Modelling of anisotropic suede-like material during the thermoforming process

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Abstract: Physical and mechanical studies of Alcantara® have shown very pronounced anisotropic nonlinear features. Using constitutive equations borrowed from the modelling of biological tissues like tendons and/or arteries under the form of hyperelastic free-energy functions, a good representation of such mechanical features can be obtained. In particular, a combination between the optimization module and a modified hyperelastic model in COMSOL Multiphysics® can be used to determine the macroscopic mechanical parameters and to apply them to the simulation of the behaviour of Alcantara® when it undergoes high-temperature processes like thermoforming.

Keywords: Thermoforming, Hyperelastic, Anisotropic

1. Introduction

Alcantara® is a trade name given to a composite material used to cover surfaces and forms in a variety of applications. The material was developed in the early 1970s by Miyoshi Okamoto, a scientist working for the Japanese chemical company Toray Industries. In 1972, a joint-venture between the ENI Italian chemical group and Toray Industries gave rise to Alcantara S.p.A.

Alcantara® is created via the combination of an advanced spinning process (producing very low denier bi-component "islands-in-the-sea" fiber) and chemical and textile production processes (needle punching, impregnation, extraction, splitting, buffing, dyeing, finishing etc.) which interact with each other. Alcantara S.p.A. has the only European integrated manufacturing cycle of ultra-micro-fibrous non-woven textiles: 3 production units (from raw materials to the final products), each supplying the following, are present in the plant.

From a technical standpoint, the resulting product can be defined as a composite material in which the reinforcement is a non-woven structure of polyester ultra-microfibers in a porous polyurethane matrix.

The appearance and tactile feel of the material is similar to that of suede, making it suitable for a large number of luxury applications, including furniture, fashion & accessories, contract and automotive. In particular, the most important market sector is currently represented by the premium automotive segment, where Alcantara® represents a new category of which it is the unique product, though many imitations have been attempted. Indeed, its characteristics (mechanical resistance, breathing ability, enduring life, easy care, colour fastness, resistance to wrinkling) make Alcantara® the best alternative to leather for applications like seating, dash trimming and headliners for many premium OEM automotive suppliers.

Although many manufacturing processes of automotive components are still based on traditional techniques, some large-scale and high-rate productions require a more industrial approach. An example is represented by thermoforming of car headliners. Thermoforming is a manufacturing process where a thermoplastic sheet is heated to a malleable forming temperature, formed to a specific shape in a mould, trimmed to create a usable product and finally cooled. The driving force to stretch the sheet into or onto a mould is provided either by vacuum or by a countermould.

Alcantara® is not able to hold the shape by itself after a thermoforming cycle, so it must be always combined with a thermoplastic backing (usually, a felt made by glass and thermoplastic polymer fibres is used for the manufacturing of car headliners). This can be achieved by sticking the product on the backing using either a resin or a thermoplastic adhesive.

Depending on the complexity of the final shape, the moulding process can be carried out either in one step (i.e., the covering and the backing are shaped together) or in two steps (i.e., the backing is pre-formed and placed in the mould, then the covering is heated and glued on it, so to avoid wrinkles near small-ray curvatures). In any case, if the covering is stretched far beyond its elastic limits (usually next to small hollows or reliefs) the material can either break or tend to a release of residual stresses which manifest itself in the form of a detaching from the backing. For this reason, a trial-and-error approach is usually applied, using either "torture moulds" (to check if the material is able to withstand the most critical deformations expected for the final shape of the manufactured part) or at worst smoothing the sharpest edges of the final mould if some unexpected problem occurs. Obviously, this approach is very expensive and time-consuming, so a software tool able to highlight the critical points and to predict whether the covering is able to withstand high local deformations or not can be very useful and cost-effective.

2. Experimental

As past experiences proved that this material is characterized by different mechanical performances in warp and weft directions, it is worth pointing out that, although the microstructure of Alcantara® was represented by a three-dimensional entanglement of PET ultra-microfibers surrounded by a PU porous matrix, a simplification has been made, assuming that the overall mechanical behaviour could be described by an orthotropic model.

Hence, tensile uniaxial tests based on the ASTM D638–I standard were performed on samples cut along 0° (warp, longitudinal), 90° (weft, transverse) and 45° (diagonal) directions, using an INSTRON 5565 dynamometer equipped with a climate chamber. For the sake of simplicity, as thermoforming of Alcantara® car parts is carried out at temperatures around 90°C, this value has been chosen for tests (Figure 1).

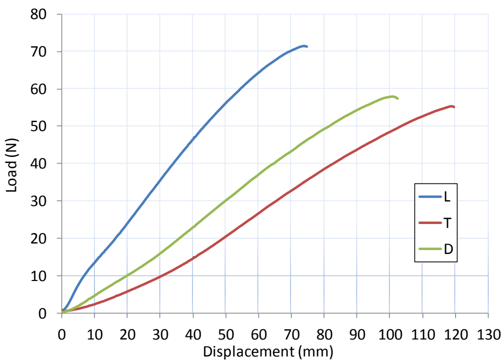

Figure 1. Load (N) / displacement (mm) curves at 90°C for the three directions analyzed: warp (blue), weft (red), diagonal (green).

Moreover, to check the predicting ability of the model, a reference mould was built, in the shape of a paraboloid with an undulate basis (Figure 2). Standard Alcantara® with a 10×10 mm grid printed on its surface, combined with an Acryl-Butadiene-Styrene 2mm-thick sheet by means of a thermoplastic adhesive polyurethane-based film, was used to get a thermoformed sample for the direct measurement of local deformations. The moulding was performed through a one-step process: firstly, the materials (held by a 650×340 mm frame throughout the entire process) are heated from the covering side by IR lamps, then both sides of the mould move towards one another to give the structure its final shape. After cooling and ejecting the finished part from the mould, local deformations can eventually be measured by comparing the final dimensions of each quadrangle on the surface with the initial square (Figure 3).

Figure 2. Reference lab-scale mould (paraboloid) for one-step thermoforming

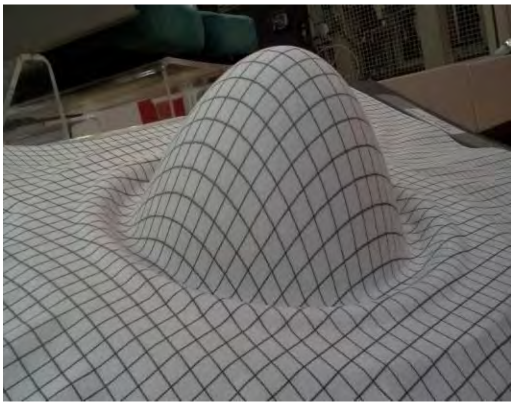

Figure 3. Example of thermoformed part for the measurement of local deformations. Backing: ABS (2 mm thick). Adhesive: Thermoplastic polyurethane-based film

3. Theory and Governing Equations

As it was said before, the microstructure of Alcantara® is characterized by a preferential orientation of the fibres due to the process sequence needed to get the final non-woven product. In particular, fibres seem randomly distributed at a micro-scale level, but at the same time they are clearly characterized by a preferential orientation in the longitudinal direction at a macroscopic level. Moreover, at deformations lower than 10% the material shows a clearly nonlinear behaviour, which can be probably ascribed to the rearrangement of fiber distribution during the first load stages. This implies the need to introduce nonlinear anisotropic constitutive equations.

A similar behaviour has been already observed for “soft composites” like fiber-reinforced rubber composites (formed by cords with high tensile strength reinforcing an elastomer, as for example tires and conveyer belts) (Tuan, et al., 2007), as well as for biological tissues like arteries and tendons, which often exhibit anisotropic properties (Gasser, et al., 2006). Therefore, a particular Helmholtz free-energy function was used, which allows to model a composite in which a matrix material is reinforced by families of fibres and the mechanical properties of this kind of composites depend on preferred fiber directions. The description of the constitutive model is given with respect to the reference undeformed configuration, under the hypotheses that the deformation occurs at a constant temperature (thereby any dependence on this parameter can be neglected as a first approximation) and that viscoelastic contributions are negligible.

The behaviour of human arteries, as well as of many biological tissues, is characterized by an initial stage (“toe region”) showing very low stiffness values, followed by a noticeable increase of the mechanical response, generally described by an exponential function (Gasser, et al., 2006). Even though Alcantara® does not show the same trend, a similarity can be found from a qualitative standpoint, allowing using the same approach.

Typically, hyperelastic constitutive equations are based on the definition of a Helmholtz free-energy density Ψ, which can be expressed as a function of the invariants of the deformation tensor according to different possible laws. The simplest approach by far is represented by the *neo-Hookean* model, where Ψ is depending upon both the first invariant I_1 and a constant commonly identified as μ:

$$\Psi = \frac{1}{2}\mu\left(I_1 - 3\right)$$

A fundamental aspect to be considered for any material described by a hyperelastic law is the degree of volumetric compressibility. Hyperelastic materials can be reasonably considered either weakly compressible or even uncompressible, with an equivalent Poisson coefficient near to the upper limit 0.5. In this case, the deformation energy density can be decoupled as a sum between a purely isochoric contribution $\overline{\Psi}$ and a purely volumetric contribution U:

$$\Psi = \overline{\Psi} + U = \frac{1}{2}\mu\left(\overline{I}_1 - 3\right) - p\left(J_{el} - 1 + \frac{p}{2\kappa}\right)$$

where:

$$\mathbf{F}(\mathbf{X}) = \partial\boldsymbol{\chi}(\mathbf{X})/\partial\mathbf{X},\ \textit{deformation gradient}$$

$$\mathbf{C} = \mathbf{F}^T\mathbf{F},\ \textit{right Cauchy} - \textit{Green tensor}$$

$$J_{el} = \det(\mathbf{F}),\ \textit{spherical (dilatational) elastic volume variation}$$

$$\overline{\mathbf{F}} = J_{el}^{-1/3}\mathbf{F},\ \textit{isochoric (distortional) deformation},\ \det(\mathbf{F}) = 1$$

$$\overline{\mathbf{C}} = \overline{\mathbf{F}}^T\overline{\mathbf{F}} = J_{el}^{-2/3}\mathbf{C},\ \textit{modified right Cauchy - Green tensor}$$

$$\overline{I}_1 = tr(\overline{\mathbf{C}}) = \overline{C}_{11} + \overline{C}_{22} + \overline{C}_{33},\ \textit{first modified invariant}$$

It was assumed that a fibre was embedded in a continuum and oriented towards a direction identified by the referential unit vector $\mathbf{a}_0$, with $|\mathbf{a}_0|=1$. The deformation $\boldsymbol{\chi}$ maps the fibre into its current configuration, where the vector

$$\mathbf{a} = \mathbf{F}\mathbf{a}_0 = \sum_j F_{jk}a_{0k}\hat{\mathbf{n}}_j$$

defines the spatial orientation and $|\mathbf{a}|$ is the stretch in the direction of the fibres. According to the above definitions, the vector

$$\overline{\mathbf{a}} = \overline{\mathbf{F}}\mathbf{a}_0$$

can be interpreted as the displacement of $\mathbf{a}_0$ related to the distortional part of the deformation gradient (coinciding with **a** for isochoric deformations).

μ (*Shear modulus*) and κ (*Bulk modulus*) represent the constitutive neo-Hookean parameters and can be determined through specific mechanical tests. In particular, a uniaxial tensile test and a volumetric test should be enough; however, the second test is usually difficult to carry out, so κ can be derived from a presumptive value of the Poisson coefficient according to the following equation (Love, 1944) (Mott, et al., 2008):

$$\kappa = \frac{2\mu(1+\nu)}{3(1-2\nu)}$$

The above equations refer to hyperelastic *isotropic* constitutive laws. To take into account anisotropy one must rewrite Ψ as the sum of three terms (Gasser, et al., 2006), i.e. the energy density of the so-called "ground matrix" (*g*), the energy density of each fiber (f_i, where the *i* suffix indicates the *i-th* fiber inside the composite) and the volumetric contribution:

$$\Psi = \overline{\Psi}_g + \sum_i \overline{\Psi}_{fi} + U$$

$$\overline{\Psi}_g = \frac{1}{2}\mu\left(\overline{I}_1 - 3\right)$$

$$\overline{\Psi}_{fi} = \frac{1}{2}\gamma_i\left(\overline{E}_i^2 - 1\right)$$

$$U = -p\left(J_{el} - 1 + \frac{p}{2\kappa}\right)$$

$\overline{E}_i$ represents a Green-Lagrange strain-like quantity which characterizes the strain in the direction of the mean orientation $\mathbf{a}_{0i}$ of the *i-th* family of fibres:

$$\overline{E}_i = \delta\,\overline{I}_1 + (1-3\delta)\overline{I}_{4i} - 1$$

$$\overline{I}_{4i} = \mathbf{a}_{0i} \otimes \mathbf{a}_{0i} : \overline{\mathbf{C}} = \sum_{i,j}\left(\mathbf{a}_{0i}\mathbf{a}_{0i}\right)_{ij} C_{ij}$$

where δ is a dispersion parameter related to the spatial distribution of fibres (the same for each family of fibres, ranging from δ=1/3, spherical symmetry, to δ=0, ideal alignment) and $\overline{I}_{4i}$ is a tensor invariant equal to the square of the stretch in the direction of $\mathbf{a}_{0i}$. determined from histological data of the tissue. A basic assumption in the present work is that both families of fibres have the same (ideal) distribution, i.e. the same parameter δ=0 is applied.

The orientation of fibres initially described by the $\mathbf{a}_{0i}$ vectors modifies during stretch following the local deformation, so the instant orientation in each point is described by the product:

$$\overline{\mathbf{a}}_i = \overline{\mathbf{F}}\mathbf{a}_{0i}$$

Hence, an anisotropic hyperelastic neo-Hookean soft-matrix composite material is univocally identified by the following parameters:

μ → isochoric strain energy density coefficient;

γ_1, γ_2 → fiber deformation coefficients, one for each mean direction;

δ → fiber distribution coefficient.

For the volumetric contribution, assuming that Alcantara® can be treated as an almost uncompressible material, a value of ν = 0.499 has been considered, which gives κ = 499.67μ.

4. COMSOL numerical model – Results and discussion

As it is very difficult to get a direct measure of each characteristic parameter, a different approach was used based on the reverse analysis of uniaxial tests performed at 90°C. Therefore, the Optimization feature has been firstly activated in the simulation of uniaxial tensile deformations of ASTM D638-I dogbone samples cut along 0°/45°/90° directions with respect to the selvedge (Figure 4).

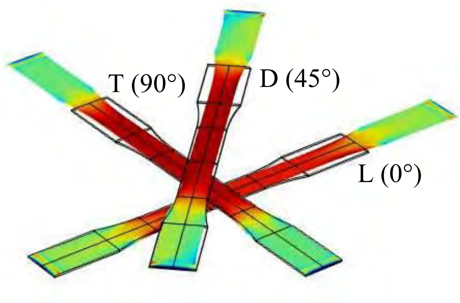

Figure 4. Simulation of the deformation (color data set: Von Mises stress) of ASTM D638-I dogbone samples cut along the 0°/45°/90° directions.

A comparison between experimental and numerical data in the common range of deformations for thermoforming applications is reported in Figure 5.

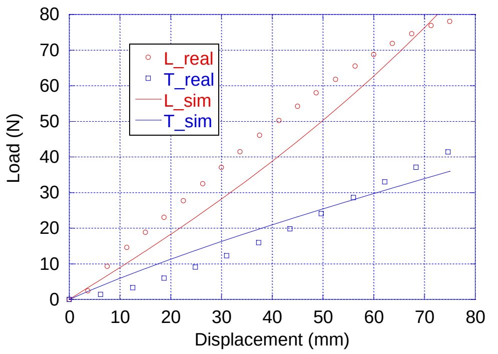

Figure 5. Experimental vs. numerical load/displacement curves for L and T uniaxial tests.

As a fair agreement was found for uniaxial configurations, the model was extended to the 3D simulation of thermoforming with the pilot mould shown in Figure 2.

To reduce the number of variables without compromising the completeness of the model, the geometry was cut through its two main symmetry planes. Boundary conditions were set as follows:

→ Fabric fixed at the external boundaries;

→ Top mould (female) fixed;

→ Bottom mould (male) moving at a constant speed;

→ Contact between the upper side of the fabric and the internal surface of the female mould, as well as between the lower side of the fabric and the external surface of the male mould;

→ Very high friction coefficient between the lower side of the fabric and the external surface of the male mould, to simulate the effect of the glue (acting instantaneously at the time of contact).

The initial geometry is shown in Figure 6.

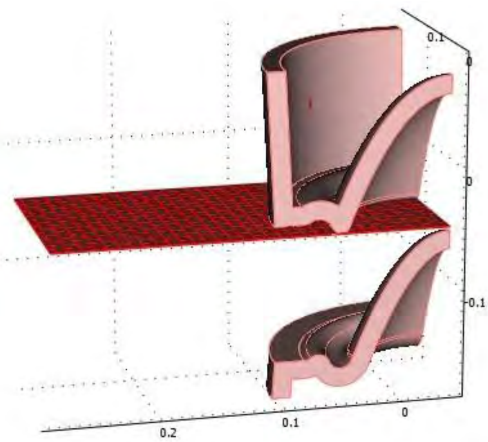

Figure 6. Initial configuration for the simulation of the thermoforming process (pilot mould).

A plot of the final deformed configuration is reported in Figure 7.

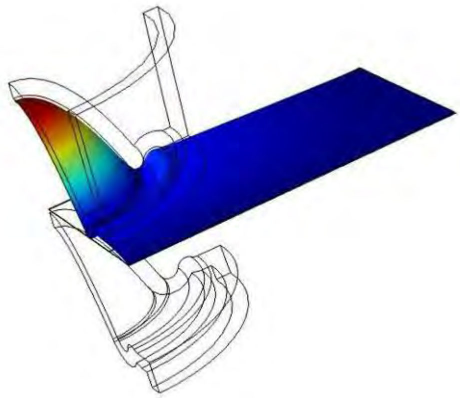

Figure 7. Deformed shape of the fabric.

7. Conclusions and future work

Starting from considerations about both the microstructure and the macroscopic behaviour of Alcantara® products, a nonlinear anisotropic mechanical model has been proposed and verified. The approach was based on constitutive equations similar to those of “soft matrix composites” like fiber-reinforced elastomers or biological tissues (e.g. arteries, tendons). In particular, the proposed model is based on the definition of a Helmholtz free-energy density as a function of different contributions coming from both matrix and fibres (for the sake of simplicity, the material has been approximate with an orthotropic structure, with only two mean fiber orientations parallel to longitudinal and transverse directions).

The constitutive parameters were determined through a combination of the Optimization module with Structural Mechanics, by imposing the minimum square difference between real and numerical load/displacement curves for three dogbone ASTM D638-I samples cut along 0°/45°/90° angles with respect to the selvedge, which underwent uniaxial tensile tests at 90°C. The model showed a fair ability to predict the real behaviour of Alcantara® under plane stress conditions, so it was applied to the simulation of thermoforming within a pilot mould. Even in this case, a reasonable agreement between real and numerical results was found.

The present work describes a first attempt to predict the mechanical behaviour of Alcantara® when it undergoes conditions of high temperature and pressure. Obviously, the above mentioned model can be enriched from many points of view, for example by using more complex hyperelastic laws, or by taking into account the temperature dependence of material characteristic parameters (to be able to describe non-isothermal processes). If a good predicting ability will be demonstrated, this will allow the application of the model to real case studies, like thermoforming of car headliners.

8. References

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