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3D finite element analysis and optimization of cap ply production system in the tire industry

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Abstract

In automotive industry, tires play a key role. They are a composite structure formed by multiple layers of different materials such as rubber compounds, steel and polyamide cords. Between the tread and steel belts, a cap ply layer is used to restrict the growth of the tire, due to centrifugal forces. Cap ply is produced by using a pultrusion process that impregnates polyamide cords with rubber, resulting in a rubberized strip. When the controlling of the process is incorrect, premature vulcanization or lack of impregnation is often observed. To optimize the production process, CFD (Computational Fluid Dynamics) simulations were performed to study the flow of rubber inside the extrusion head channels by modelling the fluid properties and the domain. Laboratory tests were also conducted to determine the physical and cure properties of the rubber compound used. Crossing the results of the simulations with the laboratory tests was found that the temperature control used was inadequate. Simulations were also supported with the results provided by a temperature sensor controlled by an external device (Arduino). By using a proportional integral derivative controller and changing the setpoints for the thermal resistance, the amount of scrap generated by vulcanized rubber and lack of rubber in the cap ply strips was reduced by 100%.

Keywords: Automotive industry; Tire; Extrusion; Rubber; Computational fluid dynamics; Viscoelasticity; Temperature control; Arduino; CFD; Vulcanization.

1. Introduction

The quality requirements on today's industry demand constant development and improvement of production systems in order to eliminate production imperfections and constraints that occur during the manufacturing processes [1]. In the automotive industry, time and effectiveness is important, since it can hugely affect the overall cost of production [2]. Specifically, in the tire industry, the rubber processing can be very challenging due to its details and knowledge needed to understand the concepts behind it. Tires are made of many different components and have been deeply studied [3]. Cap ply is one of those components, and its main goal is to restrict the growth of the tire due to centrifugal loads. Also, cap plies prevent the separation between the steel belts, which is a problem known since the invention of steel belted radial tires [4].

Cap ply is produced in cap strip lines (Fig. 1), which are an excellent alternative to a calendar, regarding more flexibility

Fig. 1. Cap strip line.

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and less intermediate processes such as slitting and mini-slitting.

Cap strip lines consist of four major parts. The production starts with multiple reels of, usually, polyamide yarn which is uncoiled into a die. An extruder and gear pump force rubber to flow into a die located inside an extruder head (Fig. 2) allowing the polyamide cords to be impregnated with rubber.

Fig. 2. Representation of a Cap strip line extruder head with cap ply strips being produced.

The cap ply strips that exit the die, exhibiting temperatures higher than 100°C and need to be cooled down rapidly to allow a correct winding of the strips without adhesion occurring between them. This is achieved by leading the cap ply strips belts into a series of eight cooling drums filled with cold water. At the end of the drums, the temperature of the belts is monitored to control the winding temperature. If the temperature is too high, adhesion will occur between the winded belts and during the unwinding process the rubber will be separated from the polyamide cords, leaving them exposed.

In the extruder head, water is often used to heat up or cooldown the rubber flowing through it. Alternatively, electric resistances can be used instead of water. The main problem with this alternative system is that it only allows the rubber to heat up, because electric thermal resistances are a source of heat generation. Water only allows maximum working temperatures of 100°C, which is not the best temperature to work with some rubber compounds. Lower temperatures mean that the rubber compound viscosity is higher, which imply that a heavier load must be done by the extruder and gear pump. However, increasing the temperature will allow the viscosity to be lower but, on the other side, can generate premature vulcanization of the rubber compound. With these statements, it can be concluded that working with temperatures too low will induce the viscosity of the rubber compound to increase, a higher generation of power on the extruder and gear pump and, usually, the high viscosity will produce cap ply strips with lack of rubber impregnation. The premature vulcanization causes a sudden increase in viscosity of the rubber compound. Generally, in cap strip systems, premature vulcanization is a localized phenomenon and often occurs near the die and causes it to clog up.

In this work a method was developed to improve cap ply strips by manipulating the temperature control system of a cap strip machine. Numerical simulations were conducted in conjunction with experimental tests. Autodesk® CFD 2019 was the software used to perform the numerical simulations, which uses the finite element method, however, the domain of control was built in Solidworks® 2018 software. Laboratory tests were also conducted to determine the viscosity of the rubber compound used as a function of shear rate and temperature. In previous works, viscosity of rubber compounds in numerical simulations were defined by, e.g., Power Law model [5, 6]. These model, and similar models define the viscosity only in function of shear rate. Autodesk® CFD 2019 allows the user to define the viscosity of the rubber compound with the second order polymer equation, which is an equation with six coefficients that are calculated with the help of Microsoft Excel's solver by using experimental data, resulting in an equation that gives viscosity in function of both temperature and shear rate. The big issue with old models is that they do not account for changes in viscosity due to temperate changes, which occur in practical scenarios.

1.1. Defining viscosity

In every fluid analysis the type of fluid in study must be known. Generally, they can be Newtonian or non-Newtonian fluid. The main difference between them is that Newtonian fluids exhibit linear stress in function with shear rate. However, non-Newtonian fluids don't follow this statement [6].

Many simulation software allows the modeling of non-Newtonian fluid by using the Power law model, Carreau model, Cross-Power Law and Herschel-Bulkley model. Autodesk® CFD has two possible equations: first order polymer and second order polymer. In this work, the second order polymer equation (1) was used.

$$\ln(\mu) = A_1 + A_2\ln(\gamma) + A_3 T + A_4\left[\ln(\gamma)\right]^2 + A_5\left[\ln(\gamma)\right]T + A_6 T^2 \quad (1)$$

This equation allows the user to define the viscosity of the fluid in function with shear rate and temperature, based on experimental data. Instead of having an equation that defines viscosity in function with shear rate, at a specific temperature, we have viscosity in function with shear rate at any temperatures.

1.2. Governing equations

Every CFD code has three main components: a pre-processor, a solver and a post-processor. In the pre-processor the user must assign all the inputs related to the flow problem and define the grid (also known by mesh) parameters. The solver can use three different techniques: finite element, finite difference and spectral methods. At this stage, the CFD code follows this sequence [7]:

- Integration of the governing equations in all the elements contained inside the domain;
- Discretization - conversion of the integral equation into a system of algebraic equations;
- By an iterative method, the algebraic equations are solved.

The post processor offers tools to visualize the vector plots, particle tracing, the mesh used and any other kind of result.

Every CFD code is different and might offer other functionalities. In this study, the commercial CFD code Autodesk® CFD 2019 was used. The governing equations mentioned previously follow the laws of conservation of mass, energy, and momentum [8].

In a fluid element, the mass balance can be translated to the rate of increase of mass in that fluid element is equal to the net rate of the flow of mass into the fluid element. Thus, the mass conservation equation is given below by equation (2) [7].

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0 \quad (2)$$

The energy equation (3) is derived from the first law of thermodynamics which states that "the rate of change of energy of a fluid particle is equal to the rate of change of heat addition to the fluid particle plus the rate of work done on the particle plus the rate of work done on the particle [7].

$$\rho\frac{DE}{Dt}=-\mathrm{div}(pu)+\frac{\partial(u\tau_{xx})}{\partial x}+\frac{\partial(u\tau_{yx})}{\partial y}+\frac{\partial(u\tau_{zx})}{\partial z}+ \frac{\partial(v\tau_{xy})}{\partial x}+\frac{\partial(v\tau_{yy})}{\partial y}+\frac{\partial(v\tau_{zy})}{\partial z}+\frac{\partial(w\tau_{xz})}{\partial x}+\frac{\partial(w\tau_{yz})}{\partial y}+ \frac{\partial(w\tau_{zz})}{\partial z}+\mathrm{div}\left(-K\ \mathrm{grad}\ T\right)+S_E \quad (3)$$

where E is the specific energy, p the pressure, T the temperature, S_E a source of energy per unit volume and time and τ_{ij} the viscous stresses in ij direction.

1.3. Premature vulcanization

Premature vulcanization, also known as scorch, occurs when the rubber compound becomes partially vulcanized before it reaches its final state and shape before the vulcanization process. This phenomenon can occur as soon as the vulcanization ingredients are added to the rubber compound. Many factors have impact on the scorch time (the amount of time it takes before vulcanization starts) such as ingredients added to the mixture (additives) and storage conditions. Previous works found that the scorch time increases in an exponential manner with the decrease of temperature [9]. Also the addition of fillers, such as carbon black, proved that by increasing the content of carbon black in the mixture resulted in a lower scorch time [10, 11]. Generally, polymers with low moisture (below 0,15 %water) have a high scorch time [12]. This means that the addition of high levels of moisture result in faster cure rates, i.e., lower scorch times [13].

The scorch time is a very important parameter for rubber processing because it gives information about the vulcanization characteristics of the rubber compound being used. By knowing this parameter, operators know the amount of time available to process the rubber compound at a given temperature before it starts to vulcanize. Scorch time differs from compound to compound, meaning that compound is unique.

1.4. Process control

Cap strip lines have a mechanism of heat exchanging by passing a fluid through the main body and the extruder head. In this case study, the fluid used for heat exchanging was water, but to optimize the process and reduce maintenance, the inlet and outlet of water of the extruder head was replaced with two electrical thermal resistances of 1800 W each. Those components were controlled by a hysteresis current controller, also known as ON-OFF controller, meaning that the resistances only worked at 0 W or 1800 W without intermediate values. Due to an incorrect temperature control used, high peaks of heat were generated and led to localized premature vulcanization. In addition, in some occasions, the overall temperature of the extruder head was too low which caused the lack of impregnation on the cap strip belts. To solve this issue, it was used computational fluid dynamics and experimental tests to understand how to avoid premature vulcanization and to understand the temperature gradient on the extruder head.

2. Experimental

2.1. Laboratory tests

To determine the scorch time, Mooney scorch tests were performed using a Monsanto Mooney MV 2000E viscosimeter. Two samples from the same batch and mixer were collected on the mixing department. In the laboratory half of the sample were milled (M), to simulate the processing of the extruder, and the other half was left without any modification (S). The samples were left in the laboratory for 24 hours at controlled room temperature of 20°C to allow the rubber to cooldown due to the milling process.

After the 24 hours, a die was used to cut 15 samples of the (M) sample and other 15 samples were cut from the sample (S)(Fig. 3). Each sample is composed by two rubber discs, one

Fig. 3. (a) Milled (M) and (b) normal samples (S).

is a simple disc and the other has a small hole in the middle to fit the rotor shaft. After the cutting process, the 30 samples were cut to 11 ± 0,1 g.

The tests were performed for 80°C, 90°C, 100°C, 110°C and 120°C for 30 minutes each sample. For each temperature 3 samples of (M) and 3 samples of (S) were used, meaning that six tests were performed for each temperature. It was found that the difference between the normal samples and the milled samples was not significant. According to the results, the rubber compound used in the cap ply production suffers premature vulcanization for temperatures above 110°C (for 30 minutes). With these results, it was understood that processing that rubber compound at 110°C for 30 minutes or more, will result in poor quality products.

For the simulation data, a rubber process analyzer (Alpha Technologies RPA 2000) was used. The samples used were from the same batch as the ones used in the scorch tests. This test was performed for the same five different temperatures as used in the scorch tests. Thirty samples were cut with 5,5 ± 0,1 g each. Fifteen of the thirty samples were also milled, and the others were not. In these tests, it was found that milling the rubber compound revealed a consistent difference of viscosity. Fig. 4 shows the curves given by the RPA (Rubber Process Analyzer) Frequency Sweep test at 110°C.

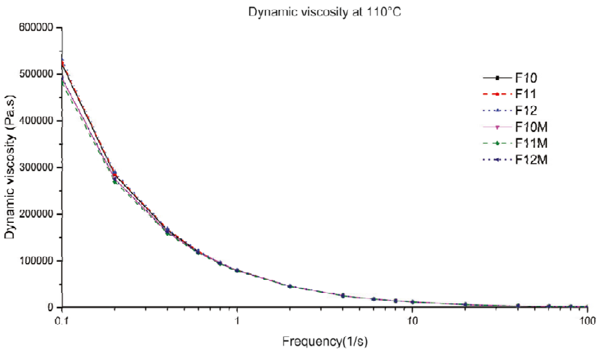

Fig. 4. Dynamic viscosity at 110°C. Samples with the "M" index represent the samples that were milled.

Since our control domain was simplified by suppressing the extruder and gear pump, viscosity values of the milled compound were used to obtain the second order polymer equation coefficients. The viscosity values given by the milled samples give a more realistic approach because the samples have been submitted to shear forces identical to those observed inside an extruder.

2.2. Thermography

An initial approach to the problem was done by using an infrared thermographic camera Fluke Ti300+. The extruder head was left working at nominal speed and, after one hour, the machine was stopped, and the extruder head opened. Immediately after the stop, the thermographic camera was used to take pictures of the extruder head. The emissivity was set to ε =0,95 because the extruder head has a rough surface and with rubber coloration (black) due to the carbon black residue stuck on the surface. However, in the flow channel inside the extruder head, the surface has a polished finish and results observed on the thermographic images show an unrealistic temperature gradient on the flow channel (Fig. 5).

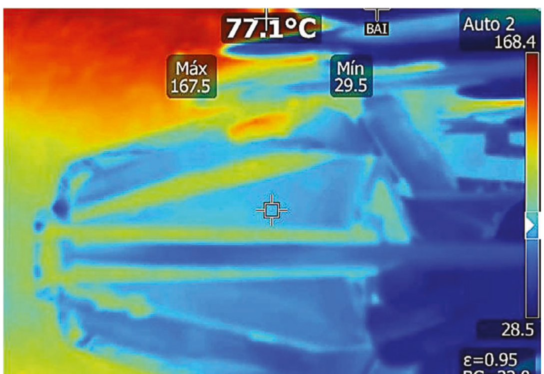

Fig. 5. Thermographic image of the interior of the extruder head.

Looking at Fig. , it can be concluded that around the flow channel, the temperature was higher than 110°C. Since that the rubber compound has around 30 minutes to be processed at 110°C before premature vulcanization occurs, this setup proved to be inefficient. Especially when the cap strip is running at low speeds, the rubber compound might take more than 30 minutes to travel from the extruder hopper to the die exit, meaning that with this setup it had a high tendency to show premature vulcanization.

In addition to the interior thermographic image, external images were also taken. The incorrect temperature control was causing the thermal resistances to go up to 242°C, representing an increased danger to the operator and generating excessive heat to the rubber compound (Fig. 6).

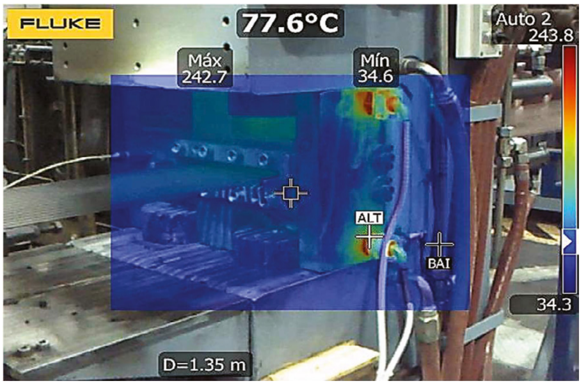

Fig. 6. Thermographic image of the exterior of the extruder head.

2.3. Temperature sensor location

The thermography images showed that the highest temperatures were located near the end of the flow, because that is the region where most heat generation happens due to the electric resistances. Before any modification, the extruder head only had one temperature sensor, located right after the gear pump, i.e., in the beginning of the flow inside the extruder head (Fig. 7).

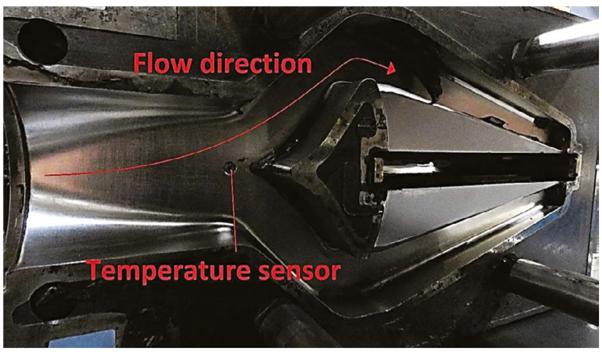

Fig. 7. Location of the temperature sensor inside the extruder head.

This location chosen for the temperature sensor is not adequate because the rubber travels from the extruder through the gear pump and then reaches the extruder head and this temperature sensor is located between the gear pump outlet and extruder head inlet, so it is far from the region of interest, where major changes in temperature occur due to the existence of electric thermal resistances (Fig. 8).

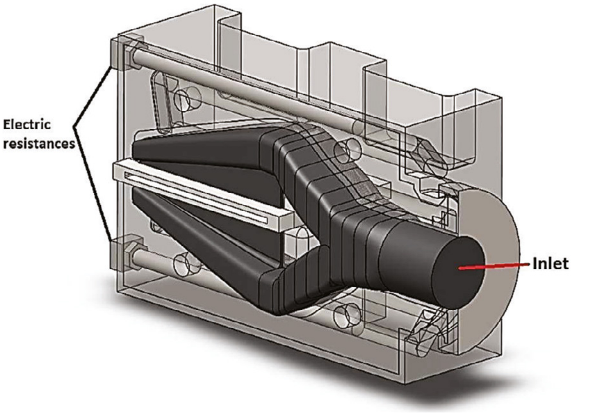

Fig. 8. Location of the electric thermal resistances inside the extruder head.

2.4. Log files

Near the end of the flow, two purges are placed to allow the operator to open then on the machine startup to allow the rubber to heat up more quickly. To avoid high costs for the company, an adaptor was made to allocate an RTD PT 100 temperature sensor (Fig. 9), making this a cheap alternative to register temperature data.

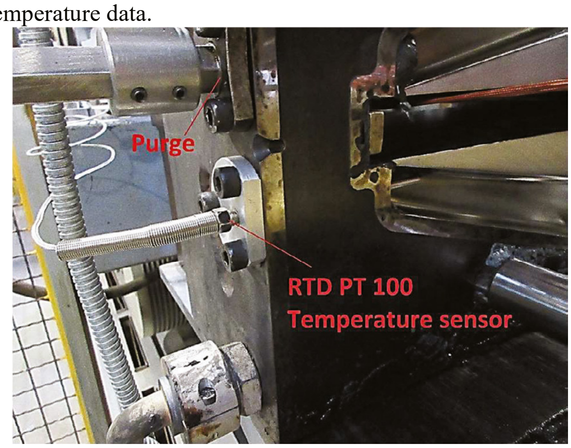

Fig. 9. Replacement of one purge with a temperature sensor.

This temperature sensor was connected to an Arduino Uno and a code was created to register the temperature every 30 seconds and save the data on a log file inside a micro SD card.

To connect this temperature sensor with the machine's computer, would be very time consumable, so, a log file routine was created to register all the stock machine parameters. Both log files are then combined in Microsoft Excel and results were analyzed.

The log file graph presented in Fig. 10 shows that in a situation of machine stop with the extruder head closed and filled with rubber, the temperature raised from 86,6°C (Point 1) to 131,3°C (Point 2) during 34 minutes. In this situation the rubber compound was submitted to temperatures higher than 110°C for 32 minutes. It was also needed to keep in mind that the rubber had already been subjected to high temperatures inside the extruder and gear pump. This situation generated premature vulcanization, resulting in scrap material. This data proved that the controlling was not adequate.

It is also important to notice that the temperature registered by the stock extruder head's temperature sensor was decaying in time while the temperature registered by the RTD PT 100 (connected to the Arduino) was rising, which makes sense due to the power peaks observed.

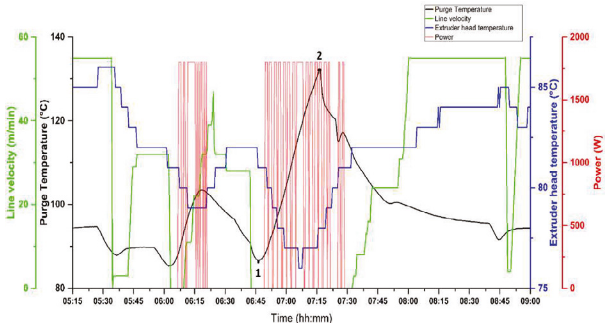

Fig. 10. Log file registering an anomaly.

3. Numerical simulation

3.1. Control domain

Using Solidworks® 2018 the control domain was modeled (Fig. 11). Simplifications were made so that the zone of interest was the extruder head. The extruder head is the part of the whole cap strip line that generates most issues related to premature vulcanization and lack of impregnation.

The extruder and gear pump were not modeled and were simplified by admitting two boundary conditions of pressure and temperature at the inlet. The main body was modeled without fillets to reduce the number of elements used when meshing. However, in the flow channel all round edges were modeled due to the impact they have in the flow behaviour. In this work, three simulations were addressed:

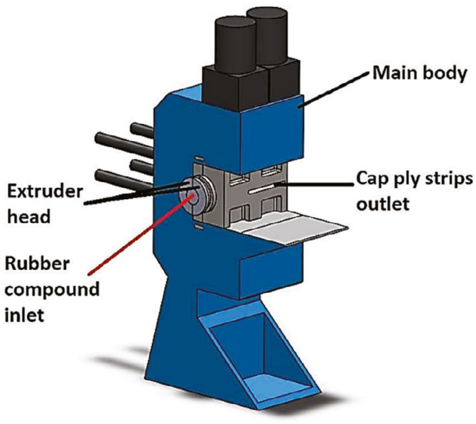

Fig. 11. Cap strip model.

- Main body with water circuit and extruder head with two electric resitances – This model was implemented at the factory and generated premature vulcanization and lack of impregnation in cap ply strips.
- Extruder head with water circuit – With this model, the temperature gradient on the extruder head was analysed.
- Extruder head with electric resistances - To compare the results with the extruder head working with the water circuit, this last model was created and conclusions were made between both heat exchanging methods.

3.2. Materials

In the three simulations performed, four different materials were used. Water was used to define the volume inside the water flow channels, steel was assigned to the extruder head and electric thermal resistances and iron for the main body, since there was no data related to the materials used in the cap strip production, an approximation regarding materials was done. These materials are included in the default materials list of the software used. For the rubber compound, laboratory tests were performed to determine its properties.

Table 1 shows the regression coefficients found for the second order polymer equation.

Table 1. Regression coefficients for the second order polymer equation.

Regression coefficients	
A_1	15,69218073
A_2	-0,920446939
A_3	0,082181351
A_4	-0,016461909
A_5	0,001074902
A_6	0,000380644

3.3. Boundary conditions

For the boundary conditions, heat generation was added to both electrical thermal resistances volume with a value of 1800 W for each one. Mass flow rate of 350 kg/h and temperature of 110 °C was added to the inlet of rubber compound and a volume flow rate of 1 m^3/h with a corresponding 95°C of temperature was assigned to the inlets of the water circuit. Finally, every outlet had a condition of 0 Pa of pressure.

3.4. Solver

To solve the simulations, transient analysis was performed. The step size used was 1s with 5 inner iterations. Gravity direction was defined, and heat transfer enabled. Due to the high viscosity of the fluid, low Reynolds number are found in this flow, so laminar analysis was chosen. To simulate a period of 10 minutes, 600 steps (with 5 inner iterations) were calculated. The lack of high-end hardware available restricted the time of simulation and lower step times had to be chosen. Tetrahedrical elements were chosen to create the mesh.

After multiple trials, results shown to be consistent and had a strong correlation with the results observed in experimental tests.

3.5. Numerical simulation results

3.5.1. Main body with water circuit and extruder head with two electric resistances

In this simulation, the main goal was to determine the regions with higher temperature gradients. Observing Fig. 12 it can concluded that when the electric resistances are working at 1800 W each, there's a significant heat concentration around the end of the flow channel, near the extruder heads outlet (Fig. 12).

Also, this numerical result provided another support information related to Fig. 10 where big differences in temperature were observed between the temperature reading of the RTD PT 100 temperature sensor (near the outlet) and the stock extruder head's temperature sensor (near the inlet). By combining this information, it is obvious that controlling the whole cap strip line process with the stock temperature sensor was not viable.

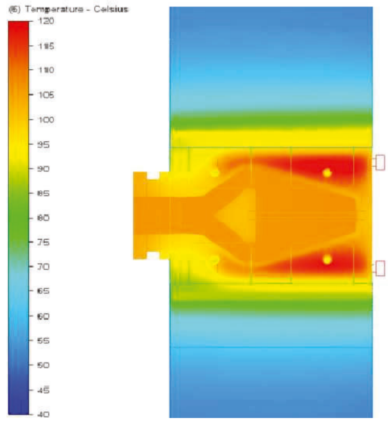

Fig. 12. Temperature gradient with electric resistances in the extruder head.

This simulation also aided in understanding why premature vulcanization of cap ply strips was occurring and, why rubber vulcanized inside the extruder head occurs, especially in the flow channel walls (Fig. 13). This happened in the flow channel walls due to the low speed of the rubber, which led to more travel time between the inlet and outlet together with high temperatures.


Fig. 13. Vulcanized rubber on the flow channel walls.

3.5.2. Extruder head with water circuit

After analyzing the temperature gradient in Fig. 12 model, a simulation of the extruder head with, exclusively, water flowing through the heat exchanging channels was conducted (Fig. 14). In this simulation, rubber flow was not modeled.

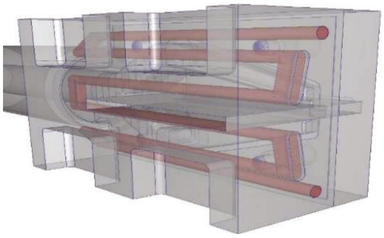

Fig. 14. Extruder head with water flow channels.

As expected, in this model the temperature gradient observed is very uniform (Fig. 15) because water is controlled by a TCU (Temperature Control Unit) which sets the maximum temperature of water around 100°C to avoid water vaporization. As seen in Fig. 14 the water circuit reaches most of the extruder head volume, meaning that its heat exchanging efficiency is high due to its coverage.

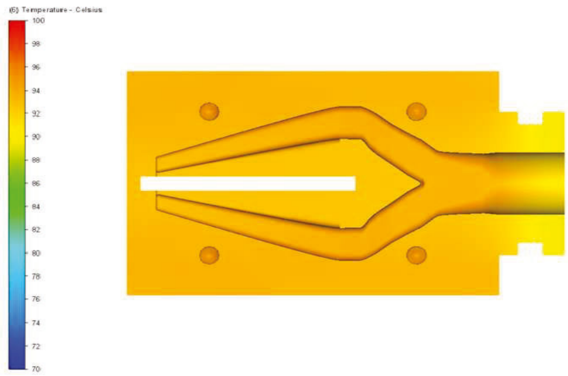

Fig. 15. Temperature gradient of the extruder head with water circuit only.

3.5.3. Extruder head with electric resistances

To compare both heat exchanging methods, one last simulation was assembled to study the temperature gradient of the extruder head with two electric resistances. At 1800 W for each electric resistance and at a steady state, the temperature observed is very high towards the right side of the extruder head, the region close to the outlet (Fig. 16 - a).

Again, the temperature around the stock temperature sensor is very different from the temperature where the RTD PT 100 temperature sensor was assembled. As seen in the experimental data, it was expected to see high temperatures close to the outlet of the extruder head, and this is observed in Fig. 16 – b where most of the volume above 110°C is in that region.

This last two simulations provided enough information to correlate with the experimental data and showed that each heat exchanging mechanism is different, having pros and cons for each scenario.

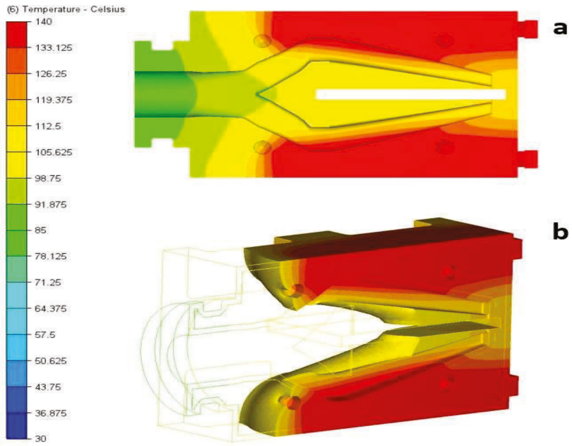

Fig. 16. Results of the simulation with electric resistances. (a) Front view of the extruder head. (b) Steel volume above 110°C.

4. Results and discussion

With the results given by the experimental tests and numerical simulations, it was found that the temperature control system was not adequate. The stock temperature sensor was not detecting much of the heat provided by the electrical thermal resistances because it was too far from the heat generation zone. The temperature sensor added and connected to the Arduino Uno, showed much more variations in temperature due to its location near the heat generation sources. After validation of the results, a new temperature sensor was added and connected to the PLC (Programmable Logic Controller) of the machine and the temperature control was renewed. Instead of the old ON-OFF controller, a PID controller was added. The replacement of controllers allowed to program the machine to use intermediate values of current and be able to control the heat generation provided by the electrical thermal resistances giving a full range of power generation from any value between 0 W and 1800 W. Previously, the setpoint was given by the stock temperature sensor. With the new system, the PLC program was programmed to read the temperature of the temperature sensor installed in the purge system. The setpoint of this temperature sensor was set to 110 °C which was the temperature given as critical to avoid premature vulcanization on the scorch tests. This method eliminated the presence of high peaks of power and temperature raises. In addition, by limiting the temperature that the rubber compound is submitted during the flow, it was possible to control the premature vulcanization phenomenon.

Also, the temperature setpoint for the new temperature sensor was set to 100°C when the extruder head is open. This allows the operator to work under lower temperatures and avoid physical damage. This condition also allows the extruder head to stay sufficiently warm to start the machine and avoid premature vulcanization or lack of impregnation of the polyamide cords.

Fig. 17 shows that with this new control system, temperatures registered on the purge zone (near the end of the flow) never exceed the 110°C. In addition, the temperatures present when the machine is stopped are always between 90°C and 100°C.

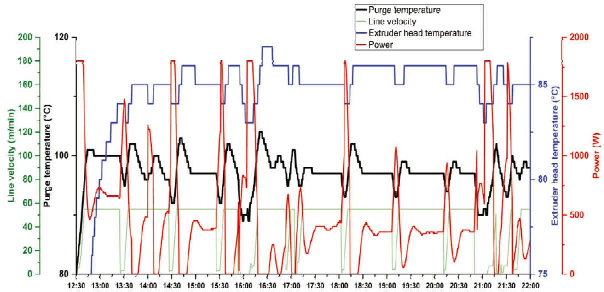

Fig. 17. Log file with the optimized control.

After three months of monitoring with the optimized control, a reduction in 100% of scrap generated, was observed.

The continuous monitoring with the optimized control showed that the premature vulcanization inside the extruder head was now very unlikely to happen. Due to the success of the new system, the system was implemented in other cap strip lines at the factory, and all showed similar behavior.

By doing experimental testing in conjunction with numerical simulations, was found that both heat exchanging mechanism were efficient to the rubber compound being used, however, the electric resistances demand a careful approach regarding its control. By installing the optimized control, scrap costs, setup times, material waste are reduced, and more productivity is observed. All the work done involved a low investment meaning that with all the benefits observed, the investment payback takes less than half a year.

5. Conclusions

In many industries, a trial and error approach is used which costs more money and time in the long run. With this work, a method was developed to understand the concepts behind the problems and to detect the problematic zones by experimental and numerical testing. With this approach it was found that understanding the scorch resistance of the rubber compound is essential. With the scorch test data, the time for processing the rubber at a given temperature is found. Numerical simulations and thermography data give extremely important information about the problematic zones inside the extruder head. This is hard to achieve without numerical simulations since the rubber flow happens inside an enclosure, therefore, it is not visible. By analyzing all the collected data, it is possible to understand where the current system is failing. In our case, the temperature sensor was in an inadequate location. To prevent higher experimental costs, an Arduino Uno was used to test a new location for a new temperature sensor, and the results indicated that this new location was more sensitive to the temperature rise due to the heat generation by the electrical thermal resistances.

The replacement of the Arduino Uno setup with a temperature sensor able to be connected to the machine's PLC, allowed to establish new setpoints for the temperature control. Also, by replacing the ON-OFF controller with a PID controller, a much more accurate control over the power generated by the electrical thermal resistances was achieved.

With this new setup, the scrap quantity (due to premature vulcanization and lack of impregnation) was reduced by 100%.

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