A new elastic-plastic material model with non-linear elastic behaviour for thermoplastic elastomers

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Abstract: Thermoplastic Elastomers (TPE) are materials, which combine the advantages of elastomers and thermoplastics. TPE is not only used as replacement for thermoplastics. More and more parts, formerly made of rubber like CVJ boots and hydraulic seals, are nowadays made of TPE.

Since the mechanical behavior of TPEs is different to elastomers, the design of TPE parts cannot be copied directly from their elastomeric counterparts. Therefore, new designs must be developed. In this process, FEA is a powerful tool to support the product development.

To provide this support, a precise numerical description of the material behavior is required. Experimental characterization of the material has shown, that the behavior is strongly non-linear, and there is a big influence of inelastic effects. Up to now, there is no material model available in ABAQUS to describe these effects. Therefore, at Freudenberg a new material model has been developed, which can describe the non-linearity as well as the inelasticity. With this model it is now possible to predict the behavior of TPE-parts, especially the effects of inelastic deformation.

1. Introduction

In recent years, more and more parts in the automotive industry were made of thermoplastic elastomers (TPE). TPEs are polymeric materials, which show some characteristics of rubber (elastic, flexible). But in contrast to rubber, where the polymeric chains are chemically cross-linked, TPEs characteristics is a physical cross-linking. Thus, TPEs stand between elastomers and thermoplastics. They combine the advantages of easy processability of thermoplastics with some elasticity of rubber.

Typical products at Freudenberg made of TPEs are hydraulic seals and CVJ boots. In the product development for these products, numerical simulation tools, like Finite Element Analysis (FEA) have been established as standard tools. The most interesting points in the development process are the stresses in the material (stress, strain) as well as the contact stresses for sealing applications, or the load-deflection curve.
for vibration applications. With FE-methods, it is possible to decide very early in the development process, if a part fulfils its requirements, and a fast and effective development process can be guaranteed.

Of course, an absolute necessity for that is to describe the material behavior in a very accurate manner. Only then it is possible to draw the correct conclusions from the results obtained by FEA. For elastomers, at Freudenberg a material model was developed which predicts the behavior over a wide range of deformations. It was also extended to describe the stress softening of rubbers, known as Mullins-Effect (Häusler, 2000).

To describe parts made of TPEs, there is also need for a special material model. At first glance, the behavior of TPEs is very similar to elastomers. In a tension experiment, the load deflection curve is highly non-linear, and after a first initial loading, the material behaves softer (like Mullins effect). Therefore, FEA was done using the hyperelastic Freudenberg material model for elastomers.

A closer look on the real behavior shows, that there are some important differences in the real behavior, which lead to unsatisfactory results obtained by FEA. In general, a hyperelastic model can only be used to predict the behavior for very low strains. For higher strains, there are big differences between the prediction of the material model, and the experimental examinations, in particular for cyclic loading of the material.

That’s why a new model has been developed, which describes the material behavior in a better way.

2. Material behavior of TPE

The static behavior of thermoplastic elastomers in a monotonic tension experiment is shown in Figure 1. In this figure, there is also shown the static behavior of a common elastomer. The difference between both materials is just the stiffness, a TPE is much stiffer then a typical elastomer. Beside this, both materials behave very similar, they show a strong nonlinear behavior, which can be described by the hyperelastic Freudenberg Model. Since experiments with different pre-loading have shown that, similar to elastomers, TPEs show a softening effect, the idea was to describe the material behavior with the Freudenberg Mullins model.

Further experiments have shown, that the assumption of an elastic material behavior, like that of elastomers, is wrong. In Figure 2, a tension experiment up to 40% technical strain is shown. In addition, the unloading curves at 10%, 20%, 30% and 40% strain are also plotted. What is seen now is, that TPEs have a strong inelastic behavior. Unloading at 40% maximum strain leads to a remaining, inelastic (or plastic) strain of about 8% technical strain. There exist other TPEs which show a much bigger effect of inelastic strain (up to 20% at that point). But even the remaining strain of 8% is to high to be neglected. If the material is loaded again, the loading and unloading curves correspond to each other. Another important result from this tension experiment is, that for low strains (up to 10% technical strain), the effect of inelasticity is very small and therefore can be neglected. The corresponding stress is about 3 MPa.

Another experiment is the uniaxial compression test. To avoid influences of the manufacturing of the test specimen and of different material batches, the experiments were done with the same type of test specimen. The result of this test can be seen in Figure 3. The behavior in compression is quantitatively and qualitatively the same: It is strongly nonlinear, for lower strains the behavior is nearly elastic, for higher
strains, there is a remaining, inelastic deformation, and the yielding of the material (beginning of inelastic deformation) starts at roughly the same strain.

The tension and compression tests have been done for different classes of TPEs (TPE-E, TPE-U, TPE-S, TPE-V). The behavior for all tested classes is qualitatively the same, the differences are only in the stiffness of the materials. In every experiment, for lower strains there was an elastic range, where the deformations remain reversible, whereas for higher strains, there remains an inelastic strain. Since this behavior is the same for all of these classes, they can be described with one single model. This model is explained in the next chapter.

3. Material model

The above presented experimental investigations have shown, which effects the new TPE material model has to take into account. This is on the one hand the nonlinear behavior during loading and unloading, and on the other hand the remaining, inelastic deformations. A good model has to consider both characteristics of TPEs.

3.1 Existing models

First, different existing and in ABAQUS available models has been tested. A hyperelastic model, which is able to describe the nonlinear behavior of the material, is unable to predict any inelastic strains. Even with the expansion to describe the Mullins effect, there will be no satisfactory results. Of course, the Mullins model can describe a history dependent material behavior, but since it stays an elastic model, it is not able to describe any remaining, inelastic deformation.

On the other hand, there exist material models which describe an inelastic behavior, e.g. steel and other metallic materials which show plastic behavior. These models are also able to predict the nonlinear behavior during the loading of the material. But unfortunately, they are unable to predict a nonlinear elastic behavior during the unloading, since metallic materials show only a linear elastic range (Hooke’s Law). That’s why these models overestimate the inelastic strains (see Figure 4).

The models for metals have also another disadvantage: They were formulated only for small elastic strains. This is correct for metallic materials, where the elastic deformations remain small. For TPEs, this assumption is wrong, since there are elastic deformations of more than 30% technical strain.

But nevertheless, the analogy between the behavior of metals and the behavior of TPEs can be used to develop a new model. What has to be done is to combine the plasticity theory for metals with the hyperelasticity theory for polymeric materials. Unfortunately, ABAQUS does not allow the combination of the *plastic card with *hyperelastic.

3.2 A new material model

In literature, there can be found only a few different theories to describe the plastic behavior of metals for finite plastic but small elastic deformation (Chaboche, 1993; Tsakmakis, 1996). The problem with theories for finite deformation is, that in the evolution equation, the material time derivative of stresses and strains have to be replaced by a so-called “objective derivative”. This is necessary to avoid stresses in the material
due to rigid body transformation. Common objective derivatives are Jaumann derivative and Oldroyd derivative (Haupt, 1989).

To distinguish between a purely elastic, and an inelastic deformation, in metal plasticity a so-called “yield surface” is used. The size of this yield surface is the yield stress, the stress at which the inelastic deformation starts. Such a yield surface can be represented as a circle in the two-dimensional stress space. A material behaves elastic, when the stress state is located inside the yield surface, otherwise it behaves elastic-plastic. The hardening of the material (change in yield stress) is described by a change of the yield surface: A change in the size is called isotropic hardening, the change of position in the stress space is called kinematic hardening. To describe these hardening effects, suitable evolution laws must be found.

In metal plasticity, inelastic deformations are correlated to a gliding of dislocation, which leads to remaining deformation. The movements of these dislocations can lead to very big inelastic deformations, although the elastic deformation, which is a change in the distance between atoms, remains very small. Such considerations can also be done for TPEs. There, an inelastic deformation can be understood as an irreversible movement of cross links. To describe the hardening of TPEs, similar assumption can be made. Of course, for TPEs both, the elastic and the inelastic deformation can be very big, and therefore the material laws for metals can not be used directly. They must be adapted to finite deformations.

At the beginning of the deformation, the yield surface is symmetric. This means, that the yield stress in tension and compression direction is the same (in our case about 3 MPa). When the material begins to yield, suitable evolution equations for isotropic and/or kinematic hardening have to be found. Since with the existing experiments we can not distinguish between both types of hardening, in the first approach we only consider the (easier, because scalar) isotropic hardening. The prediction of the yield stress can be seen in Figure 5.

What is left is a description of the elastic behavior. Since the elastic deformation is related to a reversible deformation of the polymeric chains, and the elastic unloading curves in the tension experiments show the typical shape for elastomers, it is obvious to employ the Freudenberg model for elastomers to describe the elastic behavior.

3.3 Implementation

The model is implemented as user subroutine UMAT in ABAQUS. To avoid the very high expense of analytically determining the consistent stiffness matrix, the derivative of the stress tensor with respect to the strain increment is calculated numerically. Of course, this leads to higher numerical costs, since for every integration point the stress algorithm must be calculated seven times (in a 3D analysis). But the flexibility to do little changes without changing the stiffness matrix is much more important, at least in the phase of the material model development. When the model has proved itself, a more effective algorithm can be developed, additionally.
4. Finite Element Calculation

4.1 Parameter Identification

To show the possibilities of this new material model, different Finite Element calculations were done. For that, the material parameters have to be identified. This is much more complicated than for hyperelasticity. In this case, the stress is an unique function of the strain, and to identify the material parameters, only a nonlinear equation must be solved. Since the behavior of TPEs is history dependent, and the material behavior is described by differential equations, the identification is now a more complex task. Either the method of neural networks (Huber, 1999), or a direct search method (Hartmann, 2001). Up to now, the identification is done by hand: With some simplifications, the evolution laws can be solved analytically, and the parameters can be determined by a least square fit.

In Figure 6, the model prediction for the uniaxial tension test is shown. Of course, since the material parameters were identified with these experimental data, the correlation between calculation and experiment is good. This shows, that the accuracy of the parameter identification is well. There is only a bigger deviation around the initial yield stress.

With the same set of material parameter, the uniaxial compression test was simulated (see Figure 7). Although the parameters were not identified with this experiment, the result is very good. Like for uniaxial tension, near the initial yield stress, the prediction of the model is less accurate. This deviation can be minimized by finding a better identification procedure.

4.2 Hydraulic seal

Finally, a real TPE-part was simulated. In contrast to the uniaxial tension and compression tests, in real parts the stress states are more complex (three dimensional deformation state). The geometry of the hydraulic seal and the housing is given in Figure 8. In the FE simulation, the seal is mounted and exposed to pressure loading. In Figure 9, the inelastic deformations of the unmounted seal can be seen. Due to the inelastic deformation of the seal, there can also be seen (Figure 10) a reduction of contact stresses in the unpressurized state, after the maximum pressure was applied.

5. Conclusion

A new material model, which can describe both, nonlinear elastic effects, as well as nonlinear inelastic effects, has been presented. This model closes the gap between plasticity models for metals, and the hyperelasticity models, and can be used to describe the material behavior of thermoplastic elastomers over a wide range of deformation. It has been shown, that typical effects of TPE parts, like inelastic deformation, can now be simulated. To reduce the numerical costs, the model should be implemented in a more efficient way.
6. References


![Figure 1. Comparison TPE – Elastomer](image)
Figure 2. Uniaxial tension experiment

Figure 3. Uniaxial compression experiment
Figure 4. Prediction with metal plasticity model

Figure 5. Isotropic hardening
Figure 6. Prediction of uniaxial tension test with the new TPE model

Figure 7. Prediction of uniaxial compression test with the new TPE model
Figure 8. Geometry and housing of hydraulic seal

Figure 9. Inelastic deformation of hydraulic seal
Figure 10. Contact stress of hydraulic seal in unpressurized state