rivlin hyperelastic model was used to model the behavior of the material and the membrane element was used for meshing. Sticky friction was assumed to be true at low mold temperatures. Experimental tests were conducted in order to compare the results with simulation results, and according to the researchers' statements, although the results were close to reality, more work should be done to improve the results. Warby et al. [7] performed the problem of numerical simulation of the thermoforming process at different temperatures and loads. Stress-strain diagrams were extracted at different temperatures and strain rates, and modeling of the behavior of the material was done in an elastic-plastic way. In this research, simulation was done only for the forming stage and other thermoforming stages were ignored. Pham et al. [8] worked on the modeling of the blow molding process of PET bottles and stated that when the molding is done, these materials show strain hardening properties, which strongly depends on the strain rate. and temperature dependent. In this study, the isohyperelastic model was used to describe the behavior of the material and the membrane element was used for meshing. Biaxial tensile test was used to determine the properties of the material, which obtained good results. Aus der Wiesche [9] simulated all the stages of the thermoforming process of a car fuel tank. Conductive and radiative heat transfer during heating, deformations and stresses in the forming stage and the cooling stage were simulated. The rheological and thermal behavior of the material was studied in more detail. With the information obtained from the results of the experimental method, it was found that the simulation of the transient phase during heating is very important for correctly predicting the thickness distribution of the part walls . In their research, Dong et al. [10] focused on simulating the finite elements of transparent sheets using the explicit dynamic method. The hyperelastic composite model based on the Money-Rivlin and Ogden model and sticky friction is considered in this research. The results were compared with William's analytical method and with the results of Grid strain analysis (GSA), which is an experimental method. Modeling was done only on the forming stage and isothermally. The results of the simulation obtained at a pressure of 20 kPa showed a good agreement with the experimental results, but at a pressure of 40 kPa, it was a little lower than the experimental results. Chen et al. [11] first printed a checkered grid on two sheets with thicknesses of 0.125 and 0.2 mm and then thermoformed it into a cup shape under different conditions. The effects of process parameters including mold temperature, sheet preheat temperature, mandrel speed, mandrel holding time and mandrel movement depth on the thickness distribution and dimensional changes of this square grid were investigated. The result was that with the increase in the temperature of the mold, the preheat temperature of the sheet and the time and depth of the mandrel movement, the changes in dimensions and thickness increased and decreased with the increase in the speed of the mandrel. O'Connor et al. [12] used biaxial tensile test to obtain material properties and as a result, hyperelastic material model was used to simulate compression forming process with auxiliary mandrel in ABAQUS software. Due to the cylindrical nature of the container, the axially symmetrical simulation technique was used for modeling, and the mandrel and mold were modeled rigidly. The thickness of the containers was measured in 30 different positions along their profile and compared with the actual function. The result was that the hyperelastic model is not suitable for simulating the behavior of polypropylene materials. It was also reported that the standard friction model was not suitable for simulating the friction behavior and needs further study. Oksuz et al. [13] investigated the effects of different molding conditions of polyvinyl chloride and polyethylene materials in their article. Mechanical properties and microstructure of materials were determined by tests such as tensile test, tear resistance and scanning electron microscope. The effect of different mold depths and process temperature on the samples was determined by performing thermal aging process on the first, third and seventh days. In another study by O'Conner et al. [14], the same previous work that was about simulating thermoforming with an auxiliary mandrel was done this time with a viscoelastic material model. The viscoelastic model used was the Sweeney model, which could model the longitudinal and transverse movement of polymer chains. It was stated that the used model has the ability to accurately predict the thickness distribution, especially at different temperatures and strain rates, but the temperature range of the tests should be expanded in order to develop the model parameters for a better and more economical performance of the material behavior. O'Connor et al. [15] in 2013 simulated mandrel-assisted thermoforming of polypropylene materials with a large heat-strain coupled model. They stated that their composite model has a good match with the results of the biaxial tensile test and the used model is able to model the behavior of the material during forming.

A literature survey shows that most earlier investigations employed hyperelastic or viscoelastic models to determine material properties. This study attempts to conduct a comprehensive study by considering the material model as a hyper-viscoelastic combination, presenting a comprehensive model of the heating and forming stages, conducting experimental tests, and studying the behavior of HIPS and PVC polymers during the thermoforming process.

2- Design and manufacture of the device

Design is the knowledge of creating a plan from a mental, imaginary or realistic image. The design of industrial devices has always been one of the most complex designs of the day, because in this design, factors such as safety, standards, consumption factors and waste of the device must be examined. In this section, the process of designing and manufacturing a fully automatic thermoforming machine is explained.

2-1- Standard

In the design of the current machine, things like the production capacity, the best production dimensions in such a way that these dimensions are in accordance with the size of the most produced parts and at the same time have good production conditions for the machine, are important. The dimensions designed for the device are 50 cm x 70 cm, which can be changed to 20 cm x 20 cm. This machine is designed to produce 4 molds because less number of molds increases production cost and time, and more number of molds makes production conditions difficult and reduces its quality. The design is done in such a way that the device consists of standard parts. Therefore, the after-sales service facilitates it, and it is possible to buy replacement parts easily and at a reasonable cost.

2-2- Safety

One of the most important reasons for mechanizing a system is to ensure the safety of the workforce. If safety is not considered in the design and construction of a device, while it can have more risks for the workforce, it may be the biggest weakness of the design and even the construction. In the design of the automatic thermoforming machine, by observing the safety conditions and power transmission from the motor to the conveyor belt through belts and pulleys (Fig. 1) and smooth operation, which causes a stop in the work in case of possible errors, to the extent It has been tried to ensure the safety of the device.

Fig. 1 A photo of the drive belt and pulley of the device

Another motor that is directly connected to the spiral screw is a nut that moves the tray and is coupled by teflon pins that are cut with the slightest pressure and the nut works in the screw. (ball-screw). In addition, the place where the chain travels and the belt rotates is covered by the frame. In addition, for the safety of the workforce, in the design of the device, optical sensors are considered in places where there is a possibility of danger for the operator, so that whenever the operator's hand or an object is placed in the path of these sensors, the device stops working. In addition to the above, in the design of the device, one-way pneumatic solenoid valves are used so that when the power is cut off or the device is reset by the sensors or the operator, the jacks with one-way valves will return to their original location without receiving an electrical command. Prevent the damage of the material or the jamming of the jacks and the jacks from being opened.

2-3- Consumption factors

One of the factors considered for the design of a device is the consumption costs, which has a direct relationship with the total price. The system designed for the operation of the device with PLC control is single-phase electricity and converting it to 24V, which is important both in terms of safety and the life of the sensors around the device, and it consumes little electricity.

The heating system of the device is for melting the material and bringing it to the hyperelastic level. The heating system can be designed by the methods of induction heating plate, direct heating plate, gas element plate, and combined heating plate. The combined thermal plate system is used in the design and construction of this device. The system in this type of heater, similar to spring or rod elements, can be fitted with a desired number of elements in x and y directions by placing a rake or protector. Among the advantages of this method, we can point out the precise adjustment of the temperature on the surface, easy replacement, and the uniformity of the heat between the two elements because the heat is induction. The disadvantage of this method is that it takes more time to turn on and be ready to work than other thermal plates, and it cannot be turned off during work and free time and turned on during use.

2-4- Waste

The two parameters that affect the final price of each piece of production are the production time and the amount of waste. In this process, if the number of production is limited, it is better to use a fixed width and length to avoid the wasted time of changing the mold, but as a result, the amount of waste may increase, and since the initial quantity is not massive, the waste can be ignored. Because, compared to the compensated time, changing the mold can be omitted and cost-effective. For example, it is possible to produce a piece with a width of 35 and 38 with a sheet width of 40. In this process, there is no time to change the mold, but the material cost is the same for the piece with a width of 35 and 38. It is obvious that if the number of production is significant and massive, then the cost of waste is much more than the cost of changing the mold. In the current design, while the dimensions of the production can be changed, the amount of the side of the work (which is called the edge of the production claw) is half of the amount of similar devices, and this is one of the best points of this device and one of the most important goals of its production.

2-5- Device construction

The construction of the automatic thermoforming machine consists of three stages: the feeding part, the sheet production and cutting part, and the material transfer and packaging part. Below is a brief description of each of them. The feeding part consists of two stages of opening the roll and pulling the roll. Two mechanical and electronic methods can be used to open the roll. In the electronic method, a motor is attached to the roller and the amount of opening of the roller can be adjusted by a sensor. While this method increases the construction cost, sensor settings and opening control can destroy the ease and simplicity of the work. But in the method implemented in this research, which is a mechanical design, the roll is always opened by two jacks of a fixed amount. In this function, the diameter of the roll being produced has no effect on the amount of opening of the material, and the roll is always opened by the amount of one meter roll, regardless of its diameter (Fig. 2).

Fig. 2 Photo of the feeding part of the device

The sheet production and cutting part can be designed in two ways:

a) The heater of the device should be placed before entering the material into the forming part. In this case, you can use the latest production power of the device. That is, when the material is being formed, the next material is heated and ready to be formed so that it does not need heating time in the next step. In fact, the production process is always heating and shaping. The weakness of this method is the cost of the mold and making the machine more complicated. Due to the high speed production, the production mold needs a circulating water channel and the machine must be equipped with a chiller and a cooling system to prevent the mold from heating up. . Because overheating of the mold prevents the material from cooling down and when the material is separated from the mold, it loses its shape. In this method, most similar devices with a wind cooling system on the mold compensate for the excessive heating of the mold. In addition, due to the use of food production, instead of using compressor air, which is sometimes accompanied by moisture and dust, the dependence of the heating time and shaping of the material has been prevented, and its heater heats the material at each stage. And the forming process is done after the sheet is heated and with the required amount.

b) The heater of the device should be placed in the forming part after entering the material. In this case, the material's heating time and production time are separate from each other. Actually, these two processes are executed in two separate stages. The merits of this method include the non-dependency of the heating and shaping process, the optimal heating and cooling time of the piece, the longer distance in production and as a result the mold breathes and does not overheat, and more reasonable time. Pointed to the mold to cool the material. This type of design was used in the design of the device that was done in this thesis. Some of them are given in Fig. 3.

Fig. 3 Production part of the device

2-6- Material transfer and packaging

Another production parameter is the product packaging time, and in fact, the bottleneck of a mechanized production is the points where human power is involved. The most unique strength of the currently designed device is the packaging of the manufactured products and the elimination of the conflict of labor to collect them, which in similar devices, human labor with several stages of production must collect and package the manufactured products. One of the problems we faced during the construction of this machine was to transfer the materials to a higher position in order to arrange the number of produced materials and as a result, the time to empty the tray of the machine was longer. This work was done by a chain conveyor with a height difference of 1.5 meters and an angle of 30 degrees (Fig. 4), which increases the time to stop the machine and empty its tray by one hour without any human intervention. This possibility allows the workforce to be busy with other production tasks or sometimes setting up and managing several machines at the same time during the filling of the production tray. The tray of the machine is controlled by PLC after each production cycle to the required amount and when the engine is on, the tray is lowered by a nut and a trapezoidal screw and placed on top of each other with the design of the guides according to the width and length of the produced material. (Fig. 5).

2-7- Device mechanism

In semi-automatic packaging machines, electrical parts are used during the mechanical functions of different parts of the machine to perform the production process, which are used by contactors and microswitches, timers and start and stop keys. The advantages of these systems can be mentioned as simplicity of changes and speeding up troubleshooting and low initial cost, and naturally, their biggest disadvantage is low accuracy and high depreciation of parts (due to mechanical performance and collisions), more difficult settings and limitations. circuit boards and output bases of the parts. In fact, to add each new command, many parts will be needed, and the production process requires the movement function before each step, and due to the mechanical nature of the system, the possibility of the device getting stuck is very high. In order to increase the operational reliability factor, command changes and diversity in the input and output, the automatic thermoforming machine designed by a PLC model was started and programmed by the ladder method. The safety of the device was provided by optical sensors. The conveyor belt movement system was designed by a drive, and the back and forth movement and the moment of approaching the material became very regular and gentle by changing the frequency. Due to the use of PLC, all the microswitches and wiring of the device, except the motors, the heater and the three-phase fan, were designed and implemented with 24V electricity. This issue prevents the electrical hazards of the device and prevents harmful electrical events and accidents. An example of the device's command screen is given in Fig. 6.

2-8- Device control system

As mentioned, the control of this device is controlled by a PLC, including the model B1-24mr2-dC, three modules B1-16xyr, B1-8yr, B1-L2da, a Teco inverter model s310-1.5kw and a power supply model adp-24v-1A. The PLC program is written by winProlader software and in the fence method. (Fig. 7)

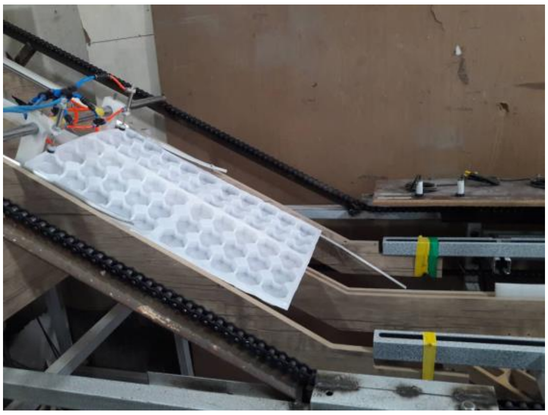

Fig. 4 Conveyor belt with height difference from the production surface

Fig. 5 Packaging tray of the produced material

Fig. 6 Device command screen

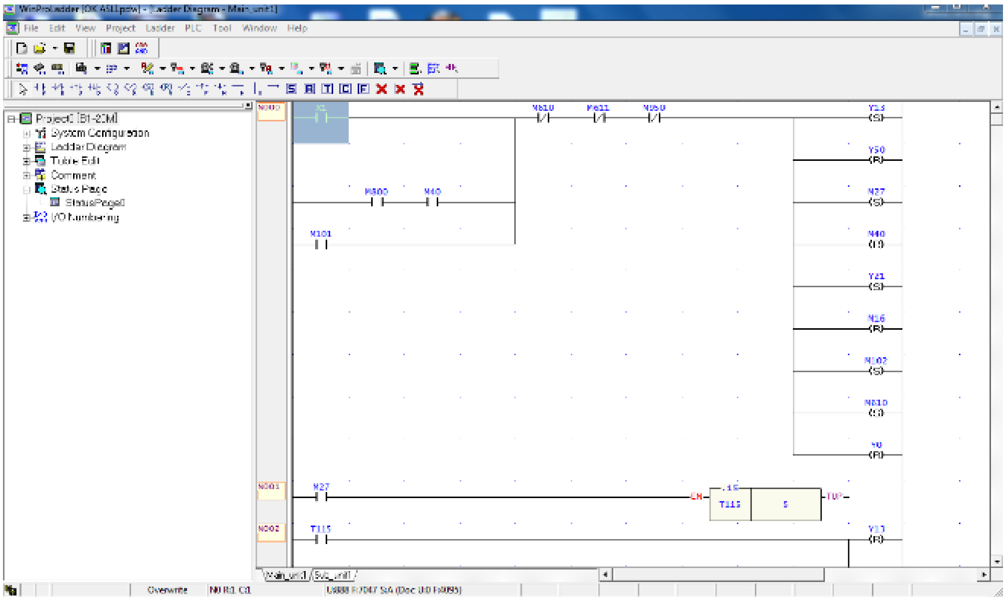

Fig. 7 Diagram of the PLC program written with winProlader software and the fence method.

RESET and SET commands are used for more reliability and accuracy. The parts that need to be controlled in the HMI use an R variable so that the time of timer can be changed in the HMI. In total, about 70 timers and 110 temporary memories have been used in this program, and most of the timers have been used to disable the internal memories. It should also be mentioned that the HMI of this device is programmed by FvDesigner software (Fig. 8).

HMI commands consist of two automatic and manual parts, which are programmed in the manual part of all operators by a zero-one key. (Fig. 9)

Fig. 8 Diagram of FvDesigner software for HMI programming

Fig. 9 Diagram of operator programming

In the automatic control part, one key for START and one key for automatic, and three mold, heater and suction timers are programmed to control the operators, which can be changed. The sensors are 24VD optical and PNP type and are connected to PLC by nine inputs. The number of outputs of this PLC is equal to 26 digital numbers and one analog number to control the inverter. The inverter is controlled by an optical sensor. In this way, the first sensor reduces the speed of the conveyor by changing the frequency and the second sensor completely stops the movement of the conveyor.

3- Results

Fig. 10 shows an example of a product manufactured with an automatic thermoforming machine. As it can be seen, the points are numbered with the help of the software, just like the model used in the analysis.

In Table 1, the results related to the thickness of different points of the product produced for two times of testing are given. The temperature in these tests was considered to be 130 degrees Celsius. As can be seen, the results for both products are almost close to each other at different points. This article confirms the production of a product with almost constant quality. To have a better understanding of the numbers presented in the above table, the results are displayed graphically in Fig. 11.

Table 1: The thickness of different points of the two produced samples

		P0	P1	P2	P3	P4	P11	P12	P13	P21	P22	P23	P24	P31	P32	P33
1	$T = 130^{o}$ C	0.2	0.19	0.18	0.16	0.13	0.11	0.16	0.19	0.18	0.17	0.14	0.11	0.15	0.18	0.09
2	$T = 130^{o}$ C	0.2	0.18	0.17	0.15	0.12	0.09	0.12	0.18	0.18	0.17	0.16	0.15	0.13	0.19	0.09

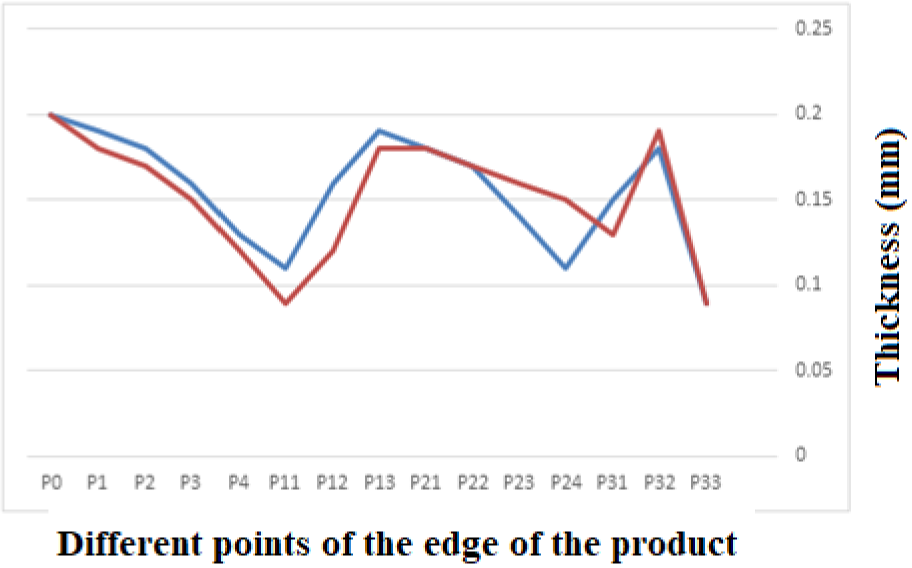

Fig. 11 Comparison of the thickness of different points of two manufactured product

4- Conclusion

According to the results obtained from experimental studies, the following can be considered as the most important results obtained:

- The maximum thickness difference in sheets with different initial thicknesses did not change. In other words, the initial thickness has no effect on the maximum thickness difference, but the average thickness value was exactly doubled by changing the initial thickness from 0.25 mm to 0.5 mm. That is, the same initial thickness ratio is maintained.
- The deformations created in the material form are mostly biaxial, but in the male form they are uniaxial.
- By heating the produced part again, the polymer completely returns to its original state, which shows that the material is hyperelastic. This phenomenon can be explained in this way that during shaping, after the completion of the part, since vacuum is still applied to the part and the polymer is also cooled in the same state, the polymer chains are completely hardened and remain in the same form as they were cooled. they stay But by heating again, the chains are released and it is possible to release the stored strain energy and return to their original state.
- Experimental observations show that a larger area of the sheet is used in the male mold than in the female mold, and due to this, the parts produced with the female mold have a lower average thickness.

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