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TOOLING DEVELOPMENT FOR THERMOPLASTIC COMPOSITES THERMOFORMING PROCESS BASED ON FEM ANALYSIS – A RIB CASE STUDY

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Abstract

Remarkable characteristics of high temperature thermoplastic (HTP) matrix used in composite materials reinforced with continuous fibres causes growing application in composite industry. Because of high processing temperature of some semi, crystalline matrix there is limited number of technologies that can be used for part manufacturing. Press forming is an example of technology that allows manufacturing high quality complex parts made of HTP reinforced fibres composite. In order to manufacture part with acceptable quality and mechanical properties, uniform pressure distribution during the process is required.

In this article, tooling design process focused on uniform pressure distribution for manufacturing of supporting rib was presented. In order to satisfy this requirement, the rubber stamp was proposed as a tool for manufacturing. Typical press forming process defects were identified and the requirements for rubber stamp were described. It was assumed that the forming process has to begin at one point on mould surface and sequentially continue in all directions. For stamp material, the two components additive silicone was selected. The hardness of the silicone was equal 40 Shore A. The rubber mechanical properties was determined through the additional tests and used for stamp designing. The tooling was designed using FEM software ABAQUS 6.12.

The sequence of stamp shape designing and optimization in order to meet the stamp requirements was presented. At the end the FEM rubber stamp designing recommendation were presented.

Keywords: *rubber thermoforming, rubber press forming, thermoplastic composite*

1. Introduction

Outstanding characteristics of PEEK matrix, such as impact damage resistance or welding capability, cause rising material usage in industry [1]. Although the matrix has many desirable features, the high processing temperature i.e. 250-400°C, limits the number of technologies that can be used for part manufacturing. Currently two of them are being used – press forming (often also called thermoforming) and automatic fibre placement (AFP).

The thermoforming process, which last 2-10 min, consists of four main stages: heating the material in IR oven, transporting hot material under the press, quick part forming and, at the end, consolidating [2, 3]. Although all stages are necessary to manufacture the part, the most critical one is forming.

In this stage, during few seconds, the material is formed from hot quasi-flat panel into desirable part shape. In order to avoid manufacturing defects, the designed forming process has to meet two requirements. Firstly, the designed process has to be realized in processing window defined in material data sheet e.g. TenCate TC1100 [3]. Secondly, the designed tooling, particularly stamp, has to allow forming process with uniform pressure distribution and the defect-free. The pressure distribution is critical to obtain uniform mechanical properties.

In order to form the fabric into the desired shape, the fabric has to be deformed through the following mechanisms [4]:

– intraply shear,
– intraply tension,
– intraply ply/tool or ply/ply shear,
– ply bending,
– compaction/consolidation.

Realization of these mechanisms demands forming forces to be applied to fabric with proper value, direction and at appropriate stage. Additionally, the tooling has to allow for fabric deformation and for uniform pressure distribution.

The tooling can be made of metal or rubber material. Nowadays industry prefer matched metal dies but in case of rib manufacturing it is difficult to apply forming pressure on vertical flanges [4] or/and dimples. Rubber in contrast to metal allows applying uniform pressure across all mould surfaces (both horizontal and vertical). That is due to its quasi-incompressible behaviour (only on condition that the rubber volume is closed). This feature makes rubber an ideal stamp material for rib manufacturing technology.

The rubber stamp design problem are extensively described in [5]. Despite of the rubber advantages like quasi-uniform pressure distribution or high strain capability, stamp designing process demands taking into account some typical rubber features which are described later in this article. To deal with it, FEM analysis could be used in order to optimize stamp shape.

This article presents the case study of FEM optimization of stamp shape. For this purpose, the requirements for stamp shape and material were described. Based on this, the rubber material was selected and its mechanical properties were determined. Then the stamp shape designing with FEM analysis was conducted. In the end of the article, the conclusion and recommendation obtained during this study were described.

2. Rubber stamp requirements

Requirements for stamp can be divided into two groups: requirements for rubber material and requirements for rubber stamp shape.

The material selected for stamp manufacturing should be characterized by:

– high thermal resistance,
– high deform capability,
– low coefficient of thermal expansion,
– low coefficient of thermal conductive,
– high tear strength,
– anti-stick capability;

The requirements for rubber stamp shape are connected with blocking fabric deformation mechanism presented in Fig. 1 [5].

On the left side, the barrelling effect is presented. Pressure applied to the rubber causes its deformation in all possible direction. If the material is clamped to the vertical wall to early, the friction force and low fibre straining capability will make impossible to fully form the part.

On the right side, the material is clamped by friction between material and the tooling. In this case, the part forming is stopped because either the area of friction is high enough to clamp the material or some assembling inaccuracy between the stamp and the mould has occurred.

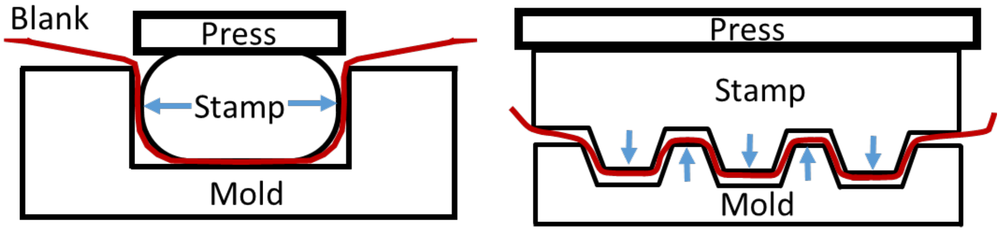

Fig. 1. Clamping laminate before forming completion. The clamping locations are presented with blue arrows

3. Process assumption

In order to design the stamp which meet the requirements, the following idea of forming process was proposed (Fig. 2).

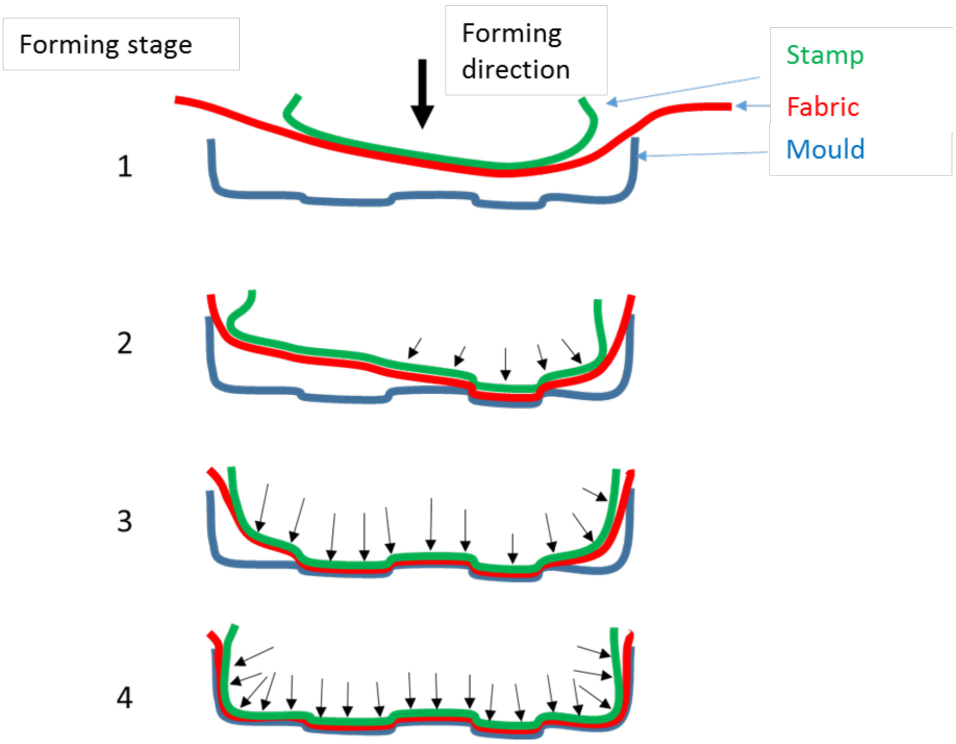

Fig. 2. The idea of sequential forming process

In this process, first the right dimpling will be formed. Than the rubber, deform sequentially to form middle segment and left dimpling. It is assumed that the fabric will be pressed sequentially from the middle point of the right dimpling to the part edge without any premature clamping.

4. Rubber mechanical performance determination

The described requirements for the stamp material can be satisfied by casting silicone with hardness 40ShA. In order to define rubber FEM material model coefficients, two uniaxial strength tests were conducted i.e. the tensile and compression tests. The samples were designed according the guidelines of PN-EN ISO 527-2:2012 for tension test and PN-87/C-04289 for compression test.

The test was controlled by constant crosshead displacement of 5 [mm/s], which was similar to displacement rate of the press during forming. Both tension and compression were conducted with the same rates. The results of tests – stress-strain curve are shown in Fig. 3.

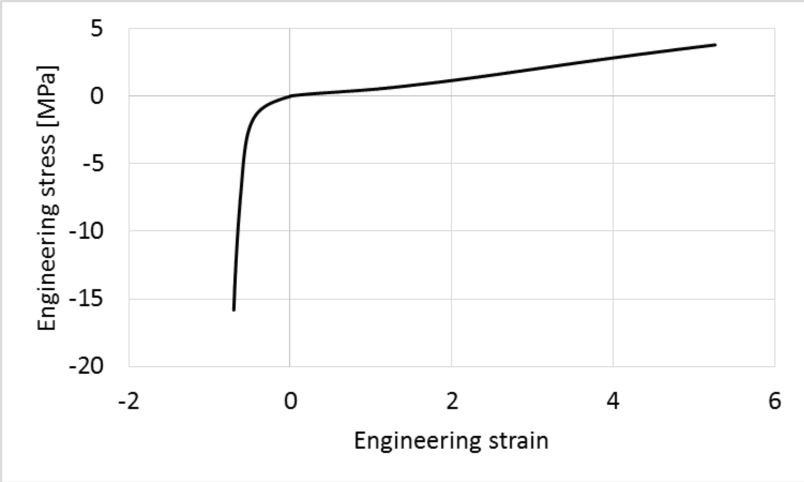

Fig. 3. Stress – strain curve for silicone

5. Part description

The designed composite rib has 1.2 mm thickness. The mould is made of aluminium alloy 7075. The geometry of the rib and the bottom mould geometry are presented in Fig. 3.

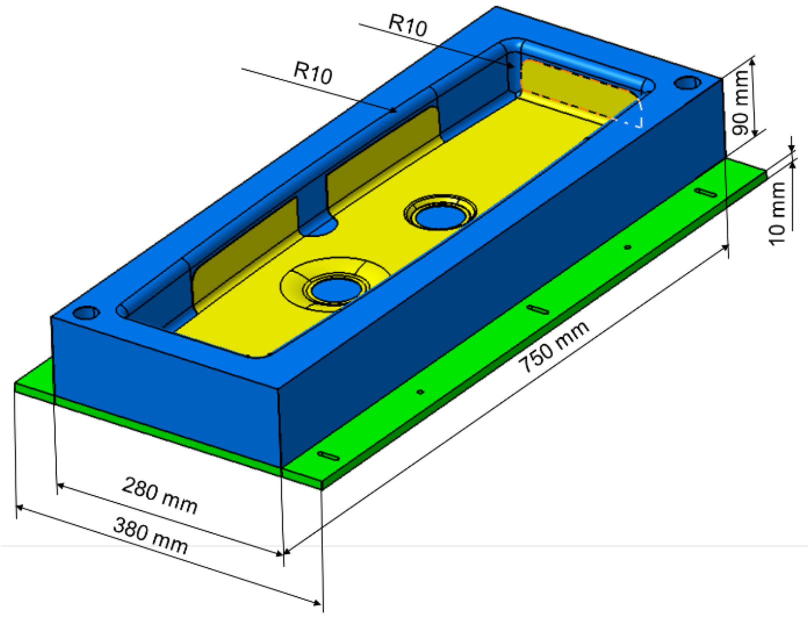

Fig. 4. Rib and bottom mould geometry

6. FEM model

The initial stamp shape was designed using 2D model. In order to optimize the rubber shape taking under consideration two designed dimples, barrelling and clamping rubber effect, the 3d model was prepared.

The model consist four parts: Rib, Rubber Stamp, Mould, Stamp Holder (Fig. 4). The Rib, Stamp Holder and Mould were modelled with rigid elements. The rubber stamp was modelled with solid elements C3D8R (according to Abaqus documentation notation [6]). For simplicity, the fabric model was neglected.

The rubber was modelled with hyperelastic material model – Mooney-Rivlin. The materials constant are presented in Tab. 1.

Tab. 1. Mooney-Rivlin material model constants

C10 [MPa]	C01 [MPa]	D1
0.255	0.089	0.0058

The boundary condition of the rigid body is presented in Tab. 2. The rubber stamp was rigidly constraint with Stamp Holder using nodal equation. The movement of the Stamp was controlled by Stamp Holder reference node and it was equal to Z (Tab. 2). The analysis was conducted using ABAQUS/Explicit 6.12.

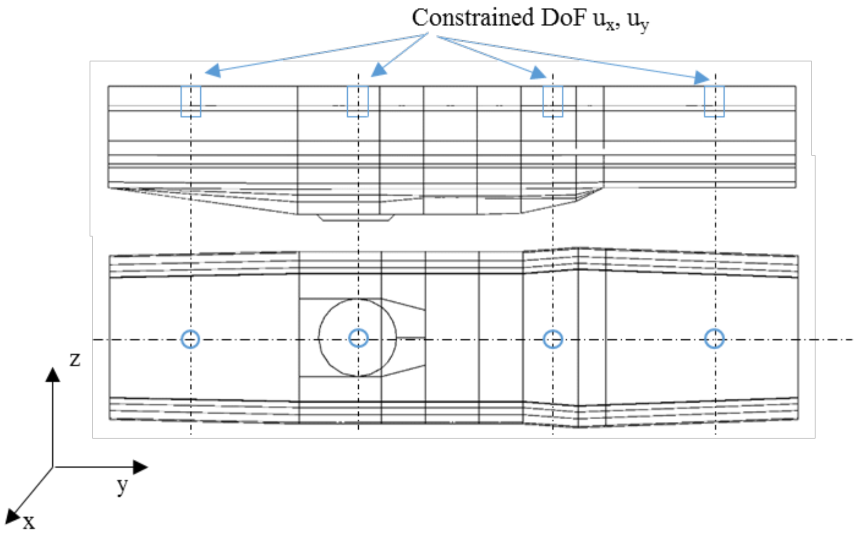

Fig. 4. The four-part model: Rib, Rubber Stamp, Mould, Stamp Holder

Tab. 2. Boundary condition of the rigid elements

Part	u_x	u_y	u_z		r_x	r_y	r_z
Silicone Holder	0	0	Z		0	0	0
Rib	0	0	0		0	0	0
Mould	0	0	0		0	0	0

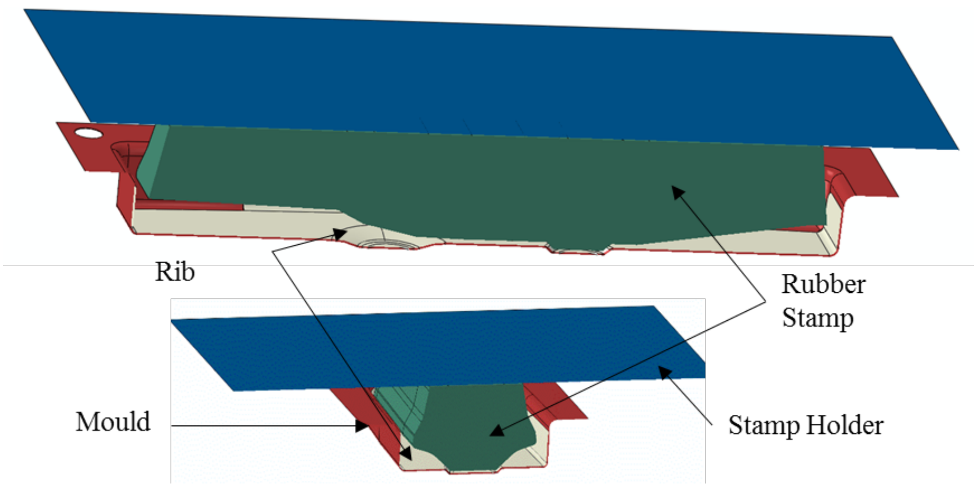

Fig. 5. FEM model; the rib, stamp holder and mould are modelled as rigid surface; the Rubber stamp is modelled as hyper elastic model

The parts were interacted with each other through General Contact Interaction. The friction coefficients were selected arbitrary and the values are presented in Tab. 3.

Tab. 3. Friction coefficient

Part 1	Part 2	Normal contact description	Tangential contact description
Rubber Holder	Stamp	„Hard" contact	Penalty, f = 0.1
Stamp	Rib	„Hard" contact	Penalty, f = 0.3
Rib	Mould	„Hard" contact	Penalty, f = 0.3

7. Results

The results of the analysis were the sequence of the rubber deformation. In total, 30 analysis were carried out. During this process, the shape of the stamp was optimized in order to obtain sequential pressure application on mould and part surface.

The analysis shows possibility of rubber deformation, which can hinder formation of the fabric Fig. 5-7. According to forming idea (Fig. 2), the rubber starts applying the pressure in right-hand side dimpling area. During press, forming the pressure area continuously grows until the press reach the position for which the whole part is formed (Fig. 2). In presented numerical model, the pressure area grows until the stamp holder reach the position for which the rubber applies the pressure to all part surfaces (both horizontal and vertical). If during forming (rubber deformation) some gap between mould and rubber occurs (Fig. 5-7), the stiff fabric fibre can disturb the forming process. For relatively high friction force and because of high fabric stiffness, the fabric will be clamped between point 1 and 2 (Fig. 5) and it will block the forming of concave part surface. The part will have improper shape, and the concave surface will not be fully consolidated. This effect will be especially important in case of carbon fabric where the tensile modulus is about 230 GPa.

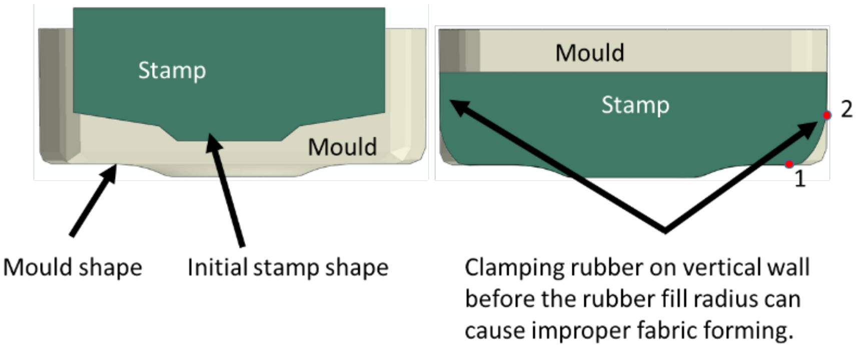

Fig. 6. Fabric fixing caused by friction force applied on the vertical wall can result in low pressure on concave part surface and increasing residual fabric stress

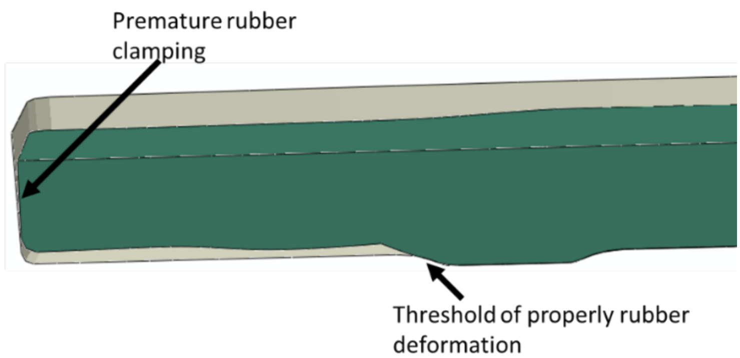

Fig. 7. Too long stamp and barrelling effect can results in fabric fixing on the vertical wall

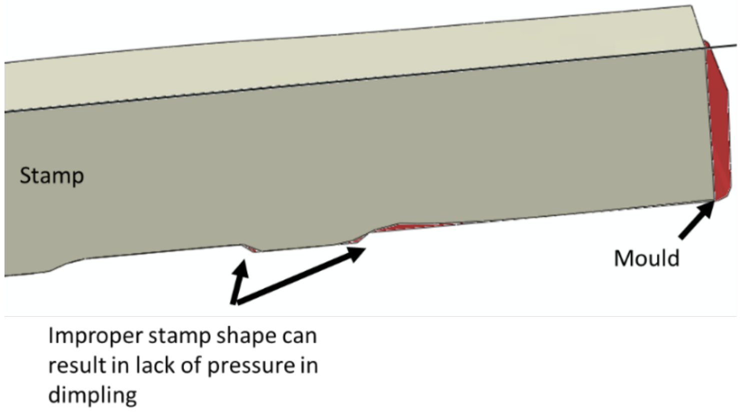

Fig. 8. Improper stamp shape can result in lack of pressure around dimpling

Figure 8 presents main stages of stamp optimization. During the optimization process, stamp details were successively corrected so that the continuous process could be obtained. The final stamp geometry is presented in Fig. 8f.

According to Fig. 2, the forming process begins at the right-hand side dimpling. Then the rubber deforms and apply the pressure in area 2 (Fig. 8f). At the same time, rubber deforms in transverse direction in area 3 and 4. Next the second dimpling (area 5) and the rest of horizontal surface (area 6) are formed. At the end of the process, the vertical walls are shaped (area 7).

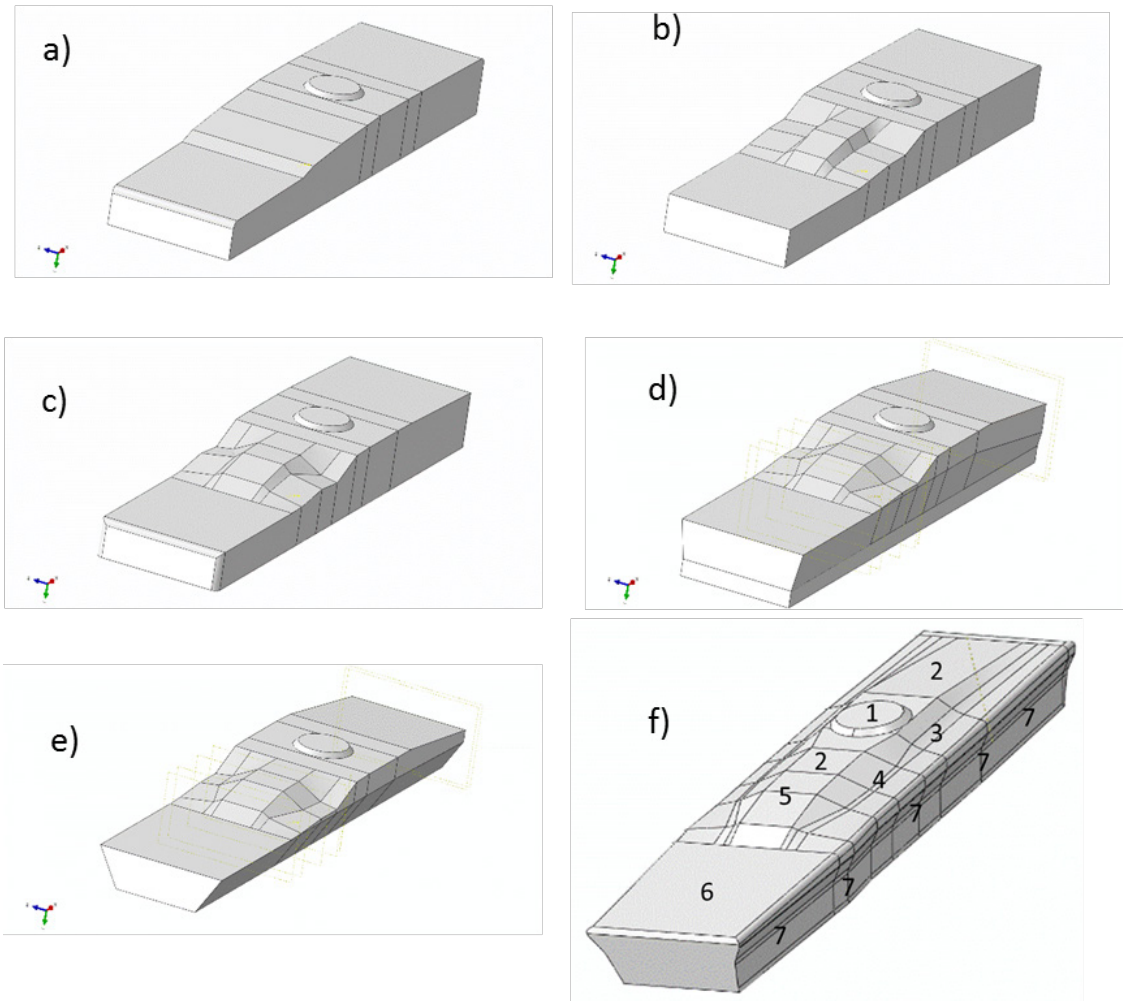

Fig. 9. The stages of optimization process

8. Recommendation

Based on the analysis the following recommendations for rubber designing are proposed.

1) The analysis has to be started from experimental determination of material properties including the volumetric test.
2) In order to limit the Poisson and barrelling effect along longitudinal axis locate the mounting pins closer to vertical walls.
3) In case of high flange of the part, increasing the rubber radius of the concave surface can help in reducing barrelling effect.

9. Conclusions

1) The rubber stamp was designed with FEM analysis based on idea of sequential deformation. The modelling allows for understanding the forming process and in result correct many errors regarding both stamp and the mould shapes.
2) Additionally experimental test regarding friction coefficient should be conducted. The rubber barrelling effect shows significant sensitivity of friction between Stamp and Stamp Holder.
3) Designed forming with high rubber deformation can require high pressing load, which causes high consolidation pressure. Too high pressure can caused excessive matrix flow and change in fibre volume fraction v_f.
4) In order to obtain more accurate results, the fabric model should be included in numerical analysis.

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