GTE blade injection moulding modeling and verification of models during process approbation

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Abstract. The simulation model for filling the mould was developed using Moldex3D, and it was experimentally verified in order to perform further optimization calculations of the moulding process conditions. The method described in the article allows adjusting the finite-element model by minimizing the airfoil profile difference between the design and experimental melt motion front due to the differentiated change of power supplied to heating elements, which heat the injection mould in simulation. As a result of calibrating the injection mould for the gas-turbine engine blade, the mean difference between the design melt motion profile and the experimental airfoil profile of no more than 4% was achieved.

1. Introduction

The strength of polymer composite material (PCM) items featuring a combined reinforcement structure and short-fibre reinforcement is conditioned by the fibre distribution and direction. It is particularly important for the GTE blades, for which strict quality requirements are placed. The strengthened blade made based on the moulded multilayer PCM allows applying high-modular fibres. The control of the reinforcement structure i.e. laying-up angles allows obtaining the required anisotropic structure considering the effective load properties. At the same time, structures made based on the multilayer PCM have a relatively low interlayer strength and are susceptible to damages represented by layer separation and cracking in the transversal direction of the reinforcement [1]. This type of PCM damage is the most dangerous since it results in a considerable reduction of flexural and torsional rigidity, furthermore, it refers to invisible damages, i.e. it may be detected only with special means and methods.

In addition, forming of the blade root area by laying-up of multilayer prepregs is difficult due to its complex geometry. In this connection, the lock portion and the inner portion are reasonable to be manufactured by injection moulding (IM) of PCM by means of filling the forming cavities of the injection mould by the PEEK melt with the reinforcing discrete carbon fibre. Therefore, the blade is manufactured of the pre-formed prepreg shells, with pouring the PEEK PMC reinforced with short fibres using the IM method.

An important factor to obtain a high-quality moulding is foremoulding its structure, in particular, distribution of the reinforcing fibre which is ensured by the structure of the moulding injection mould and process modes.

In the context of the injection mould structure, the IM process parameters are optimized using the FE simulation modelling such as Autodesk Simulation Moldflow [2] or Moldex3D [3, 4]. In general,
the modelling reliability depends on the FE model quality as well as the properly set boundary conditions. The optimized process parameters allow obtaining a precise moulding with the required anisotropy of properties.

The issues of precision analysis for the blade type products are described in detail in works [5, 6]. This experiment was aimed at the development and experimental verification of the simulation model for filling the mould in plant conditions in order to perform further optimization calculations of the moulding process conditions. Main stages of the research described below.

1. Development of the moulding simulation model considering the process peculiarities.
2. Preliminary optimization of moulding conditions. Injection mould filling process analysis and melt front motion modelling.
3. Experimental analysis of the melt front motion in the shell-free mould moulding. Verification and specification of the simulation model.
4. Modelling of the injection mould filling with the installed reinforcing shells. Reinforcing fibre orientation analysis.
5. The experimental verification of the simulation model based on the fibre orientation calculation. The first three stages are described in this article.

2. Theoretical Aspects Of Melt Motion In Moulding
The reinforcing fibre orientation is conditioned by the melt motion. Theoretic melt motion models and their numerical implementation are described in works [7, 8].

In real conditions, the flow of polymeric melt is non-stationary, quasi-viscous, and non-isothermal. Layer hardening is started near the mould walls with the material mixture distribution in the mould cavity. This process is non-linear and the material properties depend on rheological and thermal conditions.

In Moldex3D, a high-efficiency and precise finite element method for calculating the non-stationary melt flow in complex 3D cavities is implemented. In particular, the main advantage of the 3D-FVM is the possibility to implement the non-balanced gating system. The particular features of the 3D-FVM method are described in [9].

To trace the melt front motion, function \( f \) of the inclusion volume fraction is calculated by the method of 3D-FVM [2]. \( f=0 \) is to determine the air phase, \( f=1 \) is the polymer melt phase. Values within the range of \( 0<f<1 \) show that the melt is in the FE-mesh cells, its motion over time is described by the transfer equation:

\[
\frac{\partial f}{\partial t} + \nabla \cdot (uf) = 0.
\]

(1)

It should be noted that the flow rate or the injection pressure are predetermined at the injection mould inlet; the wall friction is not considered; the inlet boundary condition only is required for the hyperbolic differential transfer equation of volume fraction function.

To describe the polymer melt viscosity curve considering the shear rate, the Cross model version, namely Cross-Williams-Landell-Ferry model is used, where zero shift viscosity \( \eta_0(T, p) \) depends on temperature \( T \) and pressure \( p \). The Cross-WLF model is described by seven parameters [4]:

\[
\eta(T, P, \gamma) = \frac{\eta_0(T, P)}{1 + (\eta_0 / \eta^*)} ; \quad \eta_0(T, P) = D_1 \exp \left( \frac{-A_1(T - T_c)}{A_2 + (T - T_c)} \right)
\]

\[
T_c = D_2 + D_3P; \quad A_1 = A_1 + D_4P
\]

(2)

In formula (2), \( n \) is the power dependence exponent; \( \gamma^* \) the parameter describing the transition interval from the zero shear to the viscosity curve exponential law. Parameters \( D1, D2, D3, A1, A2 \) are the additional model constants. According to the pVT diagram, a modified Tait model describes a complex thermodynamic condition by the dependencies as follows:
\[
\dot{V} = \dot{V}_0 [1 - C \ln(1 + P/B)] + \dot{V}_i \\
\dot{V}_0 = \begin{cases} 
    b_1 + b_2 T, & \text{if } T \leq T_c \\
    b_1 + b_2 T, & \text{if } T > T_c
\end{cases} \quad \dot{B} = \begin{cases} 
    b_4 \exp(-b_5 \dot{T}), & \text{if } T \leq T_c \\
    b_4 \exp(-b_5 \dot{T}), & \text{if } T > T_c
\end{cases} \quad \dot{V}_i = \begin{cases} 
    b_7 \exp(b_8 \dot{T} - b_9 P), & \text{if } T \leq T_c \\
    0, & \text{if } T > T_c
\end{cases}
\]

\[T = T - b_3, \quad T_c = b_3 + b_4 P, \quad C = 0.0894 \quad (3)\]

13 parameters of the modified Tait model are determined based on the reference data of material properties [10].

3. Stator Blade IM Simulation Modelling

The purpose of blade simulation modelling in Moldex3D is the development of a calibration method for the finite element model to determine the impact caused by the error when setting the boundary conditions for the moulding thermal condition with the simplified representation of the injection mould structure model.

Further analysis of the flow hydrodynamics in the injection mould filling is necessary to detect challenging areas during filling as well as to establish the adequate reinforcing fibre distribution pattern. Calibration was carried out by comparing the design and experimental data of the current hydrodynamics based on a model material (PA-MXD6 polyamide) in the moulding conditions ensuring compatibility according to the PEEK blade material viscosity condition.

Based on a CAD model, using the Moldex3D Designer tools, a FE-mesh was obtained (consisting of 6,466,708 elements) which reflected the characteristic areas of the part to the most precise extent. For the blade, the airfoil represents this type of characteristic area. The density of finite elements in possibly hindered melt flowing points was selected as the largest value. The geometric shape of the injection mould was preset as a simplified properly sized parallelepiped with the surface of the joint, melt supply gates and thermostabilization channels arranging the heating elements. Moulding process parameters were set in the Moldex3D pre-processor according to table 1.

| Table 1 – Moulding process parameters |
|---------------------------------------|
| Parameter                          | Value     | Parameter                  | Value     |
|-------------------------------------|-----------|----------------------------|-----------|
| Injection pressure                  | 180 MPa   | Heating parameters: method | continuous|
| Injection rate                      | 15 mm/s   | Cooling medium temperature | 100°C     |
| Rate control - pressure control     | 98%       | Extraction temperature     | 190°C     |
| switching moment                    |           | Cooling time               | 20 s      |
| Pressure holding time               | 9.6 s     | Mould opening time         | 5 s       |
| Melt temperature                    | 280°C     |                            |           |
| Injection mould temperature         | 100°C     |                            |           |

The injection time was calculated automatically depending on the injection rate and pressure.

Figure 1 and figure 2 shows the results of airfoil filling simulation modelling at the beginning of the process and at the second stage – after full filling of the root flange.
As we can see, a minor underfill is observed in the most challenging zone, i.e. within the airfoil edge thinning area, which is eliminated with further filling of the mould. Verification of the IM simulation model in the melt filling was carried out following the results of the experiment using the algorithm as follows. 

The preliminary calculation melt front motion during filling the root and airfoil section was carried out in Moldex3D. At a fixed moment of the injection time, volume $V$ of the melt injected into the mould cavity and the gate system was determined. Further, a theoretical enveloping curve for the forward melt front was built. Experimentally, the blade sample was moulded under the design conditions with the same injected volume, $V$. The airfoil upper profile coordinates of the specially underfolded blade were measured. The relative mean square deviation between the theoretical and experimental curve was calculated by the following dependence:

\[
\sigma = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left(1 - \frac{y_{\text{theor}}}{y_{\text{exp}}} \right)^2}
\]  

In formula (4), $n$ is the number of reference points, $y_{\text{theor}}$ is the coordinate of the theoretical flow front point, $y_{\text{exp}}$ is the coordinate of the experimental flow front point.

4. Experimental Analysis of the Melt Front Motion in Moulding. Simulation Model Verification and Specification

The IM process was carried out using the Negri Bossi VE 1200 H-440 injection moulding machine equipped with a hot runner gate system mould. Injection mould (figure 3) consists of the movable 1 and stationary 2 parts. The blade forming airfoil surfaces of parts 3 and 4 and the package of inserts 5, 6 forming the blade root are thermally insulated from flange plates 7, 8 and spacers 9, 10. The PCM melt is supplied to the mould cavity through central bush 11, plate 1 with the hot channel and heated nozzle 13. The melt temperature is controlled by the thermocouple installed at injection nozzle 13. The temperature of moulding plates 3, 4 and inserts 5,6 is automatically controlled and maintained by the controller (PLC) via changing the power of cylinder heaters located in holes 14, 15.
Figure 3. Injection mould for the blade IM

Upon completion of the IM cycle and the injection mould opening, the blade is taken from the injection mould (figure 4) jointly with inserts 5 and 6 while pusher plates 16 and 17 move.

Figure 4. An opened injection mould with the moulded blade before its removal jointly with inserts.

The melt front measuring results for the experimental blade with the unfinished airfoil and comparison of the results with the theoretical melt motion profile are given in table 2 and are represented in figure 5 a and 5 b.

6 points along the experimental (\(T_{\text{exp}}\)) and theoretical (\(T_{\text{theor}}\)) front lines of the melt flow were taken. After measuring the coordinates, the difference between them as well as the mean square error were calculated.
Table 2. Evaluation of the coincidence of the theoretical and experimental front

| №  | $T_{\text{exp.}}$ | $T_{\text{theor.}}$ | $|\delta|\quad \sigma$ |
|----|-----------------|------------------|----------------|
| P1 | 55.00           | 55.00            | 0.00            |
| P2 | 118.35          | 118.35           | 0.00            |
| P3 | 122.06          | 127.04           | 4.98            |
| P4 | 118.85          | 125.32           | 6.47 0.04       |
| P5 | 105.44          | 110.13           | 4.69            |
| P6 | 55.00           | 55.00            | 0.00            |
| P’ | 98.28           | 97.45            | 0.83            |

With the given calculation option, the melt flow profile difference within 4.69–6.47 is observed. The difference is caused by the fact that the actual surface condition (in terms of roughness) is not considered by the mathematical model and real moulding temperature values somewhat differ from the design values. Consideration of roughness is possible if the friction factors between the moulding cavity material of the injection mould and the cast part are known.

![Melt motion front profile](image)

**Figure 5.** Melt motion front profile: a – experimental; b – theoretical

Since the melt motion in the injection mould is initially stipulated by its temperature gradient, the simulation model was adjusted with the target function by means of virtual adjustment of the heating elements power in the movable and static parts ensuring the required heat exchange with the melt.

5. Conclusions
Since a simplified representation of the mould design is used for the development of a finite-element model, the real pattern of the heat flow distribution differs from the modelled one. In addition, real values of the friction factor and the threshold shear value in the melt layer adjacent to the injection mould surface are unknown.

As a result, the hydrodynamics for melt flow within the injection mould may differ from the modelled one. Therefore, to perform correct calculations, the finite-element model shall be calibrated. The method described in the article allows performing the detailed adjustment by minimizing the profile difference between the design and experimental melt motion front due to the differentiated change of power supplied to heating elements, which heat the model representation of an injection mould. As a result of calibrating the injection mould for the blade airfoil, the mean difference between the design melt motion profile and the experimental profile of no more than 4% was achieved.
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References
[1] Feraboli P, Peitso E, Deleo F, Cleveland T, and Stickler P B 2008 J. Reinf. Plast. Comp. 10 1191-1214
[2] Wang J and Jin X 2010 Proc. of the Polymer Processing Society 26th Annual Meeting (Banff)
[3] Foss P H, Tseng H C, Snaverdt J, Chang Y J, Yang W H and Hsu C H 2014 Pol. Comp. 4 671-680
[4] Kitayama S, Onuki R, and Yamazaki K 2014 Int. J. of Adv. Manuf. Tech. 5-8 827-838
[5] Pechenin V A, Bolotov M A, Ruzanov N V and Kondovin V A 2016 J. Mach. Manuf. Reliab. 2 185-190
[6] Pechenin V A, Bolotov M A and Ruzanov N V 2016 Key Eng. Mat. 685 334-339
[7] Vdovin R A and Smelov V G 2014 Int. J. Eng. Tech. 5 2269-2275
[8] Nosova E A and Grechnikov F V 2016 Key Eng. Mat. 684 366-370
[9] Chang R Y and Chiou S Y 1995 Pol. Eng. Sci. 22 1733-1747
[10] Van Krevelen D W and Nijenhuis K Te 2009 Properties of polymers (Amsterdam: Elsevier)
[11] Ryazanov A I 2016 Russian Eng. Res. 36 751-754