A Numerical Study for Rubber Particles Collection Involved in New Thermoforming Composite Process Using Comsol Multiphysics

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Abstract: This paper deals of the forming process applied to the thermoplastic composites. A new thermoforming process that uses rubber particles collection as flexible mould was presented and numerically modelled. A characterization of the rubber in particles form was previously performed to value the material parameters in the user-defined hyperelastic constitutive laws employed in the FEM simulations.

Keywords: Thermoplastic composites, rubber forming, hyperelastic materials, compression tests, contact problems.

1. Introduction

Continuous fibre reinforced polymers (FRP) are being increasingly applied in structural applications, especially in the transportation and aeronautic fields. The production of FRP composite parts is typically undertaken in small series, for instance the hand lay-up method which is labour intensive and where production cost are relatively high but with low tooling costs.

In the last years, the processes of composites production have been automated in order to achieve higher production rates and a constant quality level. Such automated processes like Resin Transfer Moulding (RTM), Resin Infusion under Flexible Tooling (RIFT), Stamping of sheet Moulding Compound (SMC) and overall Pultrusion are developed and widely applied to the thermosetting composite production fields.

The use of thermoplastic continuous fibre reinforced composites (TPC) allows to increase

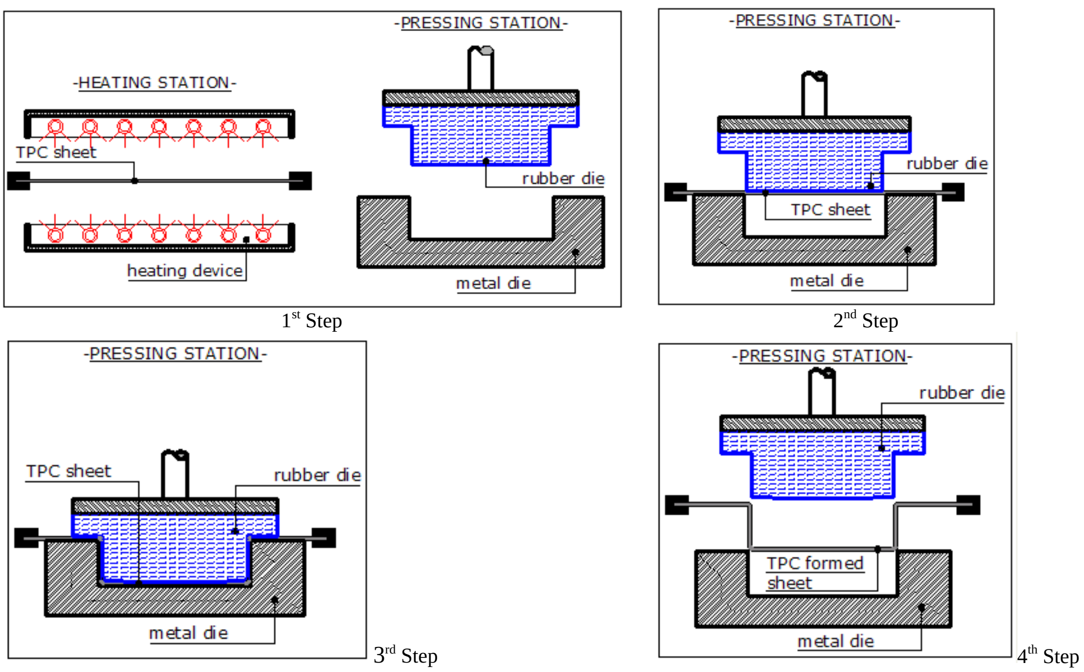


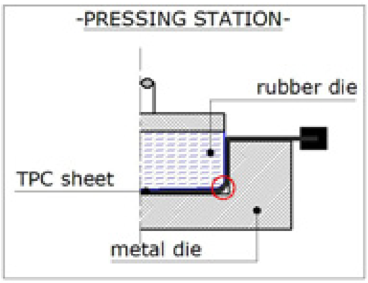
Figure 1 The basic steps in a "classic" TPC rubber forming process.

the production ratio of the above mentioned composite technologies. The matrix can be repeatedly melted and "rapidly" solidified, moreover pre-consolidated thermoplastic composite sheet material can be reheated and formed with highly automated processes [1, 2].

These processes are borrowed from the metal sheet forming ones, of which the most effective is the rubber forming process coupled with an early heating step [3]. In the rubber forming process, a flexible rubber die replaces one of the rigid metal dies of the matched metal-die forming method. A typical thermoplastic forming station consist of a rigid heated mould (of metallic material), a flexible (rubber) mould and a frame which slides the formed sheet; the steps of this technology are shown in figure 1.

The TPC sheet is firstly heated outside the forming station (also pressing station), subsequently it is moved between the matched metal and rubber dies where the final shape is pressed by an "adequately" closing pressure, in this paper such process is stated as a classic TPC thermoforming process.

The disadvantages of the matched metal and rubber dies are: limited life of the rubber die due to wear and tear at high working temperatures, the rubber thermal expansion with a coefficient in the order of 10^{-3}/K [4], the relatively low stiffness of the rubber which can result in pressure deformation causing difficulties especially filling of narrow and deep details in the metal die, figure 2.



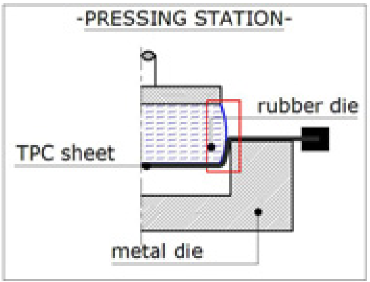


Figure 2 Rubber deformation (left side), barreling effect of rubber (right side).

2. A new rubber moulding process and objective of this study

A new thermoforming process for TPC materials was developed at the Department of Design and Production of Composite Structure at the Delft University of Technology [5] where the matched rubber die was replaced with a collection of rubber particles. In this way the disadvantages found in the classic TPC thermoforming process are overcome. The rubber particles (as shown in figure 3) have a fluid like behaviour, this means that a more uniform pressure forming distribution can be achieve on the TPC sheet. The displacement of the particles, together with the deformability of the rubber, allows to fill the mould cavity easily.

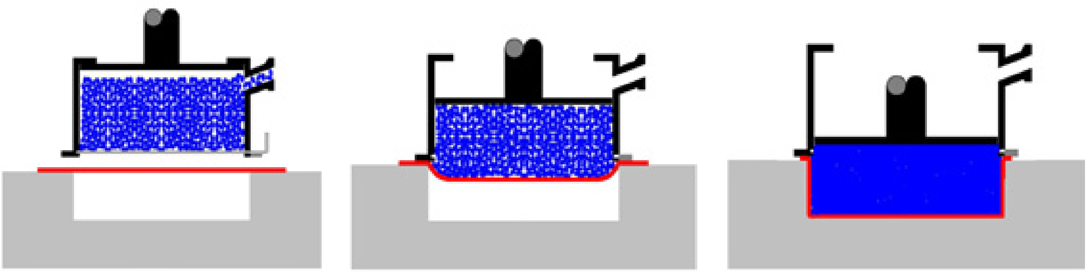


Figure 3 New thermoforming process steps.

using any shape without metal die This technology results in a more flexible forming process.

Another advantage in using rubber particles is a reduced forming tool cost with respect to the classic process as the particles can be partially replaced when the wear occurs. But the disadvantage of this new process is the surface finish that can be minimized by employing adequate rubber particles dimensions.

The process was demonstrated in an experimental set up [5], however the numerical modelling of this process that accounts for each contact interaction among the rubber particles is extremely unpractical and beyond the power of current numerical means.

A wide experimental program had as objective to validate this new process by means numerical simulations. In this paper a first numerically modelling approach using Comsol Multiphisics was presented with the aim to gain familiarity in the implementation of user defined hyper elastic constitutive laws in the software beginning from experimental material test characterizations. Using some simplifications, a numerical model was carried out to simulate the "U-beam" forming process through this new technology; finally the comparison between the experimental and the numerical results allowed to value the influence of the adopted simplifications.

Some simplifying assumptions were done in this paper; the first already introduced dealt about the collection of rubber particles was simulated as a fictitious continuum material in order to reduce the amount of sub domains to model for each particle and overcome the unknown particle orientations in the collection. During the forming process the rubber particles collection was subjected to three different type of external force: the applied load, the internal friction (interaction particle-particle) and the external friction (interaction metal mould-particles). The external friction in the modelled process was neglected because, as above stated in this section, it was not in the aim of this paper that was acquire confidence with the implementation of user-defined constitutive material laws; moreover the external friction valuation require further experimental tests. Finally, just a type of test was conducted to characterize the material behaviour: the confined compression test as showed in figure 4.

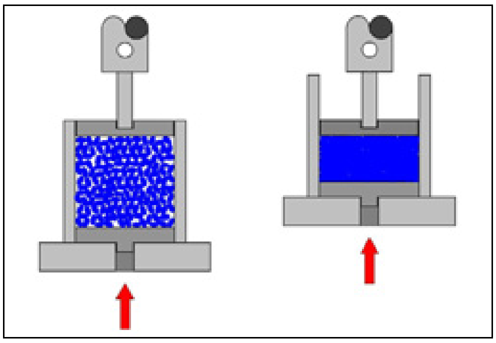


Figure 4 Experimental confined compression tests.

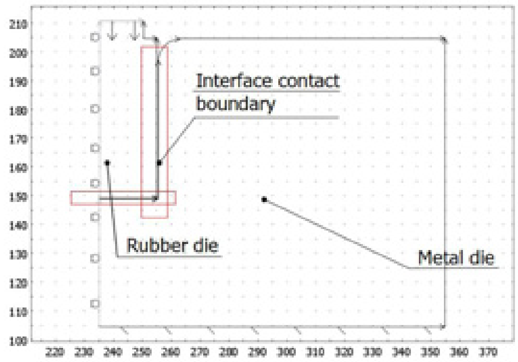


Figure 5 Subdomains, boundary condition and contact interface between rubber and metal dies.

3. Use of COMSOL Multiphysics

From some confined compression tests, **figure 4**, the material parameters were extracted using available literature of hyper elastic models [6], as described below. The compression tests were performed on three type of rubber particles collection, 20 Shore A in ellipsoid form, 30 Shore A in cubic form and 35 Shore A in ellipsoid form. The displacement rate in a compression tests was 2 mm/min that was a quasi-static mode.

The Comsol Multyphisics software was a "relatively" easy tool to build up a two-dimensional forming simulation in the Structural Mechanical module. The numerically modelled "U-beam" forming process consisted of two sub domains: a fictitious continuum rubber and metal die subdomains with a contact boundary on their interface, figure 5. The constitutive material equations for finite "large" displacement were chosen [6, 8], in they the material constants were obtained by fitting the experimental characterization data. In the Comsol model the solutions were obtained by means user definite strain energy density for hyperelastic material.

4. Determination of the material constitutive models

In order to simulate numerically the "U-beam" forming process a constitutive material law had to be adapted to model the mechanical behaviour of the rubber particles collection. More constitutive laws were considered in this study choosing among the ones present in the technical literature, in particular three hyper elastic laws were selected; the Mooney-Rivlin model:

$$W(I_1, I_2) = C_{10}(I_1 - 3) + C_{01}(I_2 - 3), \qquad (1),$$

the Beda model:

$$W(I_1, I_2) = \sum_1^M {}_i \frac{C_{i0}}{i} \cdot (I_1 - 3)^i + K \cdot \ln \frac{I_2}{3}, \qquad (2),$$

and the Ogden model:

$$W(\lambda_1, \lambda_2, \lambda_3) = \sum_1^M {}_i \frac{\mu_i}{\alpha_i} \cdot \left(\lambda_1^{\alpha i} + \lambda_2^{\alpha i} + \lambda_3^{\alpha i} - 3\right) \qquad (3)$$

All above models are constitutive laws for isotropic homogeneous hyper elastic material relating the strain energy to the principals strain invariants *(I_1, I_2, I_3)* or the principal stretches *(λ_1, λ_2, λ_3)*. In this work the material was assumed to be slightly compressible re-writing the strain energy equations decupled in two parts, the isochoric and the volumetric parts [8]:

$$W = W_{isoch} + W_{vol} \qquad (4),$$

the volumetric part was assumed in a simplified form [8]:

$$W(J) = \frac{\kappa}{2}(J - 1)^2 \qquad (5)$$

where J is the right Cauchy strain tensor determinant and κ the initial bulk modulus. The table 1 summarize the material parameters in the chosen constitutive laws and the order of the models(2) and (3), see the *M* letter.

A fundamental step in this work was the determination of the unknown parameters in the equation (4) for the three laws in (1), (2) and (3); this was done fitting the data of the confined compression tests using a non linear least square method.

The load versus displacement data from the experimental investigation were transformed in normal stress versus the 3rd principal stretch, λ_3, and fitted making use of the second Piola Kirchhhof stress tensor $\underline{\mathbf{S}}$ computed as follows:

$$\underline{S} = 2\frac{\partial W}{\partial C} \Rightarrow S_{zz} = 2\frac{\partial W}{\partial \lambda_3} \qquad (6),$$

where *W* is the strain energy equation, *C* the right Cauchy strain tensor. To compare the performance of the three hyper elastic constitutive laws employed in this study, a numerical model was carried out to reproduce the confined compression tests. This model presented a 2D axial-symmetric geometry in a Structural Mechanical module for large displacement in a quasi-static simulation; the constitutive laws were defined in the subdomain equation window using the (1), (2) and (3) fitted models. The simulations were solved applying parameterized boundary displacement conditions, figure 6 A. The numerical results were showed in figure 6 *A*, *B* and *C* together with the experimental data for the 20, 30 and 35 Shore A rubber particles hardness. As can be seen no model fitted well the experimental data on the whole applied displacement range. The Mooney-Rivlin law, the simplest model with the small number of material parameters, fitted well the experimental data just for low displacement with respect the Beda and the Ogden equations that given higher compression stress for high

Table 1 material parameter for the three constitutive used laws.

	Mooney-Rivlin	Beda	Ogden
Number of parameter	2 + 1	M = 3, + 1	M = 6, + 1
Isochoric parameters	C_{10}, C_{01}	C_{10}, C_{20}, C_{30}, K	α_1, α_2, α_3, μ_1, μ_2, μ_3
Volume parameters	κ	κ	κ

displacement. The Beda model take advantage from the two terms present in its formulation, where the higher order *(I_1-3)* was more adequate for "large" stretch values; and the Ogden model that is typically more adequate for "large" stretch values [6]; in both models the number of material parameters was higher than the simplest one, the Mooney-Rivlin. From the figures 6 *B*, *C* and *D* raises that the Beda and Ogden model predictions were dependent from the hardness of the simulated material.

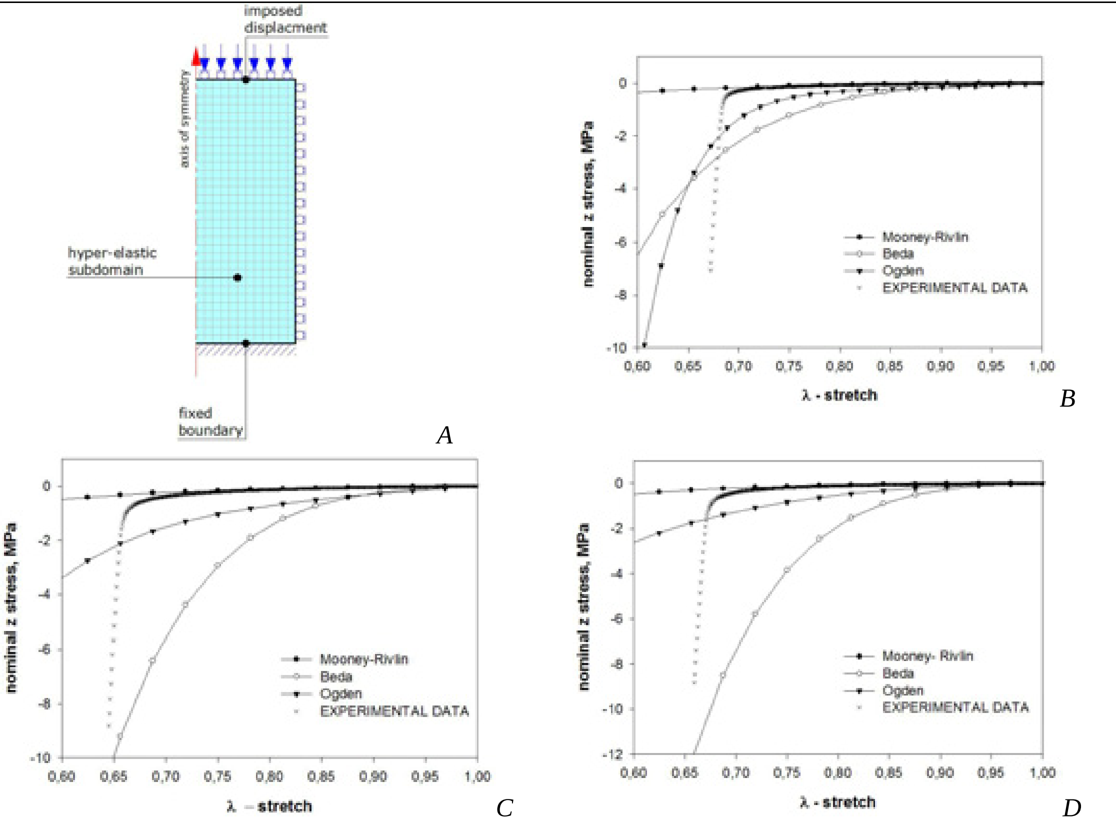


Figure 6 A, confined compression model configuration; B, experimental and numerical results for 20 Shore A rubber; C, experimental and numerical results for 30 Shore A rubber, D, experimental and numerical results for 30 Shore A rubber.

5. The "U-beam" forming process results

The same constitutive laws and the material hyperelastic parameters were used to simulate numerically the "U-beam" forming process. The process was modelled as a 2D Structural Mechanic model using a plain-strain quasi-static analysis with large displacement. Two subdomains were modelled, the metallic stainless steel and the rubber moulds; the TPC laminate was not modelled because of not influence on the pressure distribution along the metal mould surfaces. The modelled subdomains model were meshed by first order quadrilateral elements in a parameterized simulation. The figure 5 shows the "U-beam" forming configuration.

The simulation parameter was the imposed external load on the horizontal top surface of the rubber sub domain. The contact boundary conditions were activated at the rubber –metal mould interfaces.

The numerical results were showed in figure 7 (*A*, *B* and *C*) as pressure distribution along the contact line from the centre of the metallic

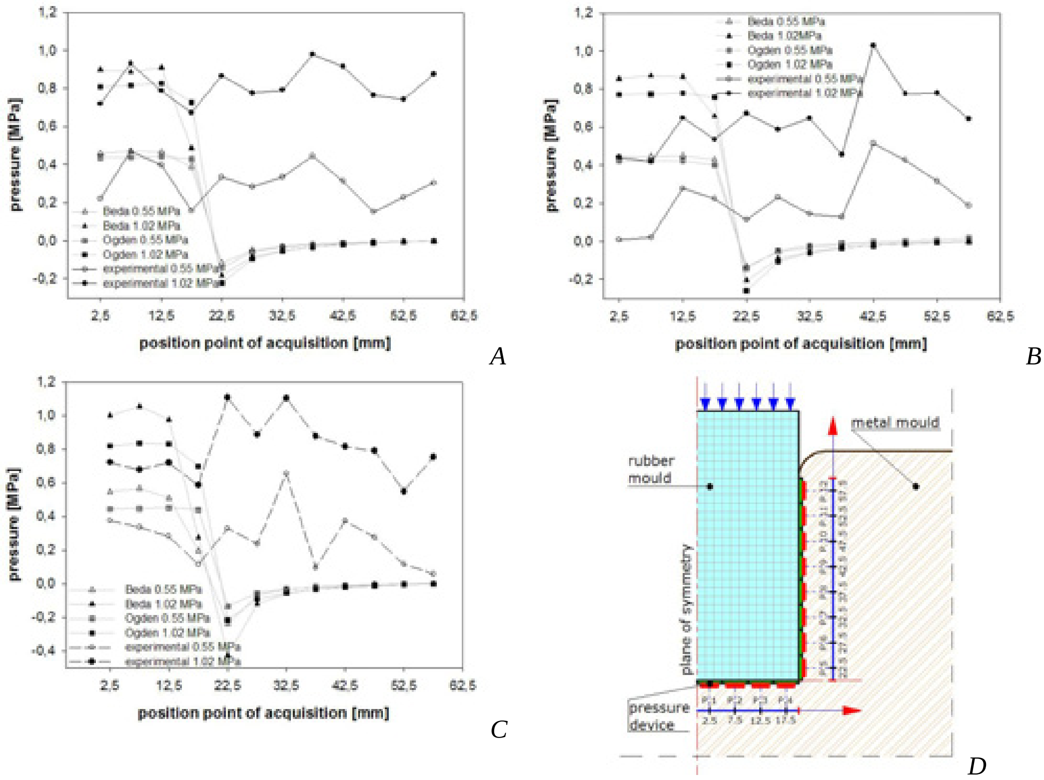


Figure 7 Pressure versus acquisition points for 20 Shore A (A), 30 Shore A (B), 35 Shore A (C) rubber particles and the experimental "U-beam" forming configuration (D).

mould, taking advantage from the geometric symmetry shape of the forming device, for the thee different rubber particles hardness, in the same figures the experimental acquired data were reported. The numerical and experimental values were referred to the point showed in figure 7 *D* that were the positions of the pressure acquisition device.

In figure 8, a typical pressure sub domain distribution using the Beda constitutive law was reported. As can be deduced from the profiles in figure 7, for the “U-beam” forming process simulation the Mooney-Rivlin model was not

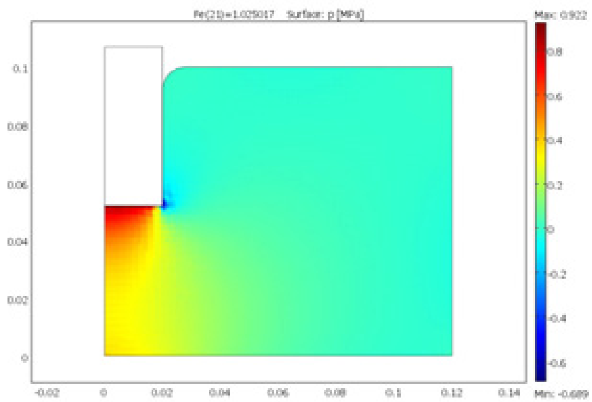


Figure 8 Pressure distribution on the metal mould sub domain for Beda hyper elastic law.

applied because the results in the previous confined tests simulations were not satisfactory.

Some evidence could be extracted from the numerical and experimental result comparisons; in the experimental investigation the use of a rubber particles collection in a forming process did not present any pressure drop at the corner, this effect was not caught by the numerical model without regards the rubber hardness. The reason of this trends could be to have ignored the external friction between the rubber particles and the metal mould [9]. In fact, while on the horizontal surface the pressure had the same shape for the experimental and numerical profiles, in the corner the numerical pressure values presented an inversion of the sign setting to zero on the vertical wall. Moreover was also believed that a best set of hyperelastic material parameters could be find performing the fitting procedure on different type of characterization tests data.

For all the simulated cases the numerical predictions, on the horizontal wall (P.1 – P.4, figure 7 *D*), were higher than the experimental measurements; the model with the Ogden constitutive laws were closer to the experimental values than the Beda ones. Finally, in the same zone, the rubber particles hardness seemed to have influence on the hyperelastic material models response.

The higher difference between numerical and experimental values, relatively to the horizontal wall, were obtained for the 30 Shore A rubber hardness that was the particles with cubic shape.

6. Conclusion

In this paper the new thermoplastic composite forming process using rubber particles collection was described. From an experimental material characterization, using confined compression tests, the constitutive material parameters for three different hyper elastic model were computed by means a fitting process; the used constitutive laws were: the Mooney-Rivlin, the Beda and the Ogden models. Two numerical models were then build up; the first model reproduced the characterization tests, the second reproduced the "U-beam" forming process. Both models were parameterized quasi-static simulations and used the hyperelastic constitutive fitted models. Some simplifying assumptions were done about the external friction (between the rubber particles and the metal moulds) and the particles collection, managed as a continuum fictitious material. For the forming process simulation only the Beda and the Ogden models were used that were also the ones with the higher number of material parameters. The Mooney-Rivlin law given numerical confined compression prediction far from the experimental measured values.

The numerical predictions did not result fit adequately the experimental measurement along the vertical metal wall, this was ascribed to the frictionless numerical model and a possible not perfect material hyperelastic parameters valuation.

These considerations suggested to carry out, in a next research, new type of characterization tests to improve the hyperelastic material parameters evaluations in the fitting phase and an experimental investigation to value the friction between the rubber particles and the metallic surface interface.

However it was found a good flexibility of the Comsol Multyphysics in its graphical interface to model user defined constitutive laws.

7. References

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