Effect of Index of non-Newtonian Behavior on Curing Rate during Injection Molding of Rubber Compound

Kamil Kyas, Michal Stanek, Jan Navratil, Miroslav Manas, David Manas, Mizera Ales, Adam Skrobak

***Abstract*—** Right used computational analyses are commonly good tool for technical industry to improve process. This paper shows using computational analysis during injection molding process and shows using computational analysis to improve the injection molding process. The main aim of the paper is presenting differences between effects on non-Newtonian behavior on cure rate in final product in rubber process. It was found that for specific geometry and processing conditions, increase in the index of non-Newtonian behaviour increases the curing rate due to viscous dissipation taking place at the flow domain walls. It was shown for variable flow rate.

***Keywords*—** rubber compound, cure rate, pressure sensor, temperature sensor, injection molding process, injection mold

I. Introduction

INJECTION molding is now a well-established fabrication process in environmental industry. It has more advantages in the most situations over the older processes of compression and transfer molding. These advantages comprise reduced labor cost, better dimensional control and shorter cure times for injection molding process. This process is still improved and other materials (not only thermoplastic) are used for example elastomeric compound. [1, 8, 12-22]

The injection molding process is a cyclical process, each cycle comprises several operations: feeding, melting and homogenization of polymer grains inside the plasticizing cylinder mold closing, injection under pressure of melt in mold's cavities and cooling or heating of polymer inside the mold, mold opening and ejection of molded piece. In figure 1 there is shown time influence for each parts of cycle. It is necessary to realize, that rubber injection molding cycle is several times longer than for thermoplastics. [2,4 - 38]

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During injection molding process, melt is subjected to more severe processing conditions than during compression or transfer molding. Values of temperatures, pressures, and shear stresses are higher, though cure times are shorter in rubber compound. Control over process variables can be more precise. [2,3,7,15-38]

Injection molding of thermoplastic material is a process in which the hot polymer is injected into a mold cavity. Heat is removed from the polymer in the mold until it is rigid and stable enough to be ejected. Therefore the design of the part and mold are critical in ensuring the successful molding process. For the recent years, the insert molding in injection molding has been very popular. The mold insert molding process is an efficient technology for injection molding process. The insert material will have a significant effect on the filling phenomena around the insert parts. The insert materials can vary. The metal inserts are used to increase the performance of drawing heat from the cavity. On the other hand, the plastic inserts reduce the cooling effects. Different insert parts have different effects for the injection molding process. [1-15, 20-38]

Tab.1 Differences between thermoplastic and elastomeric polymers.

Type of polymer	Family name	mold surface temperature [°C]	melt temperature [°C]
Elastomer	EPDM	150	90
	NBR	140	85
	NR	140	85
	SBR	140	85
Thermoplast	ABS	50	250
	ABS 20%	50	230
	PA6	65	250
	PC	82	299
	PE	52	220
	PP	50	230
	TPE	45	250

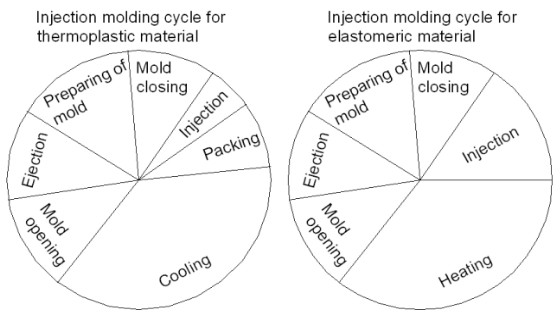

Fig.1 Injection molding cycles

Process where elastomeric compound is injected has some differences. Main difference is in the temperature, mold surface temperature is higher than melt temperature. In technical industry there are plenty of materials. Differences in process setting between each type of polymers are shown in following table. Next difference is in the cycle time period. Injection molding cycle of elastomeric compound is higher for the same volume of injected material.

The cycle time can be minimized by independently controlling barrel temperature, screw speed, mold temperature and injection pressure. That is the reason why the injection molding process should be improved and understood. [4,5,10]

Elastomeric injection molding offers a number of cost and quality advantages as well as design flexibilities and environmental friendliness through material cost reduction and recycling, and modification of the part quality and property. However, the technical challenges lie in proper design of the part, mold, and process as well as the selection of materials to obtain the desirable skin/core material distribution and adhesion. Improper part and mold design and material combination will result in core distribution within the cavity. Recall that the skin thickness and extent of core penetration depends on the viscosity ratio of the materials and the selection of process conditions. As a result, the development for a elastomeric injection mold and process set-up do not take longer time than that with the thermoplastic injection molding process. [12,14,19,33-35]

Rubber injection molding of rubber began in the early 1940s. Today, the process is used for manufacturing a wide range of industrial products.

Injection molding of rubber is a process whereby a rubber mix is injected into a closed mold where the material is shaped to the desired geometry. The material parameters that define the mold-filling process are based on the thermal and rheological properties. [1,2]

When the cavity is filled, temperature gradients persist in the rubber. With having completely filled the cavity rubber mix is vulcanized. Vulcanization is the process whereby a viscous and tacky uncured rubber is converted into an elastic material through the incorporation of chemical crosslinks between the polymer chains. The degree of cure achieved depends on the main parameters:

- the temperature of the material when the mold is completely filled;
- the temperature of the mold cavity;
- the time for which the material is kept in the mold, that is, the cure time. [1-4]

During injection molding process, melt is subjected to more severe processing conditions than during compression or transfer molding. Values of temperatures, pressures, and shear stresses are higher, though cure times are shorter in rubber compound. Control over process variables can be more precise. [2, 4]

The cycle time can be minimized by independently controlling barrel temperature, screw speed, mold temperature and injection pressure. That is the reason why the injection molding process should be improved and understood. [5,6,7]

II. Desing of mold and product

This paper deal with technical problem connected with injection molding process of elastomeric compound. This problem consists of design of injection mold, material characterization, setting of injection mold process and its analysis.

Design, material and method co-operate together in injection molding process. This experiment is focused on observing of temperature and pressure change in runners during injection molding of rubber compound with different index of non – Newtonian behavior. There were designed two cavity injection molds for this experiment. There were used trapeze runners. Mold cavity is a cube with dimension 30 x 30 x 30 mm. Mold is prepared for real injection molding process for the further research. According to these models injection molds are prepared for testing influence of setting parameters on finally properties in real process.

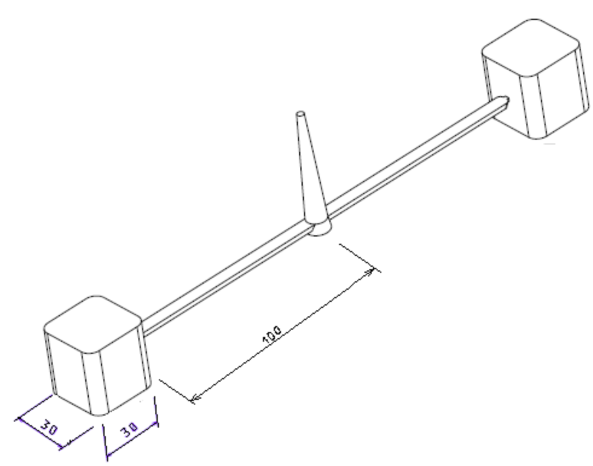

Fig.2 Dimensions of product and runners

Part with runners can be seen in Fig. For this part was designed injection mold. It is consist of four plates (two cavity plates and two clamping plates). Each plate was manufacture in 3 axis CNC machine AZK HWT C - 442. Some finish operations as drilling were handmade on convectional machines. Mold is prepared for further research.

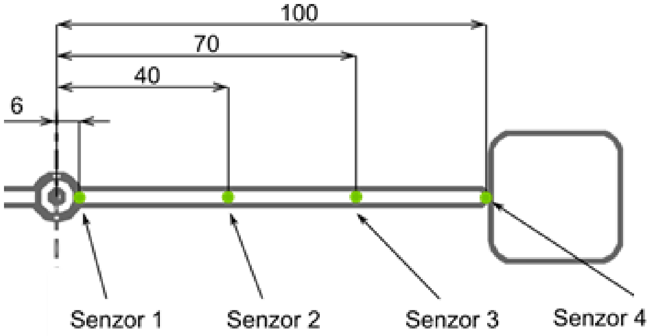

Fig.3 Dimensions of runner with used sensors

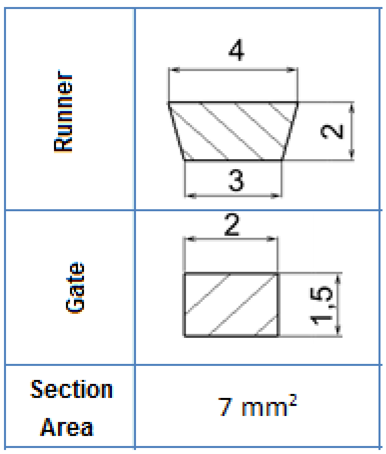

Fig.4 Dimension of trapeze runner

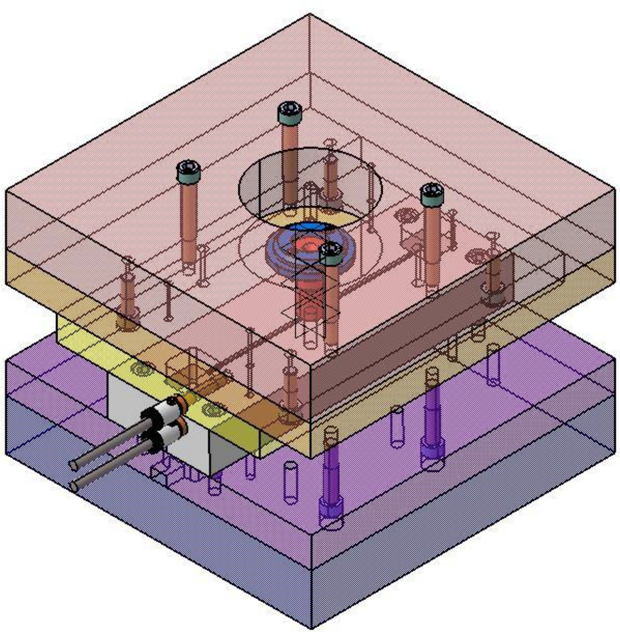

Fig.5 Model of assembled injection mold

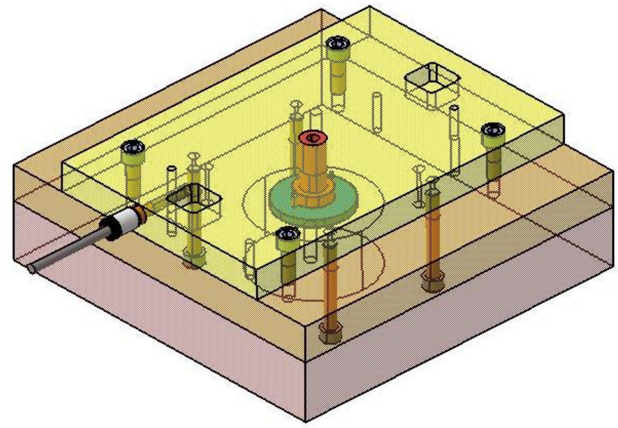

Fig.6 Model of upper part of mold

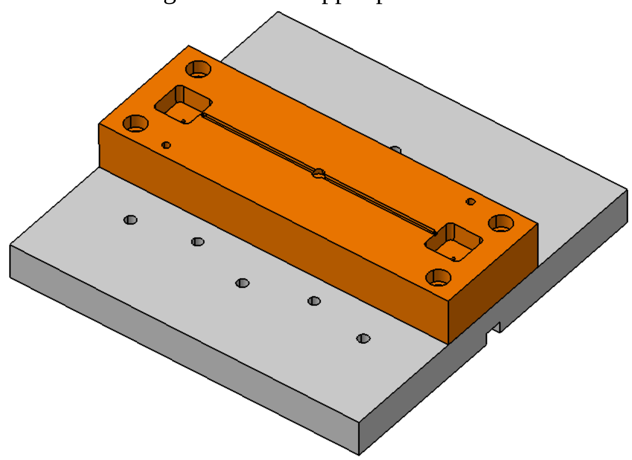

Fig.7 Universal frame with cavity plate (lower part)

III. Material, viscosity and curing model

In this work, two groups of virtual materials were created from the reference NBR material taken from the Cadmould 3D-F software database by changing index of non-Newtonian behavior by keeping the remaining parameters the same in the Carreau-WLF viscosity model, which is given by Eqs. 1-2.

$$\eta(\dot{\gamma}, T) = \frac{\eta_0 a_T}{(1+\lambda a_T \dot{\gamma})^{1-n}} \tag{1}$$

$$a_T = 10^{\left(\frac{8.86|T_0-T_S|}{101.6+T_0-T_S} - \frac{8.86|T-T_S|}{101.6+T-T_S}\right)} \tag{2}$$

where η0 is the zero shear viscosity, λ is the relaxation time, n is the index of non-Newtonian behavior and aT is the temperature shift factor, T0 is the reference temperature and Ts is the material constant. Degree of cure (α), representing the extent of reaction, for all considered virtual NBR materials was predicted by Isayev–Deng model as follows:

$$\alpha = \frac{K(t - t_i)^{n_1}}{1 + K(t - t_i)^{n_1}} \tag{3}$$

where K and n1 are kinetic constant and order of reaction, respectively. During the induction period (ti) the curing reaction does not take place. This parameter is considered to be temperature dependent by an Arrhenius-type equation:

$$t_i = t_0 \exp(T_0 / T) \tag{4}$$

where t0 and T0 are material constants. K parameter in Eq. 3 represents a rate constant with an Arrhenius-type dependence:

$$K = K_0 e^{(-E/RT)} \tag{5}$$

where K0 is a material constant, E is the activation energy and R is the gas constant.

Carreau-WLF and Isayev–Deng model parameters for all eight virtual NBR materials are provided in Table 2.

Tab.2 Carreau-WLF and Isayev–Deng model parameters

Carreau-WLF viscosity model		**Isayev–Deng curing model**	
η_0 (Pa s)	16486,	t_0 (min)	$10^{-4,5290}$
λ (s)	16	T_0 (K)	5273,2208
n	0,2; 0,5; 0,7; 1	K_0($min^{-1}n_1^{-1}$)	$10^{20,0340}$
T_0 (°C)	90	E_0 (kJ/mol)	168,6758
T_s (°C)	-88,44	n_1	2,8283

IV. Analysis of Injection Molding Process

These analyses of injection molding process were set for injecting on injection molding machine REP V27/Y125. It was analyzed in computational software Cadmould Rubber.

Tab.3 Machine parameters

Diameter of Screw	**20 mm**
Clamping force	57 kN
Max. volume of material	125 cm3

The complexity of today's plastic parts as well as the costs, quality and competition pressure makes maximizing every opportunity available to improving the production process a necessity rather than a choice. Injection molding is the primary process for conversion of plastic materials into components used in industrial and consumer applications, and CAE enables the simulation and analysis of this molding process. It has been available for over two decades, affording time to refine the technology.

Process simulation and analysis software like Cadmould use fundamental principles and scientific data unique to each material to compute the flow behaviour of the melt during the process. One of the important principles is that of Rheology, which involves the study of the flow and deformation of matter. In order to understand and control any process involving the transfer of fluids it is necessary to know how that fluid behaves under different conditions of temperature and pressure etc. The behavior of polymer melts under the influence of shear is very complex since they tend to be highly non-Newtonian; i.e. they do not obey Newton's Law of viscous flow. The viscosity of a polymer melt is therefore not constant but is highly dependent on the rate of strain. CAE programs provide a flexible and economical means of recognizing potential errors early in the design and production process. The information gained from the simulation can assist in the optimization of the process, like cutting down cycle time, or part weight. It can also support the molder in fixing certain problems, which would otherwise have to be solved by trial-and-error- methods, which consume significant amounts of time, and waste material and energy.

Fig.8 Injection molding machine REP V27/Y125

As it was told earlier for computational analysis Cadmould Rubber software was chosen. One of the reasons for choosing was easy receiving material data. Each compound is a mixture of rubber and additives. Each compound has different material characteristics. With help of Rheometr RPA 2000 we can measure material characteristic. First is viscosity which is used for flow analyses and second is cure curve for cure analysis.

Temperature and curing closely related together and it is important to know these values during elastomeric compound injection molding process. Software Cadmould Rubber has great advantage that it can show the temperature and percentage of crossed-links in each moment during injection molding cycle and in the individual layers of the product. It is necessary to consider how many layers use before setting analyze. With large number of layers time of computing increase rapidly on the other hand the results are more accurate.

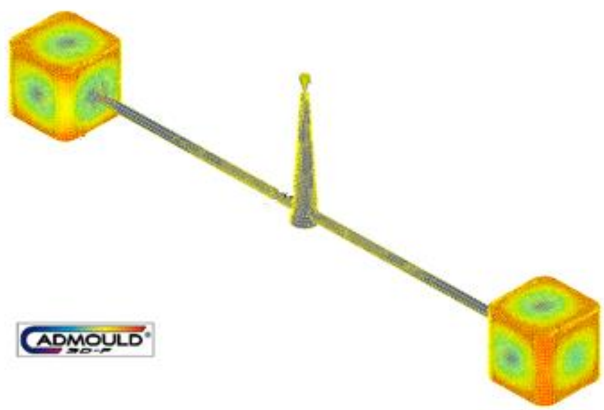

Fig.9 Sample of meshed product

In the two following pictures there can be seen quality of computational mesh. Mesh was checked by mesh statistic command. Mesh seems to be all right as for narrow as for wide trajectories.

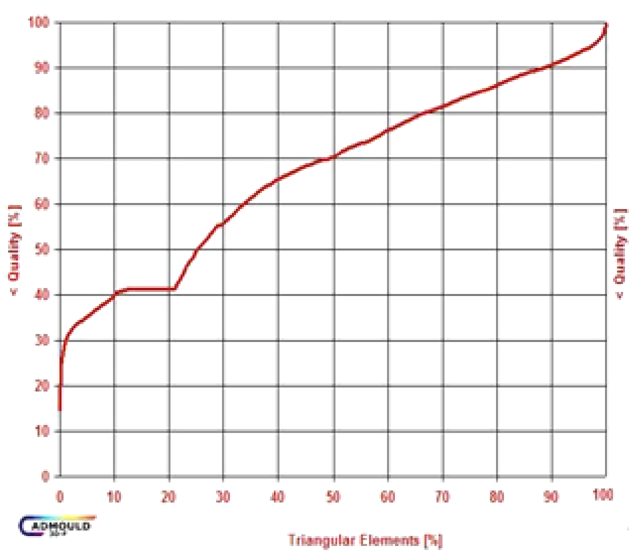

Fig.10 Mesh quality for narrows runners

It is good to know how elastomeric compound behaves in each place in cavity. Sensors can be help for the better understanding of injection molding process and they are right tools to show behavior of material in the section of part. Cadmould Rubber can render results of pressure, temperature, viscosity, shear rate and cure rate which are important for receiving final properties of elastomeric product.

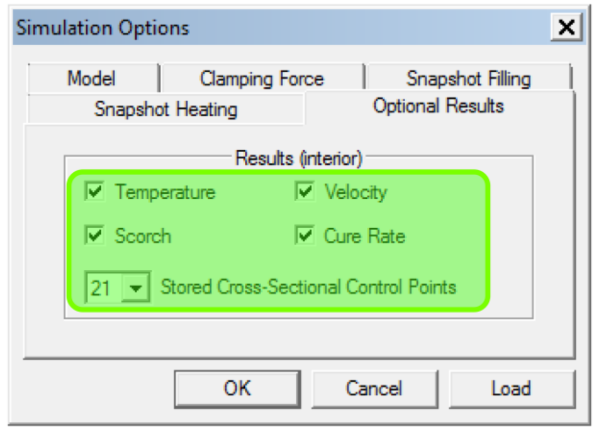

Fig.11 Simulation Options menu

Tab.4 Computer parameters

processor	**Intel® Core 2 Quad Q6600 2,40 GHz**
RAM	2048 MB
HDD	500 GB
Graphic card	NVIDIA Quadro FX 570 1010 MB
System	Windows 7 Professional 64-bit

There were switched on advanced results of analisis in Simulation Options menu. For the get fluent curved in figures there were chosen 21 layers in Cross – Sectional Control Points. Computational anaysis were computed on cumputer station with parameters which can be seen in Tab.3

V. Setting of Injection Molding Process

Filling time depended on flow rate which was caused by a speed moving of piston in injection machine. It was changed 5 mm per second to 30 mm per second as can be seen in Table After the filling a cavity pressure should be changed to holding pressure. In this case holding pressure wasn't used.

When the cavity was filled the vulcanization of material continued for 600 second. In analyses was set 200 second of post-curing at the end. All setting parameters can be seen in Table 3.

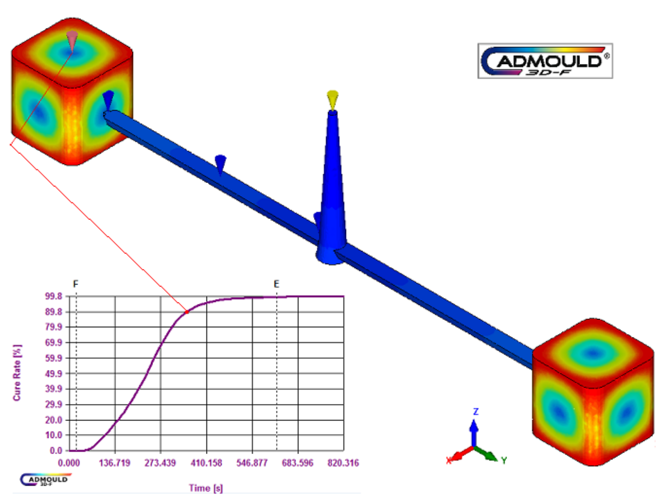

Fig.12 Sensor, where were taken results

There was measured optimum of vulcanization it is time of 90% cure rate in this research and results were compared for each changing of flow rate, mold temperature and type of runners. Sensor where were taken results was the place where the material was affected by heating at the last time.

Next evaluated parameters were temperature in the gate of runner and pressure utilized for cavity filling.

Tab.5 Process parameters

Piston rate	mm/s	*5;10;15;20;30*
Flow rate	cm^3/s	*0,7;1,5;2,3;3;38*
Pressure/controlled	%	99
Mass temperature	°C	100
Mold temperature	°C	*170*
Heating	s	600
Post curing	s	200

VI. Results

Melt is intensively heated by the wall of the mold it causes material vulcanization (cure rate). In this case there are compared any materials with different non-Newtonian behavior. The length from the wall to the center of the section of runner and perimeter of section are. In the technical experience for technical product there is used rubber compound with the index of non-Newtonian behavior from 0,2 to 0,6 according to type of rubber and additives. As it can be seen from the graphs index of non-Newtonian behavior affected temperature and it has impact on cure rate. There is significant different among each flow rate. And it can be seen differences results for the various flow rates. In the figures with small flow rate, there can be seen that is no dissipation and melt is heated only by conduction. In the other side in the higher flow rate (30mm/s) there can be seen that dissipation plus conduction is developed.

Tab.6 Results for f= 5mm/s, T=170°C

	Pressure	90% cure
	[bar]	[s]
n=0,2	347	383
n=0,5	533	378
n=0,7	703	374
n=1,0	1065	364

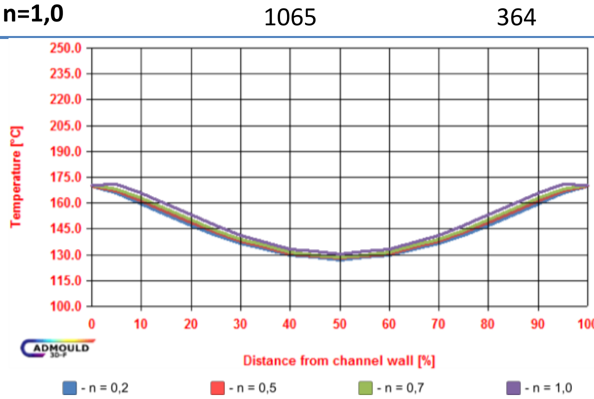

Fig.13 Temperature variation in channel (f=5mm/s)

Tab.7 Generated Shear Stress in Gate f= 5mm/s, T=170°C

	n = 0,2	n = 0,5	n = 0,7	n = 1,0
τ [kPa]	455	886	1276	2271

Tab.8 Results for f= 10mm/s, T=170°C

	Pressure	90% cure
	[bar]	[s]
n=0,2	468	397
n=0,5	867	387
n=0,7	1261	378
n=1,0	2100	352

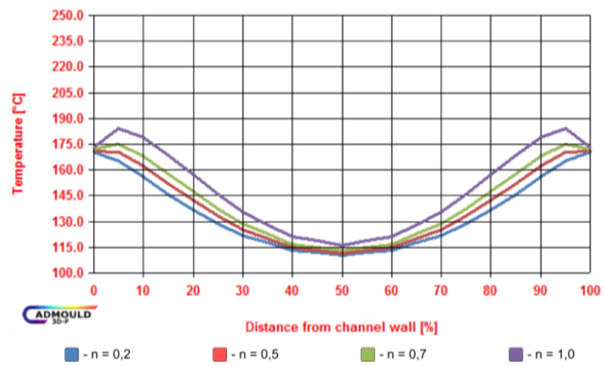

Fig.14 Temperature variation in channel (f=10mm/s)

Tab.9 Generated Shear Stress in Gate f= 5mm/s, T=170°C

	n = 0,2	n = 0,5	n = 0,7	n = 1,0
τ [kPa]	566	1418	2376	4360

Tab.10 Results for f= 15mm/s, T=170°C

	Pressure	90% cure
	[bar]	[s]
n=0,2	537	403
n=0,5	1100	388
n=0,7	1670	373
n=1,0	2836	341

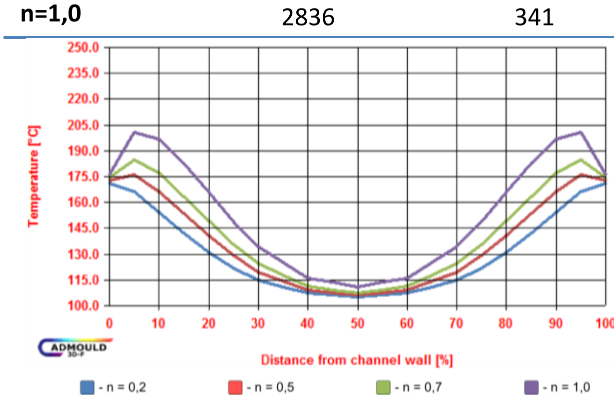

Fig.15 Temperature variation in channel (f=15mm/s)

Tab.11 Generated Shear Stress in Gate f=15mm/s, T=170°C

	n = 0,2	n = 0,5	n = 0,7	n = 1,0
τ [kPa]	661	1769	2957	5528

Tab.12 Results for f= 20mm/s, T=170°C

	Pressure	90% cure
	[bar]	[s]
n=0,2	580	406
n=0,5	1260	390
n=0,7	1949	371
n=1,0	3340	333

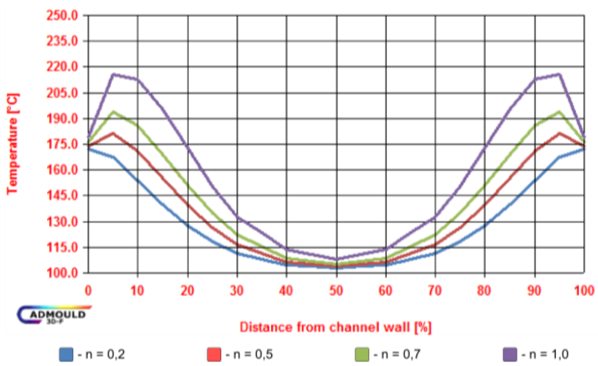

Fig.16 Temperature variation in channel (f=20mm/s)

Tab.13 Generated Shear Stress in Gate f=20mm/s, T=170°C

	n = 0,2	n = 0,5	n = 0,7	n = 1,0
τ [kPa]	695	1958	3386	6204

Tab.14 Results for f= 30mm/s, T=170°C

	Pressure	90% cure
	[bar]	[s]
n=0,2	652	410
n=0,5	1537	388
n=0,7	2418	367
n=1,0	4228	322

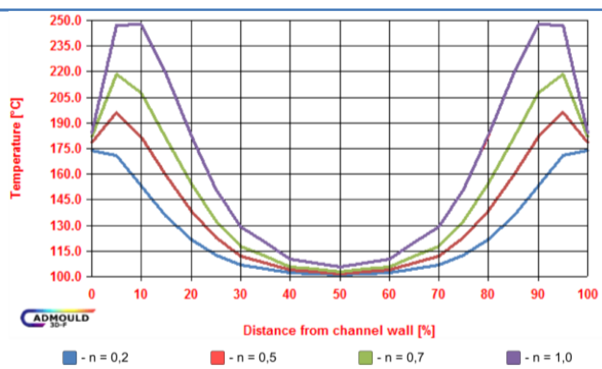

Fig.15 Temperature variation in channel (f=30mm/s)

Tab.15 Generated Shear Stress in Gate f=30mm/s, T=170°C

	n = 0,2	n = 0,5	n = 0,7	n = 1,0
τ [kPa]	758	2281	3952	6976

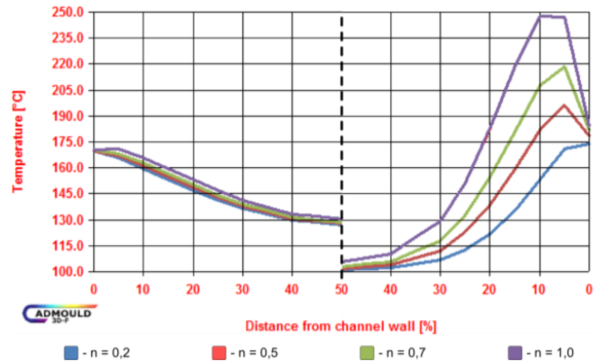

Fig.17 Comparing f=5mm/s – left, f=30mm/s – right

VII. Conclusion

During manufacturing and assembling there have to be kept rules which are done by producer. Mold maker have to watch out for assembling sensors to prepared hole. Holes have to be correctly drilled and polish.

Cross linking of elastomeric compound depends on temperature, pressure and time. For shorting of time of vulcanization can be achieved by changing other parameters (temperature and pressure). Pressure depends on injection flow rate and product volume. Shortening of time of vulcanization rapidly leads to save energy. This saving can be reduce by right setting parameters at the injection molding machine or right choosing of trajectory of runners (length and width) at mold and their combination. Cross linking of elastomeric compound depends on temperature, pressure and time. For shorting of time of vulcanization can be achieved by changing other parameters (temperature and pressure). In this work, non-isothermal injection molding process for rubber mixture considering Isayev–Deng curing kinetic model, generalized Newtonian model with Carreau-WLF viscosity was modeled by using finite element method in order to understand the effect of volume flow rate, index of non-Newtonian behavior on the temperature profile and curing rate. It was found that the temperature rice takes place at the die wall where the shear rate is the highest due the viscous dissipation, which increase the curing rate.

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