Computational fluid dynamics in RTM method of the carbon composites molding

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Abstract. The article focuses on simulating flow of epoxy resin in injection mold with carbon fiber fabric inside. Performed simulations were based on the process of manufacturing composite elements using modern RTM method. RTM method is used in production of high-end and sports car parts, and other lightweight products requiring high strength. It consists in injecting the resin under pressure into a closed mold with reinforcement. One of major problems in this method is providing adequate flow of the resin in injection mold and a complete supersaturation of reinforcement with a thermosetting resin. These aspects depend strongly on the direction of the fibers in the carbon fabric and porosity of the reinforcement. Information about proper construction of the mold and influence of fiber orientation and porosity can be obtained by numerical simulations using CFD commercial software Moldex3D. Research was based on actual process of manufacturing car mirror covers. Analysis of obtained results focused on the impact of changes in process input parameters. In particular, parameters such as the porosity and direction of fibers in the reinforcement were investigated. Test results are compared in terms of the degree of reinforcement supersaturation in the mold. Based on performed tests, appropriate conclusions were drawn.

1. Introduction

The composites are used in many industrial sectors thanks to a wide range of applications, but also thanks to many methods developed to manufacture and combine them [1]. Choosing the right technology and the right material in the manufacturing process allows to achieve satisfying results [2, 3].

RTM (Resin Transfer Moulding) is a method of producing carbon fibre based composites in a closed mould. It consists of injecting resin into the pre-arranged reinforcement [4] (showed in the figure 1). The properties of the manufactured components are strongly influenced by the resin, reinforcement and technological process parameters. Atmospheric pressure, ambient temperature, differences in volume of reinforcement also have an impact on the quality of the final workpiece [5]. Multitude of variables affecting the production process indicates the need of using computer simulations at the stage of preparation of the production process. Simulations allow to choose the injection speed and determine the time of filling the mould. It is also important to arrange reinforcement inside the mould. Uneven distribution of reinforcement in the volume of the composite leads to many negative phenomena, for example not allowing full saturation, and or influencing the occurrence of shear stresses that often deform the mould [4, 6, 7].
One of the current goals is to introduce innovative technological solutions to reduce the costs of production of carbon fibre components and open the possibility of mass production. The development of these elements using the RTM method brings up a number of challenges and a need for further studies [4, 5, 9, 10], such as described in this article.

1.1. Moldflow input
The numerical simulation was performed for selected thermosetting, epoxy resin model. The resin injection control is carried out by adjusting the flow rate. It averages approximately 0.7 cm³/sec. Additional specification describes maximum material flow pressure in the mould inlet - 7 MPa, which correspond with the documentation of the resin injection equipment.

Simulations regarding the analysis of the impact of different type and arrangement of reinforcement were carried out.

The flow of resin, in any method of injection, can be simplified in the application of the Darcy’s law. Carbon reinforcement permeability is determined by the resistance of the flow, defined by the tensors of permeability. To describe the viscosity of resin modified Castro-Macosko model was used [11 - 13] and a combined model of Kamal, Sourour and Ryan model was used to describe the viscoelastic hardening [14].

1.2. Geometry and mesh
Performed tests were based on a 3D model of the cover of car mirrors, prepared in CATIA V5-6R2014.

Simulating the flow of epoxy resin in the cavity and evaluating the parameter influences for the correct process were the main subject of research. The mould cavity model (brighter area) represent in the figure 2 included areas corresponding to the geometry of two mirror covers (right and left – black area) and cold runner system (tube in the centre). In subsequent stages of production, one pair of mirror caps is cut out from each mould.

**Figure 1. Sequence of the main steps in RTM**
Figure 2. The model of part and cavity with the filling channel and visible mirror covers geometry

Moldex3D software was used to simulate the flow of resin in injection mould in the process of manufacturing elements the RTM method. This tool is widely used in the industries involved in the production of plastic components. It allows the simulation of processing thermoplastic polymers and reactive plastics. The analysis uses the finite element method [15]. A mesh of 3D elements with a maximum edge length limited to 3mm was created. According to the rules of flow analysis, the mesh at the constraining walls was appropriately refined. [14, 16] After the meshing process completed, a model with the parameters described in table 1 was received.

| Mesh type               | Mixed                                      |
|-------------------------|--------------------------------------------|
| Cavity dimensions       | 137.1177 x 328.3881 x 412.5835 (mm)        |
| Mould dimensions        | 214.2700 x 375.0000 x 460.0000 (mm)        |
| Cavity volume           | 69.2558 (cm³)                              |
| Cold runner volume      | 104.358 (cm³)                              |
| Element number          | 871 423                                    |
| Part number             | 871 423                                    |
| Node number             | 368 756                                    |

2. Numerical tests
Many numerical tests have been carried out. Various factors influencing epoxy resin flow in the mould with the fabric and the occurrence of undesired events were taken into consideration. Among numerous adverse phenomena, air traps and unfavourable bonding angles of flowing fronts were the most concerning problems. The prepared models were analysed for the influence of the reinforcement parameters with the same position of the carbon fabric and the influence of the arrangement of the carbon fabric with equal reinforcement parameters.

2.1. The undesirable phenomena of the filling process
Visible connected lines are the most common surface defect and the most troublesome defect of all components produced by injection. In these areas, the strength of the material is reduced [17]
Another negative phenomenon is the impairment and air traps that arise in situations where the resin narrows in certain areas of the flow path, leading to the localized narrowings and thus the closure of voids that remain filled with air. This is associated with the arrangement of the reinforcement inside the cavity and determined by a different flow resistance depending on the flow direction and the geometry of the cavity.

2.2. Influence of reinforcement parameters

2.2.1. Change in porosity. Porosity was defined as a ratio of the free space, (intended to be filled with resin), to the entire volume of the mould cavity. Unfortunately, porosity is strongly dependent on the arrangement of the fabric in the mould. Manual reinforcement determines the occurrence of many random phenomena, including changes in fibres density to 1cm$^2$ and changes of porosity inside the reinforcement and higher curvature of laminated surface make greater deviation. The simulations assumed the stability of the reinforcement parameters in the entire volume of the cavity.

Changes in porosity made significant differences in time of filling the mould. This is related to the process of filling a set amount of resin. This means that the injection time is strongly dependent on the amount of free space to be filled in mould.

A similar pressure distribution in the mould has been observed in each analysed case and the maximum pressure value has slightly increased with the porosity of the fabric. Heat generated by viscous friction was noticed. With porosity of reinforcement at level 0.7 or 0.5, the generated thermal energy has not exceeded respectively 0.018 J and 0.014 J. In case of a reduction of porosity to 0.2 there is a higher resistance of flow, which increases the amount of heat generated to 0.273 J. This gives about 17 times higher value than in the previous cases studied. This growth occurs only locally, in most areas the pressure distribution is similar to other cases. This may indicate a problem with overcoming the flow resistance in areas where the walls of the mould have a nearly vertical setting.

2.2.2. Change of fiber direction. The flow of resin strongly depends on the direction of the reinforcement fibres in the mould. The direction of the arrangement and the reinforcement permeability in these directions influences the flow resistance of the resin.

Figure 3 a) shows a section of a flat plate containing 4 different areas of the same reinforcement with one main transmission direction. The injection simulations are shown on figure 3 b). Significant influence of the position of the main permeability direction that fully determines the spread of resin in a plate lined with reinforcement can be observed.

![Figure 3](image-url)  

**Figure 3.** Effect of change the angle of the reinforcement fiber to the resin flow [12] [20].
Modelling of the flow of resin by reinforcement in the mould of fabric with specific porosity and directions of permeability is a significant simplification, which assumes that the fibres of the fabric throughout the entire area are arranged uniformly in the same direction. In fact, there are often problems with the linearity of fibres in the reinforcement and the material is reduced or extended.

3. Conclusions
The RTM method of producing composite elements is not commonly used. This is due to the very high costs of preparing the production process. Still, the RTM method is the most effective of the currently used methods of producing Epoxy-Carbon elements.

To reduce the cost of implementing new composite components, virtual production preparation should be applied. Analysis of the process of filling the mould and solution for it is most often based on the use of FEM simulation and selection of appropriate injection parameters and appropriate design solutions of the mould. The use of computer simulations allows to reduce the costs associated with the preparation of the prototype.

In this work, the CAD model corresponds to the actual components produced for the automotive industry. The model does not incorporate the heating channels and the cooling system of the mould.

The effect of reinforcement on resin flow is significant. The most potent factor influencing the results of calculations is porosity. The porosity determines the injection time and the amount of resin necessary to fill the mould. Low porosity of the fabric increases the amount of heat generated and, in turn, increases the accuracy of the mould filling. In cases where the low porosity of the reinforcement was considered the best saturation, the occurrence of air traps was limited, and the bonding of resin fronts at a small angle were rare.

The process of filling the mold was comparable in all the tests performed. For the tests carried out it was noted that the method of setting the fabric does not significantly affect the injection time and other parameters.

The form prepared for the production of RTM should allow to put the reinforcement in one simple slice to avoid bends and other complications of the shape. A constant thickness of the cavity should also be maintained. To further simulate the processes involved, especially those related to the air traps, the higher accuracy mesh of finite elements needs to be generated in the walls of an element.

By using a numerical simulation in the design phase and the variant optimization of the RTM parameters in the manufacturing of composite elements, there is a possibility to eliminate inconvenient situations and obtain high surface quality of the workpiece on both sides of the mould.

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