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A case study of simulating various number of gate positions and their impact through T-RTM technology

Blagovest Bankov
Department of „Armament and Technology for Design“
National Military University “Vasil Levski”
Shumen, Bulgaria
blagovest.bankov@gmail.com

Abstract. **The study presented aims to investigate the influence from different gate positioning on the final product in T-RTM technology. The research is done using the specialized Moldex3D software. The studies conducted found that the symmetrical arrangement of injection ports and the approach to progressive injection with reduced pressure on the secondary gates result in significantly better deformation outcomes, with values close to 95% better compared to the deformation results in the approach with simultaneously open ports.**

Keywords: Injection Molding, Moldex3D, Polymer, T-RTM

I. INTRODUCTION

With the development of the global market, composite materials have significantly penetrated the manufacturing strategies of many industries, such as automotive, rail transport, the space industry, aircraft construction, etc., with one of the main goals being the reduction of the overall weight and improvement of various characteristics of the products, which directly affect the life cycle of the final product [1], [2], [3], [4], [5], [6], [7].

In recent years, there has been significant discussion about the possibility of using materials that can be easily recycled after their use to protect the environment [8], [9], [10], [11], [12]. One of the technologies that facilitates this development is "Thermoplastic Resin Transfer Molding" (T-RTM), combining the advantages of the known "Resin Transfer Molding" (RTM) technology with those of the thermoplastic matrix (recyclability, processability, plasticity, durability, etc.) and the high-pressure injection from the "High-Pressure Resin Transfer Molding" (HP-RTM) technology [13], [14], [15], [16].

Manufacturers opting to use T-RTM technology face a number of questions, but thanks to advanced computer technologies and various specialized software products that allow the creation of virtual prototypes and their examination through different mathematical models, these questions can be significantly more easily addressed [15], [17], [18], [19], [20].

Properly determining the number and location of injection points is crucial [21], [22], [23], [24], [25], [26], in various polymer product creation technologies, as this can significantly affect the different characteristics of the final product [27], [28], [29], [30].

From the perspective of design, manufacturing, and commissioning of molding tools, it's important that these two issues are resolved early on due to the potential for exponential increase in tool correction costs, delays in manufacturing processes, and loss of potential profits.

Incorrect parameter determination leads to several consequences, such as:

- Change in processing pressure;
- Failure to fill the mold completely;
- Appearance of weld lines, contributing to reduced mechanical properties of the product;
- Uneven shrinkage of the polymer - deviations in dimensions and weight;
- Deformations, warping of the product;
- Prerequisites for the entrapment of air volumes.

Due to the tremendous impact on the process, it is extremely important to correctly determine the number, position, and operation of the injection points.

Further studies and improvements of the technologies have found various combinations to improve the filling process with control over the inflows, some of which are:

- Injecting polymer simultaneously from all gates;
- Injecting polymer with progressive opening and closing of individual filling points;
- Fixed filling pressure through all injection points;
- Variable pressure in different filling zones.

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Fig. 1 visually shows the different variations of injection, as well as the change in melt speed in single-point and multi-point injection.

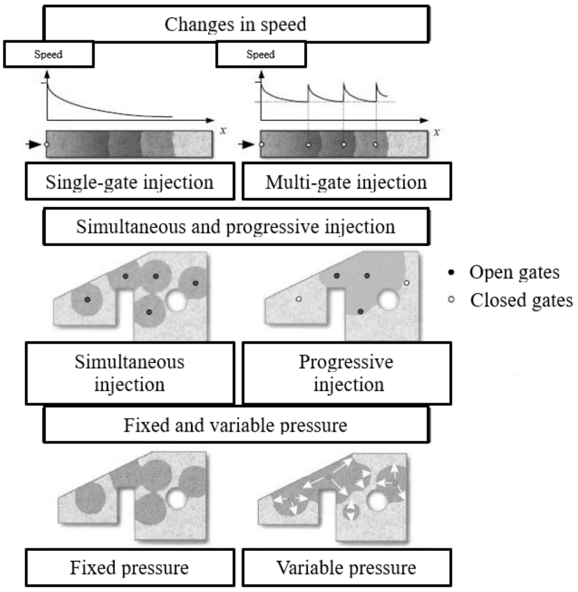

Fig. 1. Variations of injection [27].

This study examines the impact of the position and number of injection points in the T-RTM technology, with virtual prototypes of the analyzed object being created with different configurations of the placement of injection openings and their operation. The software tools used are:

- SolidWorks – for designing the virtual models;
- Rhinoceros – for creating mesh models;
- Moldex3D – for analyzing the filling process.

II. MATERIALS AND METHODS

To conduct the study, it is necessary to go through various stages (Fig. 2), which includes:

- Design of the basic geometry;
- Determining the number and location of injection points;
- Creating a finite element mesh model
- Setting material properties;
- Setting process parameters;
- Choosing an approach for managing the injection points.

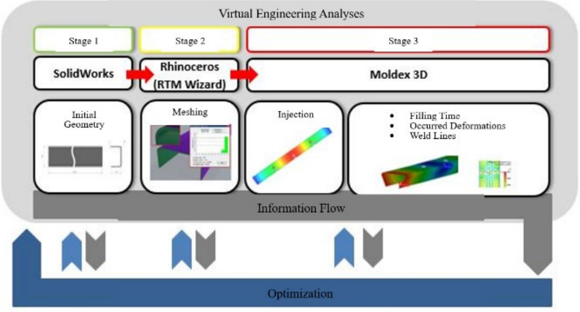

Fig. 2. Stages of creating the analysis.

A. Virtual models

To determine the optimal position of the injection points, a set of variations is considered (Fig. 3), through which the goal is to analyze the filling speed of the mold, the possibility of weld lines appearance, and the deformation values that occur in the detail.

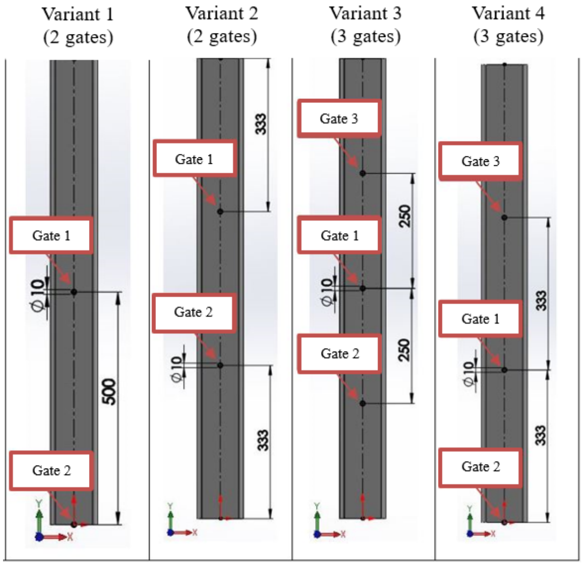

Fig. 3. Initial models for study.

B. Mesh model

The construction of the finite element mesh model was carried out using specialized software "Rhinoceros", and the available tools for this purpose, where the fiber orientation of the available preform was also determined. (Fig. 4).

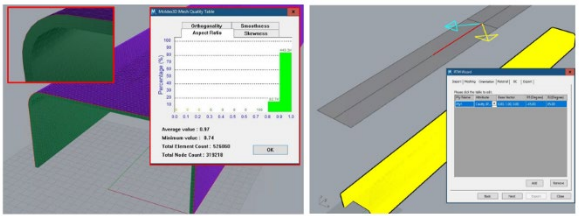

Fig. 4. Mesh model and fiber orientation.

C. Materials

The material characteristics used for the preform are shown in Table 1. For the matrix component of the composite, material characteristics of the thermoplastic polymer Polyamide 6 (PA6) were used.

TABLE 1 MATERIAL CHARACTERISTICS OF THE PREFORM

Variable	**Aramid Fiber Kevlar 49**		
	Designation of the variable	***Value***	***Dimension***
Permeability	K11	1.92e-08	m^3
	K22	1.92e-08	
	K33	1.00e-08	
Porosity	φ	0.33	-
Young's modulus	E1	57.89e+09	Pa
	E2	57.89e+09	
	E3	6.89e+08	
Poisson's ratio	v12	0.35	-
	v23	0.35	
	v13	0.3	

Variable	**Aramid Fiber Kevlar 49**		
	Designation of the variable	***Value***	***Dimension***
Shear modulus	G12	16.49e+09	Pa
	G23	16.49e+09	
	G13	1.81e+09	
Coefficient of linear thermal expansion	CLTE1	-2e-06	1/K
	CLTE2	-2e-06	
	CLTE3	1e-06	

All variants have been subjected to analyses with similar initial process parameters shown in Table 2.

TABLE 2 INITIAL PROCESS SETTINGS

Variable	***Value***	***Dimension***
Filling time	360	sec
Filling pressure	150	MPa
Resin temperature	140	°C
Mold temperature	90	°C
Curing time	5	Sec

Several injection variants have been studied:

- With identical pressure at the inlets;
- With different pressure at the inlets.

D. The approach for the gates controlling

The approach chosen involves the progressive opening and closing of the injection ports, with this action being controlled through the simulation of a pressure sensor that manages the flow gates.

To determine the exact position of the sensor, three models were made to study their behavior (Fig. 5).

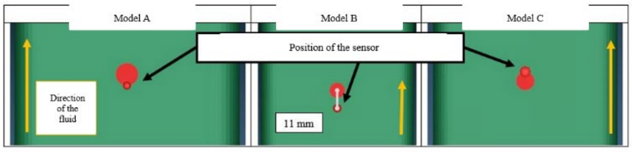

Fig. 5. Studied models for the position of the pressure sensor.

In Fig. 6, the initial moments after the injection ports are opened in the models are shown, and it can be observed that the most at-risk model for the appearance of weld lines is Model B, while the lowest risk is Model C. Table 3 shows the results after the molds are filled, indicating that Model A has the most balanced indicators in terms of time and chances for the appearance of weld lines.

Based on the results, Model A is chosen, with the position of the sensor immediately before the injection port, as the most balanced and low-risk for the occurrence of weld lines.

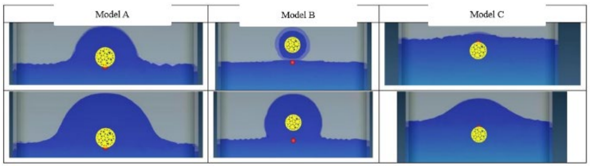

Fig. 6. Initial moments of filling.

TABLE 3 FINAL RESULTS OF THE FILLING

Model	***Filling of the mold (%)***	***Filling time (sec)***	***Maximum deformations (mm)***	***Presence of weld lines***
A	100	268.50	16.46	No
B	100	261.63	16.46	No
C	100	279.16	16.46	No

III. RESULTS AND DISCUSSION

In Table 4 and Table 5, the results of studies with two different pressures (150 and 100 MPa) are compared, including the sequence of opening the injection ports for polymer injection.

Due to the presence of two combinations of opening points, the results of both variations in models B5 and B6 are shown.

TABLE 4 RESULTS AT 150 MPA PRESSURE

Model	***Sequence of opening***			***Filling of the mold (%)***	***Filling time (sec)***	***Maximum deformations (mm)***	***Presence of weld lines***
V1	1	2	-	70,45	-	-	No
V2	1	2	-	100	268.50	16.46	No
V31	2	1	3	100	222.42	16.45	No
V32	1	2&3		100	153.25	16.45	No
V41	2	1	3	98,15	-	-	No
V42	1	2&3		100	265.46	16.44	No

TABLE 5 RESULTS AT 100 MPA PRESSURE

Model	***Sequence of opening***			***Filling of the mold (%)***	***Filling time (sec)***	***Maximum deformations (mm)***	***Presence of weld lines***
V1	1	2	-	63.35	-	-	No
V2	1	2	-	92.98	-	-	No
V31	2	1	3	100	358.18	6.90	No
V32	1	2&3		100	248.28	6.90	No
V41	2	1	3	62.32	-	-	No
V42	1	2&3		95.51	-	-	No

Fig. 7 shows a graph comparing the mean values of the deformations that occurred throughout the volume of the detail under different injection combinations in models V31 and V32.

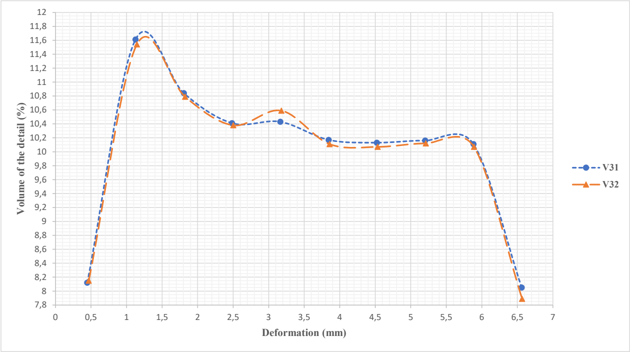

Fig. 7. Occurred deformations.

From the above figure, it is observed that the more balanced fluid flow, caused by symmetrically distributed inlets, shows better results in terms of deformations.

To compare the results of the study with variable pressure in the injection ports, model V32 was examined in more detail, with different variants of the distances between the initial injection point at intervals of 50 mm (Fig. 8) being designed.

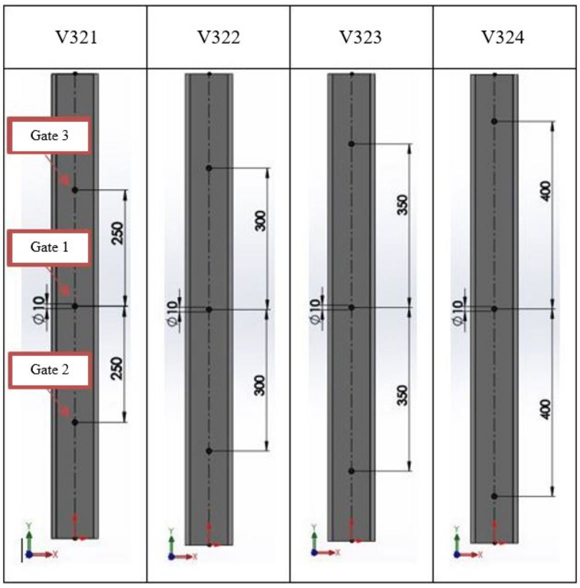

Fig. 8. Additional models for study.

The results of the study, with a pressure of 150 MPa in the first inlet and 100 MPa in the other two points, are shown in Table 6, from which it is determined that model V322 fills the fastest.

TABLE 6 RESULTS FROM THE VARIABLE PRESSURE (150/100 MPA)

Model	***Filling of the mold (%)***	***Filling time (sec)***	***Maximum deformations (mm)***	***Presence of weld lines***
V321	100	194.98	6.90	No
V322	100	190.47	6.90	No
V323	100	201.83	6.90	No
V324	100	230.96	6.91	No

In a further study, with the pressure reduced to 65 MPa in the secondary injections, it was found that the deformation fell below 0.500 mm in all models (Fig. 9), which represents a decrease of nearly 95% from the previous results (with 100 MPa in the secondary gates).

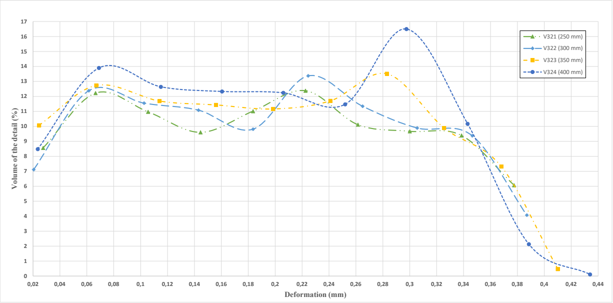

Fig. 9. Deformation.

The rate (Figure 12) and shear forces (Figure 13) obtained during filling, which are related to the flow rate and the drop in pressure, have been examined. Too high values can be a precondition for the occurrence of defects in the product, such as cracking [31].

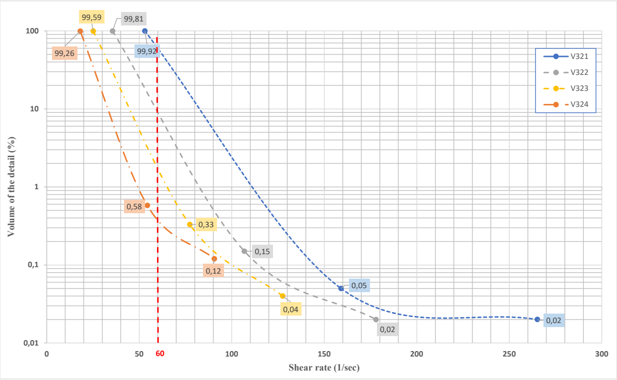

Fig. 10. Shear rate.

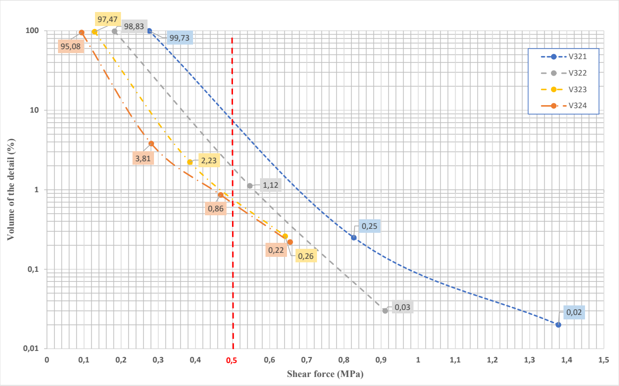

Fig. 11. Shear force.

Upon examining the forces and shear rates, their relationship with the occurred deformations is established, with the peak of lower values in the model with 400 mm (Model V324) being due to the lower values of forces and speed.

The secondary injection points closer to the primary one experience difficulties in filling the mold, and the shear forces increase, leading to an increase in the affected volumes of the detail between the values of 0.36 to 0.40 mm.

IV. CONCLUSION

By using a multi-step approach to analyze the impact of filling points in T-RTM technology, it has been established that the position and number of filling points significantly influence the complex fluid flow, the possibility of filling the mold, and the necessary time for this.

Using more injection points allows for the choice of a strategy for their progressive opening with specifically set pressure, which supports the balancing of the fluid flow in T-RTM technology and reduces the values of the occurred deformations.

A relationship has been noted between the deformations, forces, and shear rates, the set pressure, and the position of the inlets.

It has been established that, even in T-RTM technology, the correct positioning of injection ports reduces the deformations that occur in the product, with the best results observed when they are symmetrically arranged.

Progressive opening of the injection points helps to eliminate weld lines, thereby ensuring the uniform wetting of the reinforcing fibers.

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