

Modeling of forming process of composite materials based on thermoplastic matrix

Fedulov B.N., Kantor M.M., Safonov A.A. and Ushakov A.E.

Skolkovo Institute of Science and Technology

Abstract: Composite materials based on thermoplastic matrix became a popular choice as a material for modern structures. Nevertheless, the manufacturing process of this type of materials have many technology parameters, which have to be determined before the first composite part is produced. The study of influence of all parameters on final quality of composite part by means of technological experiments are time and cost consuming. This makes engineers to study the way of the modeling of thermoplastic composite forming process. This research is dedicated to the modeling of thermoplastic material under different conditions. Several approaches to capture specific for this material features are performed. The method to model the influence of crystallinity on mechanical properties of composite material and on final residual stresses is analyzed. An approach to model shear nonlinearity in composite prepregs is performed. The analysis of defects initiation in the thermoplastic composites under technological temperature cycle is also performed. All numerical procedures and special subroutines based on Abaqus software are presented. Eventually a complete set of engineering tools using Abaqus software needed to model the forming process of thermoplastic composite details is realized.

Keywords: Composite material, Thermoplastic composite material, Thermoplastic material forming, Thermoplastic composite residual stress, Technology process thermoplastic material, Failure due to technology residual stress. Nonlinear shear behavior of thermoplastic composites.

1. Introduction

Thermoplastic composites took a significant part in the market of new materials. This type of materials gives essential and cost effective results in automotive and aerospace industries. Fast fabrication, easy storing and capability of welding make them attractive as a choice for the modern constructions. Composites with thermoplastic matrix have special characteristics based on their thermoplastic features. The main feature of this kind of material is the presence of crystallinity in its internal structure. The degree of crystallinity determines significantly the mechanical properties of the material. Low ratio of crystallinity leads to the low stiffness of the material, and on the contrary, maximum value of the crystallinity ratio gives highest values of the material stiffness. Another special aspect is additional volumetric shrinkage due to increase of the ratio of crystallinity. This volumetric shrinkage caused by chemical material phase transition can be the reason of the essential residual stress, which cannot be ignored. Manufacturing experiments with variation of all technological parameters, in the way to get good quality product, takes a lot of time and eventually are expensive. This fact makes all attempts of modeling a complete manufacturing

cycle of the product based on thermoplastic matrix essentially important from the view of the practice.

2. Forming process

The first modeling step of the thermoplastic composite product manufacturing is its forming. In order to analyze models and validate the technology process it was proposed a special double-dome surface represented in work [1] (Figure 1):

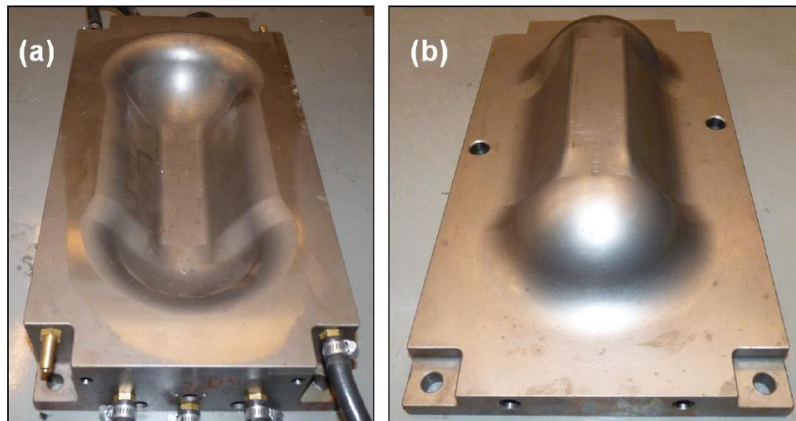


Figure 1: Double-dome surfaces: (a) female die, (b) male punch. [2]

The corresponded virtual model based on Abaqus software was developed (Figure 2):

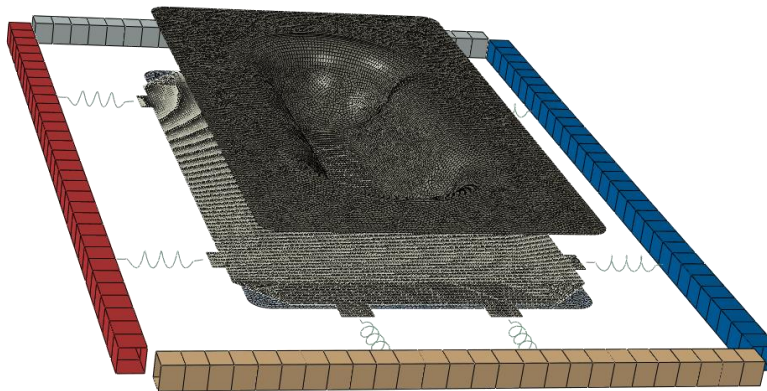


Figure 2: Double dome surfaces and prepreg Finite Element Model

Thermoplastic preform during forming process has about 200°C-400°C temperature and demonstrates weak properties in the direction with no reinforced fibers. The idea realized in this work is that usage of material model based on standard Abaqus lamina properties with low shear modulus. After few attempts of modeling and analyzing experimental data from picture frame tests (Figure 3) the ideal plasticity in case of shear loading was added.

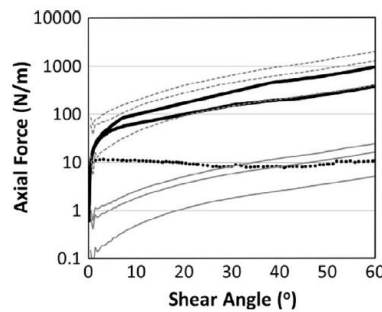


Figure 3: Different specimens shear test curves [2]

Large majority of researchers uses explicit solvers in order to perform forming simulation and this is justified on grounds of equilibrium and contact convergence problems. However, explicit solver makes everybody uses some special technics to reduce calculation time especially in case of the usage of stiffness dependent material damping. Our research is successful attempt of implicit solver application for thermoplastic forming problems. We face with contact convergence problems when the default contact stabilization was used. On the one hand, the default contact stabilization implies the reduction of stabilization from the beginning of the step to the end of the step due to reduction factor, such behavior causes the contact convergence problems at the end of the step, on the other hand, it implies that the magnitude of stabilization is additionally multiplied by the fraction of the step remaining, correspondingly such behavior cause problems in the start increments. We recommend using the reduction factor for contact stabilization equals 1 and constant amplitude through the step. These settings will ensure constant contact stabilization through the modeling step. On the Figure 4 one can see the contact stabilization settings used in the research. Figure 5 shows the final result of the thermoplastic forming. Shear angles in radians are presented in the contour plot.

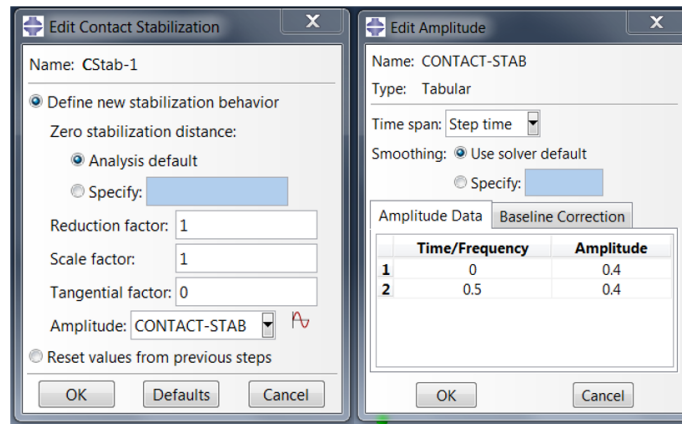


Figure 4: Contact stabilization settings used in the research

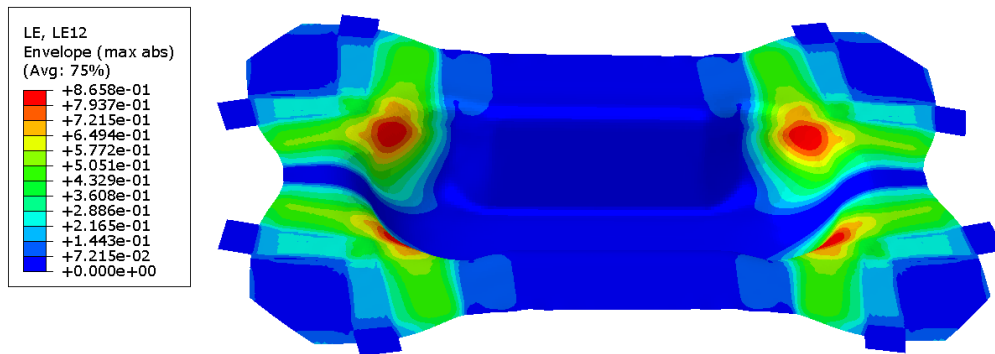


Figure 5: Finale stage of the thermoplastic forming, shear angles, radians

More over our forming modeling analysis shows that the usage of plasticity model presented in the work [3] has a real perspective. Figure 6 shows that during the thermoplastic forming one can find that there are prepreg areas subjected to biaxial compression and biaxial tension. Stress state parameter triaxiality is shown on the Figure 6 contour plot.

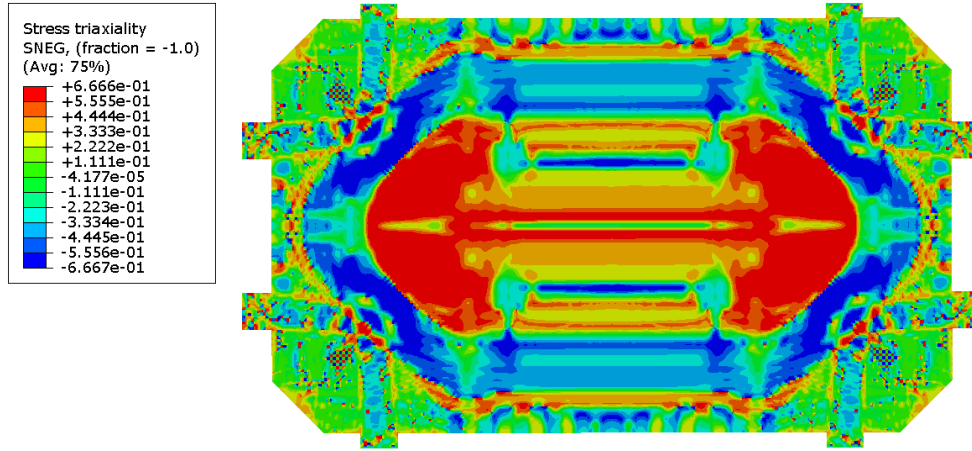


Figure 6: Stress triaxiality

Plasticity criteria from [3]:

$$\sqrt{A_{ijkl}(\xi)\sigma_{ij}\sigma_{kl}} = \text{Const}, \quad (1)$$

where $\sigma = \sigma/\sigma_0$, $\sigma = \sigma_{ii}/3$, $\sigma_0 = \sqrt{3/2}S_{ij}S_{ij}$, $S_{ij} = \sigma_{ij} - \sigma\delta_{ij}$.

Parameter ξ helps to identify the type of stress and chose particular constants A_{ijkl} for example in cases of tension, compression or pure shear. Plasticity flow with criterion (1) can be realized on the base of Abaqus USDFLD subroutine. Strain rate dependency can be added by means of standard Abaqus tools into the yield condition also.

3. Crystallinity model

Crystallinity ratio is a temperature history depended value, thus it has integral of temperature value in its definition. The most popular approach to obtain value of the crystallinity is described in [4]. There are two mechanisms to grow crystals: first one is the nucleation and second is the growing of present ones. The total value of crystallinity is the sum of results of these two mechanisms with special weights:

$$X_{vc} = X_{vc\infty}(w_1F_{vc1} + w_2F_{vc2})$$

where

X_{vc} – Degree of crystallization

$X_{vc\infty}$ - Equilibrium degree of crystallinity

w_1 - Weight factor for first mechanism (grow of crystals)

w_2 - Weight factor for second mechanism (nucleation of crystals)

$$w_1 + w_2 = 1$$

Each mechanism contribution is summarizing by next equation:

$$F_{vci} = 1 - \exp \left[-C_{1i} \int_0^t \exp \left\{ - \left[\frac{C_{2i}}{(T - T_g + 51.6)} + \frac{C_{3i}}{T(T_{mi} - T)^2} \right] \right\} n_i t^{n_i-1} dt \right]$$

where

$C_{11}, C_{21}, C_{31}, C_{12}, C_{22}, C_{32},$ – Experimental constants

T_g - Glass transition temperature

T_{m1}, T_{m2} – Temperatures for melting of crystals

n_1, n_2 – Avrami constants for corresponding mechanisms

The calculation of crystallinity parameter X_{vc} was realized by special subroutine and used in UMAT program to influence on mechanical properties of thermoplastic composite.

For the case of 35°C cool rate and for 40 plies specimen, based on PEEK matrix, typical distribution of crystallinity shown on Figure 7.

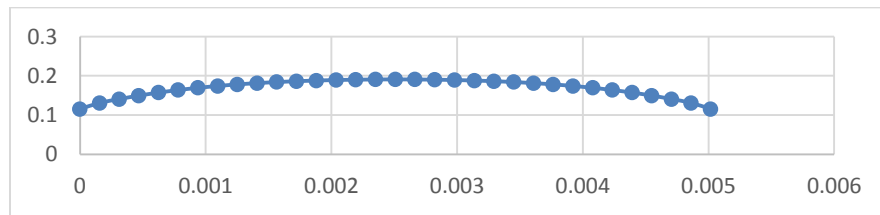


Figure 7: crystallinity distribution through the thickness of 40 plies specimen

4. Residual stress

In order to approximate effective properties of composite material and calculate additional volumetric shrinkage there is an idea to use crystallinity distribution at the next step. The

reasonable approach is to use Chamis [5] and Bogetti [6] micromechanics equations in combination with work [4], where average property of thermoplastic matrix (PEEK) are obtained. Transversal residual stresses values through the thickness are shown on Figure 8 for the 40 ply unidirectional specimen. One can see that taking into account crystallinity influence gives a result, which is more correct.

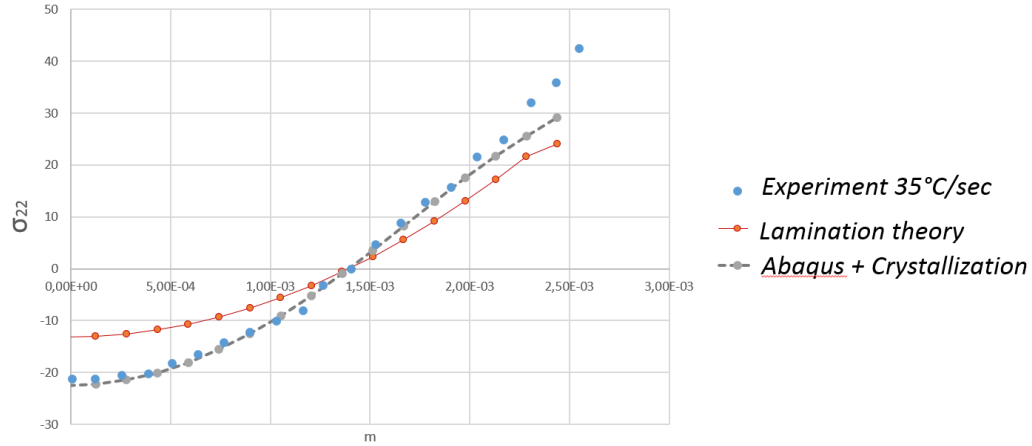


Figure 8: Residual transversal stress distribution in 40 ply unidirectional specimen

5. Thermoplastic matrix failure

We can estimate failure of thermoplastic product during cool down process by application of the obtained residual stress to the meso-model, (Figure 9).

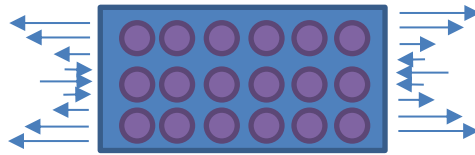


Figure 9 Applying forces to the meso-model

Briefly, a complete algorithm of failure estimation is shown on Figure 10.

Material model used for matrix failure prediction is taken from the work [8] and based on Drucker-Prager plasticity [9]. Failure accumulation is based on work [10] and has integral form with capability to take into account the history of loading of the material:

$$\omega_D = \int_0^t \frac{d\varepsilon^{pl}}{\varepsilon_D^{pl}(\xi, \dot{\varepsilon})}$$

$$\omega_D = 1 - \text{matrix failure}$$

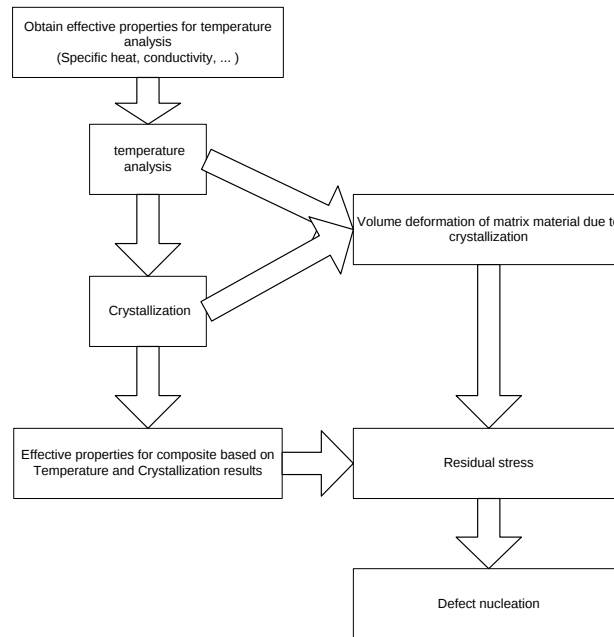


Figure 10: Algorithm scheme for matrix failure estimation

Figure 11 shows the fringe of parameter ω_D at the initiation of failure, in case of plane strain transversal tension condition of meso-model.

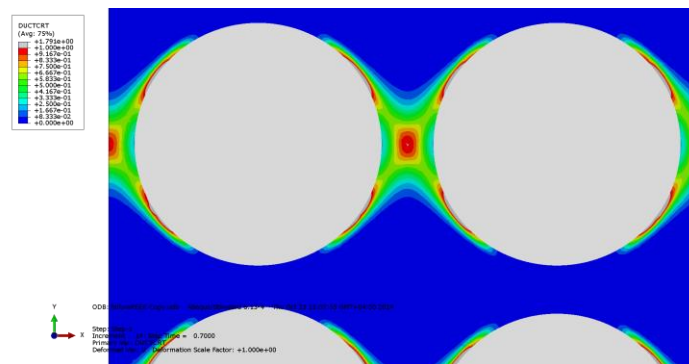


Figure 11: Distribution of parameter ω_D at initiation of failure

Figure 12 shows the areas of active yielding during loading.

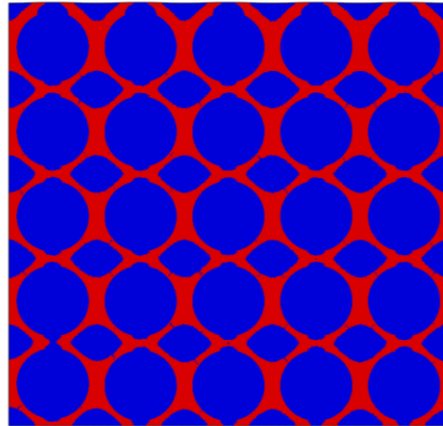


Figure 12: Active yielding areas

6. Conclusions

The approach to estimate manufacturing failure of thermoplastic composite products is presented. It was shown that in the case of thermoplastic matrix the ratio of crystallinity plays important role in predicting of the residual stress. It is possible to conclude that Abaqus software has all necessary tools to realize a complete cycle of design development of thermoplastic products, from forming process to meso-level failure prediction.

7. Acknowledgments

This work was supported by RFBR grant 14-01-31322 and the part of this work was carried out in the Perm National Research Polytechnic University with support of the Government of Russian Federation (The decree № 220 on April 9, 2010) under the Contract № 14.B25.310006, on June 24, 2013.

8. References

1. Composites Benchmark Forum; 2008. <http://www.wovencomposites.org/index.php> [accessed 07.12.12].
2. Harrison, P., Gomes, P., Correia, R., Abdiwi, F., and Yu, W.R. (2012) Press forming the double-dome benchmark geometry using a 0/90 uniaxial cross-ply advanced thermoplastic composite. In: ECCM 15 - 15th European Conference on Composite Materials, Venice, Italy, 24-28 Jun 2012.
3. Lomakin E.V., Melnikov A.M., Fedulov B.N. Constitutive models for anisotropic materials susceptible to loading conditions // Mechanics and Model-Based Control of Advanced Engineering Systems, Springer Verlag GmbH, Berlin, 2014

4. Crystallization kinetics of polyetheretherketone (peek) matrices Chris N. Velisaris and James C. Seferis. *Polymer Engineering & Science*. Volume 26, Issue 22, pages 1574–1581, December 1986 DOI: 10.1002/pen.760262208
5. Chavis C. C. Simplified composite micromechanics equations for hygral, thermal and mechanical properties. 38th Ann. Conf. of the Society of the Plastics INdustry (SPI) Reinforced Plastics/Composites Inst., Houston, Tex., 7-11 Feb. 1983
6. Travis A. Bogetti, John W. Gillespie Jr, Process-Induced Stress and Deformation in Thick-Section Thermoset Composite Laminates. *Journal of Composite Materials* May 1992 vol. 26 no. 5 626-660.
7. Wesley E. Lawrence¹, James C. Seferis¹, and John W. Gillespie Jr.². Material response of a semicrystalline thermoplastic polymer and composite in relation to process cooling history. *Polymer Composites* Volume 13, Issue 2, pages 86–96, February 1992
8. Lei Yang, Ying Yan, Jian Ma, Bo Liu. Effects of inter-fiber spacing and thermal residual stress on transverse failure of fiber-reinforced polymer–matrix composites. *Computational Materials Science*. Volume 68, February 2013, Pages 255–262
9. Abaqus 6.14 manual
10. Hooputra, H., H. Gese, H. Dell, and H. Werner, “A Comprehensive Failure Model for Crashworthiness Simulation of Aluminium Extrusions,” *International Journal of Crashworthiness*, vol. 9, no.5, pp. 449–464, 2004.