# FAILURE CRITERION FOR THERMOPLASTIC COMPOSITES FOR CHARACTERIZATION OF MANUFACTURING PROCESS

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**Abstract**
This research describes the possibility to analyze the quality of thermoplastic composite details in terms of strength and integrity and focuses on manufacturing process. The main idea of presented work is to understand the type of transformation of plasticity model for neat thermoplastic matrix in case of different combinations of the degree of crystallinity and temperature of the material. The obtained changes of plasticity conditions can be implemented into the strength analysis of composite details during thermoplastic matrix solidification caused by manufacturing cool down processes.

## 1. Introduction

Thermoplastic composites are gaining popularity as a structural material in a number of industries. Its ability to change the phase-state of thermoplastic matrix to soft one during heating up and crystallization with subsequent cooling makes them beneficial in the cases when fast and mass production of lightweight structures are essential. Many approaches to model these phase transitions are developed that can forecast matrix shrinkage during its solidification [1-3]. Eventually they can be used to model the residual stress distribution. Nevertheless, the low-studied subject is concerned the strength of thermoplastic materials or reliable modelling techniques [4, 5], which describe the possible defects formation induced by manufacturing processes such as temperature drop and possible subsequent machining.

## 2. Plasticity and damge model for thermoplastic material

Following works [6-8] we can formulate criterion of plasticity for the material in essentially general form:

$$f(\xi)\sigma_0 = k_0, \tag{1}$$

where $\xi = \sigma/\sigma_0, \sigma = \sigma_{ii}/3, \sigma_0 = \sqrt{\frac{3}{2}S_{ij}S_{ij}}, S_{ij} = \sigma_{ij} - \delta_{ij}\sigma, \delta_{ij} = 0\ (i \neq j), \delta_{ii} = 1.$

The parameter $k_0$(units Pa) is an analogue to the yield limit in the case of von Mises plasticity ($f(\xi) \equiv 1$). Hardening of the material can be described by the use of equivalent plastic deformation, which is based on energy of the plastic strain:

$$\varepsilon_{eq}^{pl} = \int \frac{\sigma_{ij} d\varepsilon_{ij}^{pl}}{\sigma_t^{pl}},$$

where $\sigma_t^{pl}$ – is an experimental tension stress.

Failure criterion is formulated using damage parameter, which is a sum of plastic strains with weights $\varepsilon_D^{pl}(\xi)$ for different stress states:

$$D^{pl} = \int \frac{d\varepsilon_{eq}^{pl}}{\varepsilon_D^{pl}(\xi)} = 1, \quad (2)$$

As it was shown in research [4], the data for material constants shown in Table 1, with linear dependency of $f(\xi) = 1 + C\xi$, gives a good approximation of failure of composite using micromechanical technique.

**Table 1.** Mechanical constants and data for PEEK material simulation

| Mechanical constants | | Tensile hardening | | Failure strain | |
|---|---|---|---|---|---|
| Modulus, GPa | 3.6 | $\sigma_t^{pl}$, MPa | $\varepsilon_{eq}^{pl}$, m/m | Triaxiality, $\xi$ | $\varepsilon_D^{pl}$ m/m |
| Poisson's ratio | 0.3 | 77 | 0 | -0.333 | 1.5 |
| $k_0$, MPa | 89.8 | 81 | 0.1 | 0 | 1 |
| $C$ | 0.5 | 100 | 0.5 | 0.333 | 0.7 |
| Dilatation angle, ° | 27 | 101 | 2 | 0.5 | 0.6 |

Figure 1 shows three different variants of periodic cells with random placements of fibers at maximum stresses and strains in case of transversal loading.

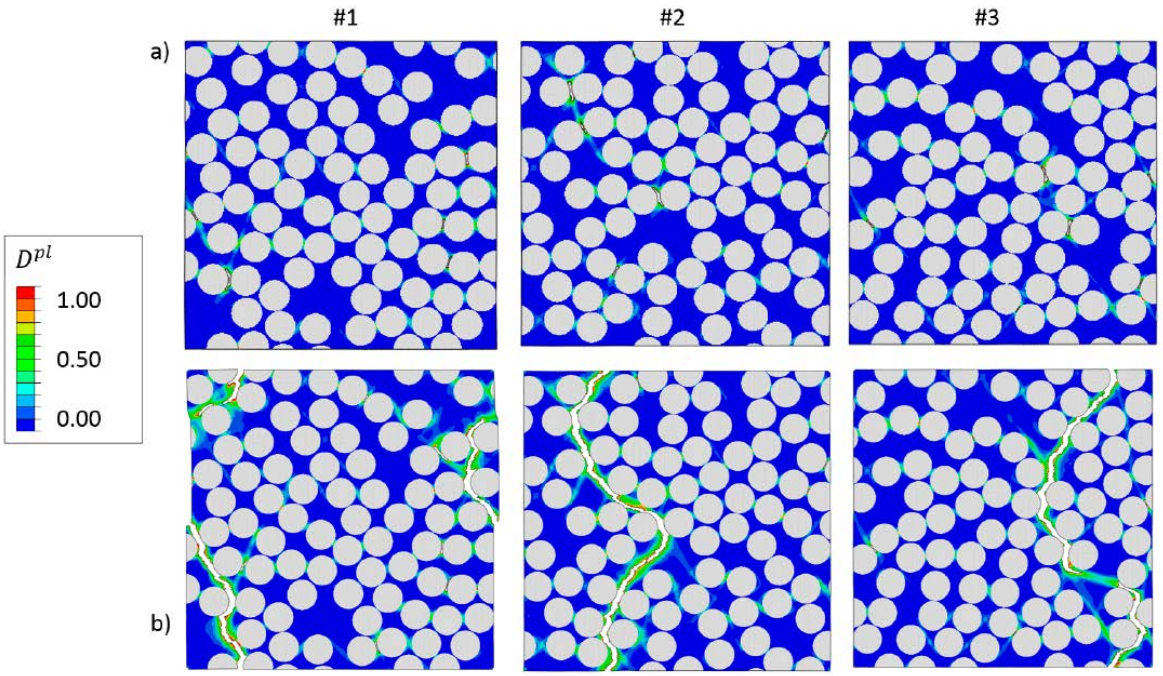


**Figure 1.** Damage parameter distribution for transversal loading at maximum stress (a) and strain (b) achieved in modelling strain.

Figure 2 shows transversal loading diagrams for different cells corresponding to the samples presented in figure 1. It is possible to see that the typical maximum stresses for composite used in this research is very close to the value predicted by the developed model.

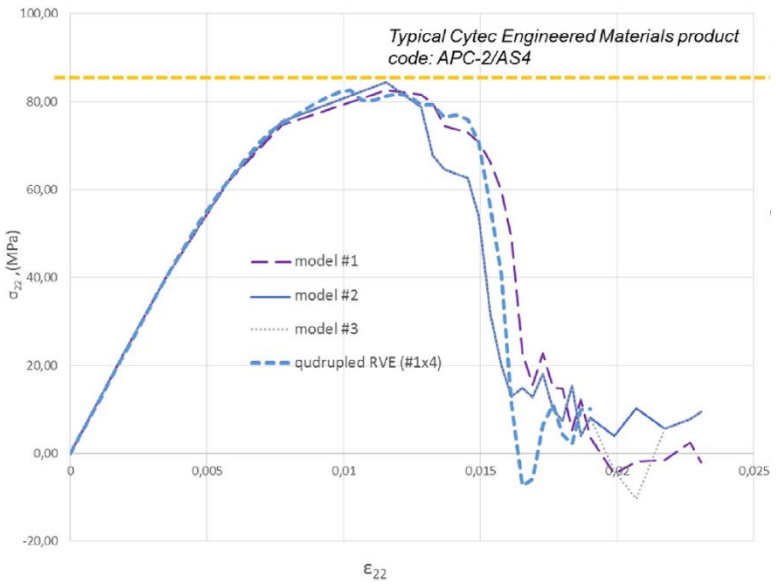


**Figure 2.** Transversal loading diagrams obtained in modelling for different randomly placed fibers arrangements.

## 3. Strength properties evolution

In the previous section, a plasticity model for thermoplastic polymer matrix PEEK is proposed. The plasticity criterion for such a model can be written in the following form:

$$\sigma_0(1 + C\xi) = k_0(\varepsilon_{eq}^{pl}), \tag{3}$$

The corresponding set of input parameters is given in Table 1. All values were obtained for room temperature and maximum degree of crystallinity. To evaluate the strength in the process of cooling of the composite on the basis of the studying matrix material, it is necessary to propose a modification of the input parameters or the entire plasticity model, depending on the temperature and the degree of crystallinity, just like the matrix stiffness modulus in the process of specimen cooling.

Let us suppose that for the modification of plastic properties, only input parameters can be changed depending on the temperature $T$ of the material and the degree of crystallinity $X_{vc}$.

As a first step, let us consider the effect of the degree of crystallinity $X_{vc}$. Work [9] presents the results of uniaxial tensile experiments, for different samples obtained under different conditions of technological cooling, and, as a result, with different values of the degree of crystallinity (Fig. 3). Analysing the changes in yield stresses as a function of parameter $X_{vc}$ (Fig. 4), it can be seen that the linear interpolation of the experimental points gives a rather good approximation. Such a change in the the yield stress can be taken into account by changing only the parameter $k$ in the relation (3). Thus, using linear interpolation of points (Fig. 4) for the criterion (3), the influence of the degree of crystallinity can be taken into account as follows:

$$\sigma_0(1 + C\xi) = k_0\big(1 + \alpha(X_{vc} - X_{vc}^{\infty})\big), \tag{4}$$

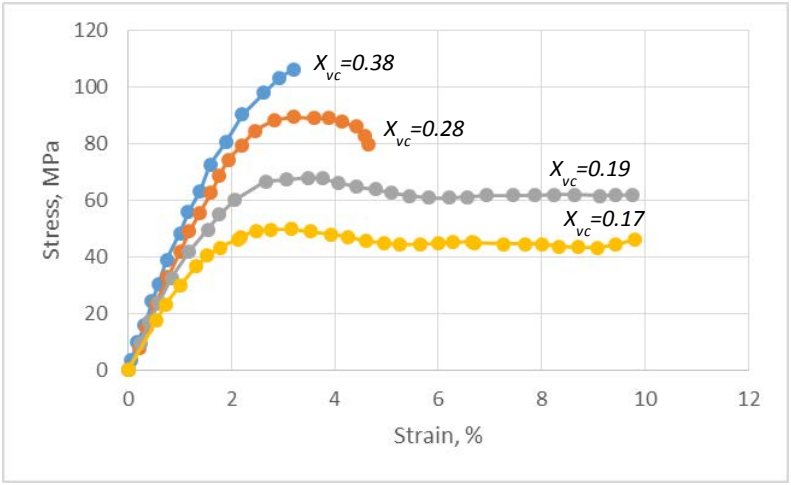


**Figure 3.** Tensile stress-strain curves for different crystallinity degrees.

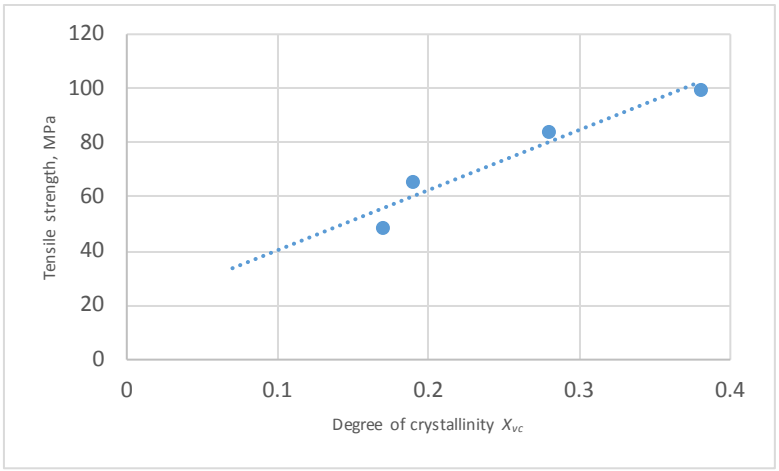


**Figure 4.** Linear approximation of tension strength stress values in dependence of crystallinity (PEEK).

At the next step, we consider the possibility of taking into account the influence of temperature for the criterion (3). Vicktrex technical documentation for PEEK 450G material [10] shows the tensile strength and failure load under bending conditions as a function of temperature (Fig. 5).

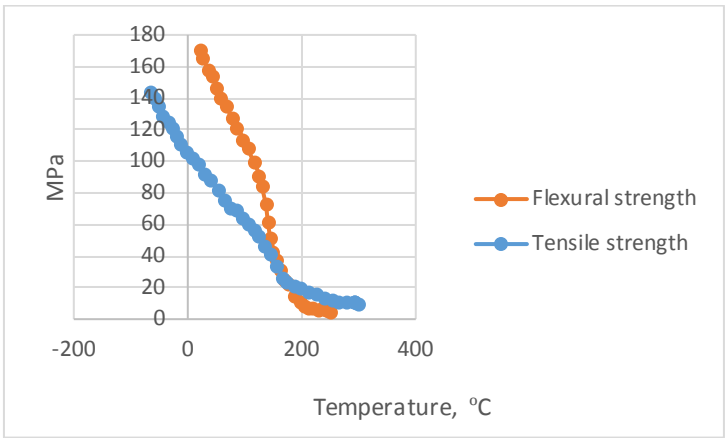


**Figure 5.** PEEK strength data at different temperatures

It is possible to show that similarly to the effect of the degree of crystallinity, the dependence on temperature can also be taken into account only by changing the parameter *k* in the criterion (3). Figure 6 shows the ratio of this dependence on temperature. It can be seen that at temperatures below 143°C, the ratio can be approximated by a constant. The temperature of 143 °C is chosen, since it is the glass transition temperature.

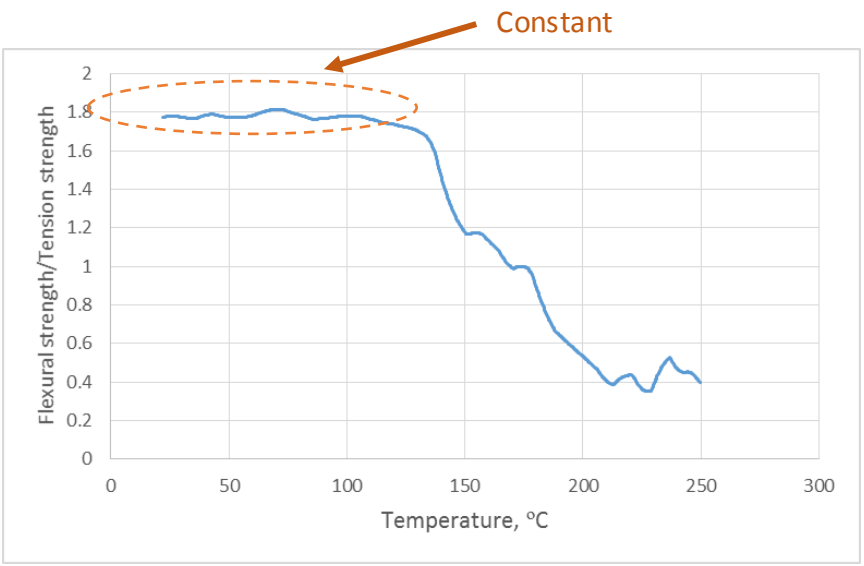


**Figure 6**. Ratio of flexural and tensile strength for different temperatures (PEEK). (исправить на оси ординат Tensile)

Dependencies for tensile and flexural strengths obviously have different values, which can be explained by different stress states in the specimens for these types of experiments. This effect accurately analyzed in [4]. The problem with the analysis of this strength experimental data is that we need to show the possibility to characterise exactly this effect by simple modification of model input constants. Let us reduce this task to the temperature range where constant ratio of flexural and tensile strengths is satisfied.

In the case of constant ratio of flexural and tensile strengths determined in experiments where loads $P_t$ (load from experiment under tension) and $P_f$ (load from flexural experiments) are applied correspondingly, we can assume that the stress components increase proportionally to loading parameter *t*. Without loss of generality, we can state that if

$$P_f / P_t = P_f^0 t_{failure}^f / P_t^0 t_{failure}^t = const,$$

where $t_{failure}^f$- loading parameter corresponding to flexural failure load, $t_{failure}^t$-loading parameter corresponding to tensile failure load; $P_f^0$ and $P_t^0$ – normalized values of applied loads, then, obviously, the ratio of corresponding loading parameter *t* remains constant for the chosen range of temperature. Thus using the criterion (3) with linear dependency on triaxiality parameter, we can write:

$$\begin{aligned}(1 + C\xi^f){\sigma_0}^f t_{failure}^f &= k,\\ (1 + C\xi^t){\sigma_0}^t t_{failure}^t &= k,\end{aligned} \qquad (5)$$

where $\xi^f$ - triaxiality parameter for flexural loading, ${\sigma_0}^f = \sigma_0/t^f_{failure}$ - normalized to von Mises stress for flexural loading, $\xi^t$ - triaxiality parameter for tensile loading, ${\sigma_0}^t = \sigma_0/t^t_{failure}$ - normalized to von Mises stress for tensile loading.

We apparently can satisfy tension strength reduction due to temperature increase by means of linear dependency of parameter $k$ on temperature (Fig.7).

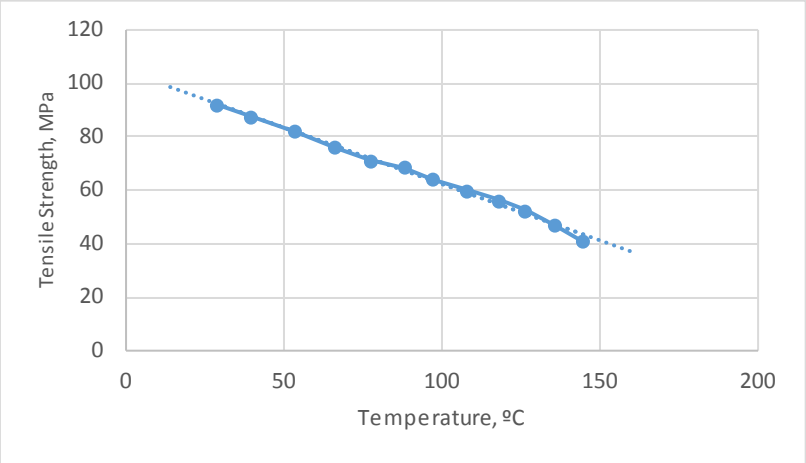


**Figure 7**. Linear approximation of tension strength stress values in dependence of temperatures (PEEK).

Based on resuls of tensile strength experiments in range of temperatures 24<*T*<143, we can write for parameter *k* and criterion (3) the following relation:

$$f(\xi)\sigma_0 = k_0\big(1 + \beta(T - 24)\big)\,, \tag{6}$$

where $\beta$ for PEEK material has a value of 0.4/°C.

Using the equations (5), and keeping the temperature dependency only in reduction of material parameter $k$, and no change of parameter *C* in equation (4), we can obtain the following relations:

$$t^f_{failure} = \frac{k_0\big(1 + \beta(T - 24)\big)}{1 + C\xi^f {\sigma_0}^f},$$

$$t^t_{failure} = \frac{k_0\big(1 + \beta(T - 24)\big)}{1 + C\xi^t {\sigma_0}^t},$$

that the resulting ratio of $\frac{t^f_{failure}}{t^t_{failure}} = const$ , which consequently means the constant ratio of limit loads for flexure and tension experiments (Fig.6). Thus, we can state that at list for two different stress states equation (6) satisfies experimental data shown in fig. 5 for temperature range 24<*T*<143.

Eventually, to take into account different stress states in failure experiments, it is reasonable to assume that plasticity condition for PEEK material with dependence of materil parameters on temperature can be written as:

$$\sigma_0(1 + C\xi) = k_0\big(1 + \beta(T - T_0)\big)\,. \tag{9}$$

Having modification of plasticity criterion (5) due to degree of crystallinity and temperature changes, and because of lack of experimental data for the cases of different combinations of *T* and $X_{vc}$, we can propose the superposition of these two approaches for the formulation of plasticity criterion for PEEK material:

$$\sigma_0(1 + C\xi) = k_0(\varepsilon_{eq}^{pl})\big(1 + \alpha(X_{vc} - X_{vc}^{\infty})\big)\big(1 + \beta(T - T_0)\big).$$

Where input values for PEEK are shown in Table 2.

**Table 2**. Plasticity modelling parameters for PEEK

| | |
|---|---|
| $C$ | 0.5 |
| $k_0$ | 89.8 (MPa) |
| $\alpha$ | 2.38 |
| $X_{vc}^{\infty}$ | 0.38 |
| $\beta$ | 0.4 (1/°C) |
| $T_0$ | 24 (°C) |

## 3. Conclusions

The proposed plasticity model gives the possibility to complete a number of models for thermoplastic material with one more, which can be used to predict the strength properties. The use of demonstrated technique gives the potential opportunity to examine the quality of a manufactured product and to predict it's strength properties on the base of only temperature regime history as an input data.

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