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Monitoring of shear heating effects during injection molding of rubber to improve the process control

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Abstract
This work aims to get new insights into the "process monitoring tool" proposed by the authors for the online monitoring of the shear heating phenomenon during injection molding of technical rubber parts. The online monitoring is based on direct measurement of the surface rubber temperature (shear heating temperature, T_{SH}) by an infrared thermal camera of the rubber as it leaves the extruder barrel of the injection molding machine. The measured rubber temperature is a process indicator giving the thermal history of the rubber compound injection and process safety. Therefore, this fast process control is applied to industrial applications to investigate the processing behavior of ethylene acrylate (AEM) rubber compounds. In particular, the relationships between T_{SH} vs injection pressure, vs injection speed, vs screw speed rotation and vs screw length over diameter ratio (*L/D* ratio) and vs AEM rubber compound properties variation due to exceeding the shelf life are investigated. The results show that T_{SH} is manly influenced by the screw *L/D* ratio, followed by injection pressure and screw speed rotation (especially if are set to higher levels), whereas the injection speed is the least effective parameter to reduce T_{SH}. Furthermore, a previously found robust correlation between the shear heating parameter (η_{SH}) and the minimum torque measured in rheometric laboratory tests (M_L) is used to show the noteworthy deviation from the proportional trend when the AEM rubber compound exceeded it shelf life. Therefore, the coefficient of determination of $\log\eta_{SH}$ vs M_L curves provides a good indication of process stability, while it is running.

Keywords Industrial applications · Injection molding · Process control · Rubber · Shear heating · Viscosity

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Introduction

Injection molding is one of the most commonly used processing technologies enabling the manufacture of rubber technical parts [1, 2]. The injection molding machine is still seen as a black box, because the output, the quality of the final product, is influenced by many, interplaying, parameters, related to the rubber properties, mold design, process setup parameters and injection molding machine capability [2].

Once the parameters of the injection machine are set, the final quality of the product depends on the properties of the rubber compound, which are temperature, pressure and time dependent. The rubber temperature is therefore a very influencing parameter on the final parts quality. A rubber temperature increase during the injection stage reduces rubber compound viscosity, but it may trigger the curing reaction. If curing occurs when rubber is flowing, viscosity increases, and flow stops.

Therefore, an optimal rubber temperature during the injection process must ensure a balance between relatively low viscosity (therefore low injection time) and a scorch safety condition (curing starts after complete mold filling) [2–5]. In spite of its importance, the rubber temperature during flow cannot be directly controlled, because it is raised not only by the heating system of the machine and by the curing reaction (if by mistake it occurs during flow) but also by shear heating, i.e., temperature increase due to viscous heat dissipation [2–14]. For most rubber compounds, characterized by a viscosity higher than plastics, the latter phenomenon is predominant and it is very difficult to be replicated in the laboratory.

To improve the quality of the final parts and reduce waste production, with both economical and environmental advantages, a thorough monitoring and control of the injection molding process is required. Moreover, also the processability of the raw rubber needs to be continuously controlled, because it is subject to fluctuations, from batch to batch and with storage time and temperature. A longer storage time may cause an increase in viscosity and a reduction of incubation time, thus reducing the processing window [15]. In industrial practice, the control of the process is exerted through: setup of machine parameters and laboratory tests on compounds before production run, and/or sorting of faulty parts after production run. However, an online monitoring could potentially help the modification of machine setup parameters at the first symptoms of defect formation, thus minimizing the time between the occurrence of defects and the fast corrective measures implementation [16–18]. The authors recently proposed a method for the online monitoring of the industrial injection molding process based on the measurement of rubber surface temperature (T_{SH}) and showed how this can significatively improve the control of the process [6, 19]. More in the details, the surface temperature of the rubber, T_{SH}, is measured by an infrared camera during rubber purging at the nozzle outlet of the injection molding machine extruder, several times during a daily production run. The use of infrared thermal camera does not disturb the rubber flow, and it is a noncontact method characterized by a very fast response [20–22]. This measure provides already an indication of the temperature of rubber at the mold entrance and could be used directly to monitor the risk of getting faulty parts. However, the temperature alone does not allow a comparison of the behavior of different rubber compounds, because the dependency on temperature of their properties is different for each compound. Therefore, the authors [6, 19] proposed, to convert T_{SH} into a technological parameter having the dimensions of a viscosity, the shear heating parameter (η_{SH}). This parameter is a combination of rubber material and machine properties:

$$\eta_{SH} = \Delta T_{SH} \cdot \frac{\rho C_p}{4v} \alpha \quad (1)$$

Where ΔT_{SH} (°C) is the temperature difference between T_{SH} and the initial temperature (considering 20 °C as initial temperature), ρ is the rubber density (kg/m^3), C_p is the specific heat capacity (J/kg/°C), v (s^{-1}) is a flow rate parameter, and α is a function of process parameters such as screw length over diameter (*L/D*), screw speed rotation, injection pressure, speed and time, barrel temperature setup and other factors [19]. In the present work, $\alpha = 1/(L/D)$.

The authors found a robust correlation between the shear heating parameter and the minimum torque measured in rheometric laboratory tests (M_L), a correlation valid for different rubber compounds and different injection molding machines and process parameters setup. Such a correlation can be used as a tool for process control and allows to predict the process parameter setup useful for molding of a new rubber compound.

The aim of the present work is to investigate the effects on T_{SH} of the main process parameters setup and the effects of variation of rubber properties due to exceeding the shelf life. Therefore, the relationships between T_{SH} measured by an infrared camera vs injection pressure, vs injection speed, vs screw speed rotation and vs *L/D* ratio were investigated. The effects of such parameters on the shear heating parameter (η_{SH}) are also shown.

Experimental

Materials

Nine different rubber compounds based on different elastomers were investigated: three types of diamine cured ethylene acrylate rubber (DIA-AEMs) black colored, two with 60 Shore-A and one with 70 Shore-A of hardness; one DIA-AEM brown colored, diamine cured with 60 Shore-A of hardness; two types of ethylene propylene diene monomer rubbers black colored, with 60 Shore-A of hardness, one peroxide cured (PO-EPDM), and one sulfur cured (S-EPDM); two types of diamine cured hydrogenated acrylonitrile rubbers (DIA-HNBRs) with 60 Shore-A of hardness, one black and one red colored; finally one peroxide cured fluoroelastomer (PO-FKM), green colored, with 60 Shore-A of hardness.

Table 1 Rubber compounds investigated with their filler type and content according to IMDS data

Rubber compound	Color	Hardness, Shore-A*	Filler content wt.%	Filler type
DIA-AEM60-1	Black	60 ± 5	40.0–46.0	Carbon black
DIA-AEM60-2	Black	60 ± 5	35.0–45.0	Carbon black
DIA-AEM70-1	Black	70 ± 5	30.0–40.0	Carbon black
DIA-AEM60-3	Brown	60 ± 5	38.0–46.0	Silicon dioxide
PO-EPDM60	Black	60 ± 5	28.0–33.0	Carbon black
S-EPDM60	Black	60 ± 5	26.3–33.5	Carbon black
DIA-HNBR60-1	Black	60 ± 5	44.5–48.5	Carbon black
DIA-HNBR60-2	Red	60 ± 5	40.0–48.0	Calcined kaolin
PO-FKM60	Green	60 ± 5	18.0–23.0	Barium sulfate

*According to *ASTM D2240-15*

These industrial grade rubber compounds were developed in accordance with automotive industry standard specifications, and their formulations cannot be disclosed for confidentiality reasons. The filler type and content are in accordance with available *International Material Data System* (IMDS) data and are reported in Table 1.

Both black and whitefilled rubber compounds were characterized by both laboratory tests and processing injection trials in the molding machine during daily production runs.

Laboratory tests

The above-mentioned rubber compounds were analyzed by using both uncured and cured standard samples, and the analytical instrumentation located in the R&D laboratory of *Italian Gasket* plant.

A laboratory compression molding press from *Gibitre Instruments Srl* was used to mold 200 × 200 × 2 mm standard rubber slabs. After 1 day of stabilization, the cured samples were used for density (ρ) measurements, performed at room temperature, by a digital densimeter from *Doss* (accuracy: 0.001 g), and according to *ASTM D297-15*. The density value to be used for Eq. 1 should be measured at the temperature and pressure in the injection molding machine extruder. However, to use an industrially applicable method, the density at room temperature and pressure was considered to be a reasonable approximation of density at higher temperature and pressure.

In addition, the cured standard samples were used for specific heat capacity (C_p) measurements by differential scanning calorimetry (DSC) in a 214 Polyma, from *NETZSCH GmbH*. The C_p data were recorded from 45 to 245 °C with a heating rate of 20 °C/min and referring to *ASTM E1269-11(2018)*.

The uncured standard samples were used to measure the minimum torque M_L data by an Moving Die Rheometer, MDR 2000 from *Alpha Technologies* according to *ASTM D5289-95* at a frequency of 1.7 Hz and 3° of oscillation amplitude. The vulcanization curve of each rubber compound was measured for 12 min at 177 °C, thus by using an historical and "die-hard" internal methodology.

The processing trials, mainly focused on the injection stage of molding process, were performed by using horizontal injection molding machines located in the Italian plant of *Italian Gasket*. Six horizontal injection molding machines were selected for the daily production runs processing characterization.

Processing trials

Two 300 Ton Engel from *ENGEL AUSTRIA GmbH* both having first-in first-out (FIFO) screw, *L/D* ratio of about 6, were used to produce O-rings and technical items. In detail, one 300 Ton Engel was used to produce two kinds of O-rings having different sizes and based on DIA-AEM70-1 (70 Shore-A and black colored), and on DIA-AEM60-1 (60 Shore-A and black colored), respectively. The other one 300 Ton Engel was used to produce two different frame gaskets based on PO-EPDM60 (60 Shore-A and black colored) and PO-FKM60 (60 Shore-A and green colored), respectively.

A 450 Ton IMG from *IMG Srl*, with FIFO screw, *L/D* ratio of about 12, was used to produce bellows based on S-EPDM60 (60 Shore-A and black colored).

A 190 Ton MIR also this from *IMG Srl* with reciprocating screw, *L/D* ratio of about 15, was used to produce sealing rings based on DIA-AEM60-3 (60 Shore-A and brown colored). Furthermore, another 190 Ton MIR with reciprocating screw and with *L/D* ratio of about 16 was used to produce technical rubber items based on DIA-AEM60-2 (60 Shore-A and black colored). Finally, another 190 Ton MIR with reciprocating screw, but with *L/D* ratio of about 18, was used to produce intake manifold gaskets based on DIA-HNBR60-1 (60 Shore-A and black colored) and DIA-HNBR60-2 (60 Shore-A and red colored), respectively.

The processing trials have concerned daily production runs of each rubber compound, and after the start-up stage, the thermal controls by the infrared (IR) camera were performed.

Figure 1 shows a simple scheme for the rubber surface temperature control by IR thermal camera (online monitoring).

The thermal measure for each rubber compound and respective production run was performed every hour, 3 measures at each time, for the purpose of controlling the shear heating effect during the injection stage. A thermal imaging camera, Diacam C.A 1882, *Chauvin Arnoux Group*, having ± 2 °C of accuracy and 0.08 °C of thermal sensitivity, was used to control rubber surface temperature (T_{SH}) as it leaves the extruder barrel of the injection molding machine (Fig. 1).

The IR thermal camera was used to measure the rubber surface temperature by detecting the emitted electromagnetic radiation. The rubber emissivity was set to 0.95 in accordance with the software material database, and image analysis was provided by the software tools (Fig. 1). The accuracy and sensitivity were selected in order to be lower than a temperature difference of 5 °C during stable production run on the basis of industrial experience.

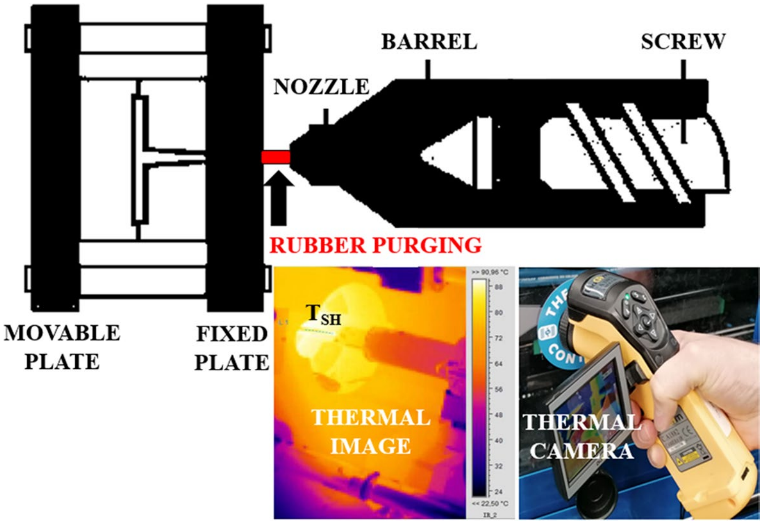

Fig. 1 Scheme for the rubber surface temperature control as it leaves the extruder barrel of the injection molding machine by IR thermal camera

The molded parts coming from each investigated production run, after stabilization, deburring, post-cure (if required) and final controls, were used as gaskets in the automotive industry.

The processing characterization was completed by investigating the process parameters setup effects on the rubber shear heating temperature. For this analysis, a 300 Ton Maplan from *MAPLAN GmbH* having FIFO screw, *L/D* ratio of about 14, was used to produce O-rings based on DIA-AEM60-2. Therefore, the relationships between T_{SH} measured by an infrared camera vs injection pressure, vs injection speed and vs screw speed rotation were investigated, respectively. The effect of each parameter is investigated by varying the level of the parameter itself, and keeping constant all the other parameters.

Furthermore, a relationship between $T_{SH\ vs}$ screw *L/D* ratio was investigated by using the same DIA-AEM60-2 rubber compound, but processed in different injection molding machines: a 300 Ton Maplan (FIFO screw $L/D \approx 14$), 300 Ton Engel (FIFO screw $L/D \approx 6$), a 190 Ton MIR (reciprocating screw $L/D \approx 16$) and a 190 Ton MIR (reciprocating screw $L/D \approx 18$), respectively.

Results and discussion

The processing characterization was partially focused on the effects of process parameters setup on the rubber shear heating temperature, and it was referred to the processing of DIA-AEM60-2 rubber compound in a 300 Ton Maplan (FIFO screw $L/D \approx 14$) horizontal injection molding machine, producing O-rings. Therefore, Fig. 2 shows the relationship between T_{SH} measured by an infrared camera vs injection pressure.

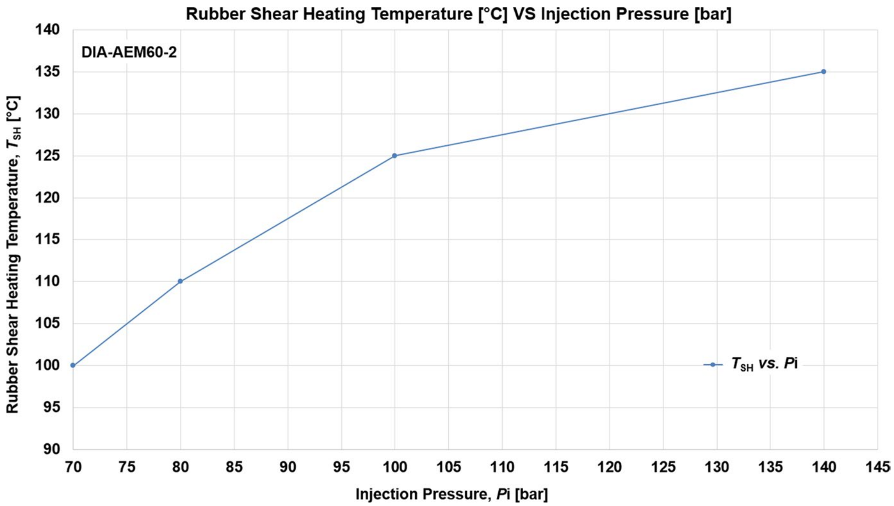

Fig. 2 Relationship between temperature T_{SH} and injection pressure for DIA-AEM60-2

Comprehensibly, a reduction of injection pressure decreased the shear heating effect during the injection stage. The injection pressure reduction, from 140 to 70 bar, allowed a T_{SH} reduction of about 35 °C, though maintaining a stable rubber compound processability with a negligible filling time variation. The trend is qualitatively expected because the shear heating temperature is by definition proportional to pressure drop in adiabatic conditions.

Figure 3 shows the relationship between T_{SH} measured by an infrared camera vs screw speed rotation, in which a similar proportional trend to the previous case of

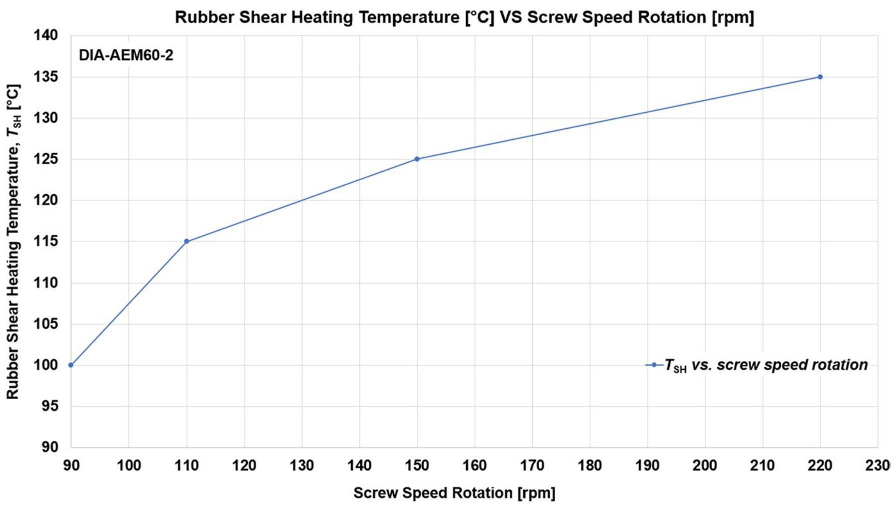

Fig. 3 Relationship between temperature T_{SH} and screw speed rotation for DIA-AEM60-2

injection pressure was observed. Also in this case, a screw speed rotation reduction, from 220 to 90 rpm, allowed a T_{SH} reduction of about 35 °C, though maintaining a stable rubber compound processability with a negligible filling time variation.

The proportional trend can be explained by the fact that by increasing the screw speed rotation, the shear rate of rubber compound is increased along the screw direction.

Figure 4 shows the relationship between T_{SH} measured by an infrared camera vs injection speed, where a proportional trend similar to the previous cases of injection pressure and screw speed rotation was observed. The injection speed reduction, from 40 to 15 mm/s, allowed a T_{SH} reduction of about 30 °C; however, the largest T_{SH} decrease (about 20 °C) was measured between 20 mm/s and 15 mm/s. On the contrary, only 10 °C of T_{SH} decrease was measured between 40 mm/s and 20 mm/s. Moreover, also in this case an injection speed reduction did not significantly affect the rubber compound processability. Increasing the injection speed causes an increase in shear rate especially in the extruder head, and thus, T_{SH} increases.

Figure 5 instead shows the relationship between T_{SH} measured by an infrared camera vs screw *L/D* ratio, in which a linear trend was observed. Clearly, from the 190 Ton MIR (reciprocating screw *L/D* ≈ 18) to the 300 Ton Engel (FIFO screw *L/D* ≈ 6), a T_{SH} reduction of about 40 °C was measured. Therefore for the DIA-AEM60-2 rubber compound, and by using the same philosophy of process parameters setup, the injection molding machines with higher screw *L/D* ratio showed the most significant shear heating effect T_{SH}. Furthermore also in this case, based on different injection molding machines with different screws, a very stable rubber compound processability was observed. Thus, production runs were carried out without relevant variations of cure rate, cure state (physical properties, e.g., hardness) and with minor quality issue. The main reason for the increase of T_{SH} of the rubber compound with increasing the screw *L/D* ratio can be ascribed the longer residence time.

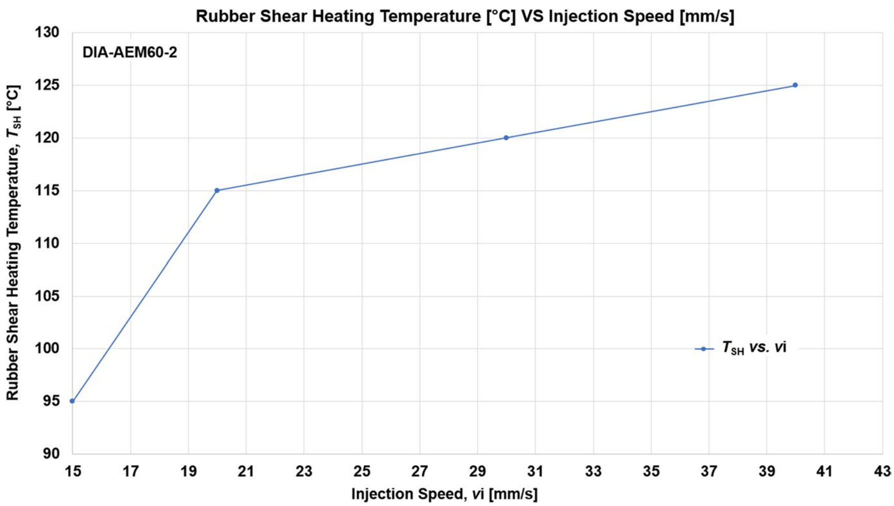

Fig. 4 Relationship between temperature T_{SH} and injection speed for DIA-AEM60-2

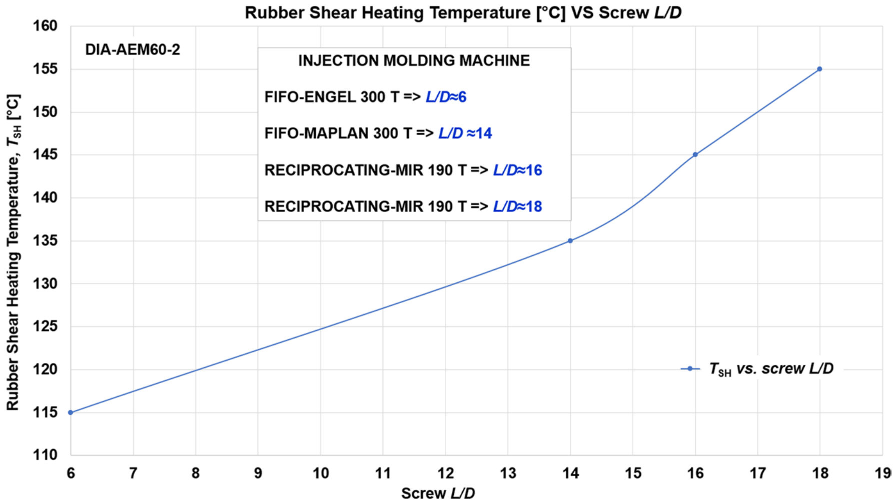

Fig. 5 Relationship between temperature T_{SH} and screw *L/D* ratio for DIA-AEM60-2

Therefore, for DIA-AEM60-2 rubber compound, T_{SH} is manly influenced by the screw *L/D* ratio. Nevertheless, also the process parameters such as injection pressure and screw speed rotation clearly showed that they contribute consistently to the T_{SH} increase, especially if they are set to higher levels. Finally, also the injection speed has provided its most relevant contribution to the T_{SH} increase, if it is set to lower levels (Fig. 4). Typically in the industrial practice the most easy parameter which is fine tuned to reduce T_{SH} is the screw speed rotation. On the contrary, the injection speed is the least effective parameter to reduce T_{SH}.

Besides the effect of setup parameters, also the effects of rubber properties variation on T_{SH} are shown in this work. At this aim, a single rubber compound was studied, DIA-AEM70-1, and its properties varied due to exceeding the shelf life. It is well known that rubber compounds change their properties with storage time and temperature. Even under proper storage conditions, after some weeks the incubation time decreases, thus causing a risk of premature start of curing reaction, and the viscosity increases. This is reflected in deteriorated mechanical properties of the cured rubber [15]. Typically, the AEM rubber compounds are characterized by a shelf life of about 1 month, obviously if properly stored according to *ISO 2230:2002—Rubber products—Guidelines for storage*. Therefore, the DIA-AEM70-1 rubber compound was processed both within the shelf life (2 weeks after the compounding) and off of it (5 weeks after the compounding) in a 300 Ton Engel by producing O-rings, and the differences in processability were investigated with particular care.

Table 2 reports the results for both the investigations of DIA-AEM70-1: a stable production run, within the material shelf life, designated DIA-AEM70-1-OK, and an unstable production run, out of the material shelf life, designated DIA-AEM70-1-KO. About laboratory test, the data of density (ρ), specific heat capacity (C_p) and minimum torque (M_L) at 177 °C are reported. Table 2 also reports the average experimental data from laboratory test of other eight different rubber

Table 2 Average experimental data from laboratory tests

Rubber compound	Density (ρ) kg/m^3	Specific heat capacity (C_p)* J/kg/°C	Minimum torque (M_L)** dN m
DIA-AEM60-1	1267 ± 1	2930 ± 3	1.24 ± 0.011
DIA-AEM60-2	1243 ± 1	2931 ± 4	0.40 ± 0.011
DIA-AEM70-1-OK	1240 ± 1	1650 ± 3	0.77 ± 0.010
DIA-AEM70-1-KO	1240 ± 1	1920 ± 3	0.84 ± 0.010
DIA-AEM60-3	1389 ± 2	1459 ± 3	0.38 ± 0.017
PO-EPDM60	1090 ± 1	4180 ± 2	1.40 ± 0.015
S-EPDM60	1140 ± 1	4150 ± 3	0.93 ± 0.023
DIA-HNBR60-1	1273 ± 2	3240 ± 3	0.58 ± 0.018
DIA-HNBR60-2	1331 ± 1	2770 ± 3	0.47 ± 0.036
PO-FKM60	2029 ± 1	1345 ± 2	0.69 ± 0.018

*At T_{SH}

**At 177 °C

compounds, based on different elastomer, having eight industrial production runs with long process stability, without significant deviations of set parameters and with very little scrap. These additional eight different rubber compounds provide the data to build the robust correlation between the shear heating parameter and M_L for stable production runs, which is used as a reference to evaluate the processability of DIA-AEM70-1-OK and DIA-AEM70-1-KO compounds.

Table 3 reports the average experimental data from processing characterization of the eight different rubber compounds, and screw L/D ratio of the used injection molding machines. About the processing characterization, the data of barrel temperature setup (T_{Barrel}), measured shear heating temperature (T_{SH}) of the

Table 3 Average experimental data from processing characterization

Rubber compound	L/D	Barrel temperature (T_{Barrel}) °C	Shear heating temperature (T_{SH}) °C	Temperature difference in shear heating (ΔT_{SH})* °C
DIA-AEM60-1	6	80.0	114.0 ± 2.5	94.0
DIA-AEM60-2	16	75.0	115.0 ± 3.0	95.0
DIA-AEM70-1-OK	6	75.0	130.0 ± 2.5	110.0
DIA-AEM70-1-KO	6	75.0	226.0 ± 3.0	206.0
DIA-AEM60-3	15	75.0	125.0 ± 2.5	105.0
PO-EPDM60	6	95.0	105.0 ± 2.5	85.0
S-EPDM60	12	70.0	155.0 ± 3.0	135.0
DIA-HNBR60-1	18	75.0	136.0 ± 2.5	116.0
DIA-HNBR60-2	18	75.0	132.0 ± 3.0	112.0
PO-FKM60	6	80.0	110.0 ± 2.5	90.0

*Considering 20 °C as initial temperature rubber by infrared thermal camera and the temperature difference in shear heating (ΔT_{SH}) considering 20 °C as initial temperature are reported.

Table 3 also reports the results for both the investigated DIA-AEM70-1-OK and DIA-AEM70-1-KO.

Finally, Table 4 reports the average data of calculated shear heating parameter (η_{SH}) at 10 s^{-1} and the corresponding logarithmic values for the rubber compounds of Tables 2 and 3.

The η_{SH} was calculated by using Eq. 1, where the flow rate parameter v [s^{-1}] is directly related to the shear rate. Therefore, a conventional value of flow rate of 10 s^{-1} was chosen based on the commonly achievable order of magnitude of shear rate in the plasticizing extruder of the injection molding machine.

The results of calculated η_{SH} were compared with minimum torque, M_L, from MDR routine rheometric laboratory measurements for the nine different industrial rubber compounds. Therefore, a robust correlation between η_{SH} and M_L, labeled roadmap, was obtained by considering various rubber compounds having different elastomeric matrices, different injection molding machines and process parameter setups, by producing different geometries of the molded parts (both O-rings and technical rubber items).

In this work, the robust correlation between η_{SH} and M_L is used to investigate the effect of shelf life variation for the DIA-AEM70-1 rubber compound during its production run.

Figure 6 shows the relationship between logη_{SH} at 10 s^{-1} and M_L from 12 min at 177 °C by MDR, giving a comparison between the nine rubber compounds investigated and the nine industrial production runs having long process stability without the relevant quality issue of final parts, including the DIA-AEM70-1-OK run. Therefore, a good correlation was established between the results of the laboratory test, M_L, and the technological parameter (η_{SH}) and characterized by a proportional trend with R^2 of 0.936 according to a power regression law.

Table 4 Average data of shear heating parameter (η_{SH}) at 10 s^{-1}

Rubber compound	Shear heating parameter (η_{SH})* Pa s	Log shear heating parameter Log(η_{SH})* Log Pa s
DIA-AEM60-1	1.50×10^6	6.18
DIA-AEM60-2	5.37×10^5	5.73
DIA-AEM70-1-OK	9.68×10^5	5.99
DIA-AEM70-1-KO	2.11×10^6	6.32
DIA-AEM60-3	3.64×10^5	5.56
PO-EPDM60	1.67×10^6	6.22
S-EPDM60	1.31×10^6	6.12
DIA-HNBR60-1	6.69×10^5	5.83
DIA-HNBR60-2	5.77×10^5	5.76
PO-FKM60	1.06×10^6	6.02

*At 10 s^{-1} and ΔT_{SH}

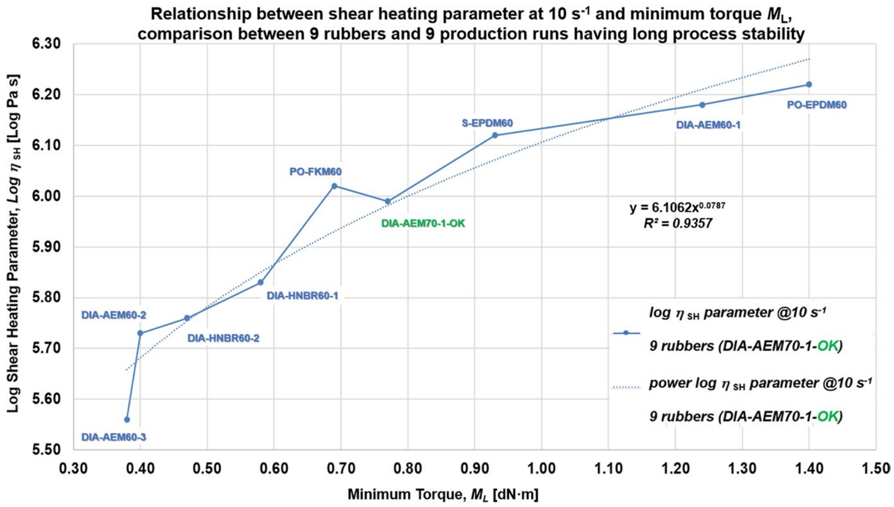

Fig. 6 Relationship between shear heating parameter η_{SH} at 10 s^{-1} and minimum torque M_L, comparison between 9 rubbers and 9 production runs having long process stability

A similar roadmap was previously shown by the authors [19] for the following eight rubber systems: DIA-AEM60-1, DIA-AEM60-2, DIA-AEM60-3, PO-EPDM60, S-EPDM60, DIA-HNBR60-1, DIA-HNBR60-2 and PO-FKM60.

In the present work, the previous investigation was extended to DIA-AEM70-1 rubber compound to obtain the correlation in Fig. 6. The existence of such a correlation is, therefore, confirmed and strengthened by the new data based on 70 Shore-A of hardness. It is interesting to remark that the newly introduced compound has a higher hardness compared to the others: This seems to indicate that the validity of such correlations is not strictly related to rubber of the same hardness degree.

The nine industrial production runs investigated in this work are characterized by different injection molding machines, different molded part geometries and by very stable production runs, with very little scrap after molded part stabilization, deburring and post-cure. Therefore, this roadmap was found to be useful for process control and allows to make predictions on different rubber compounds, with the purpose of supporting the process engineer and the plant operator, in the improvement of process control by thermal online measurements.

In this work, AEM rubber parts affected by scorch problems, mold fouling and thermal degradation due to plasticizer loss are investigated as follows. Figure 7a, b shows the cavities of movable plate during the DIA-AEM70-1 production runs, DIA-AEM70-1-OK (within the material shelf life) and DIA-AEM70-1-KO (out of the material shelf life), respectively. These production runs were chosen as a case study to show how the rubber compound shelf life, once exceeded, affects negatively on the rubber shear heating temperature, processing behavior and mold fouling.

Particularly, Fig. 7a shows the movable mold plate of DIA-AEM70-1-OK, where a not excessively fouling, even after a week of production run, was found. Instead Fig. 7b shows the movable mold plate of DIA-AEM70-1-KO, where a

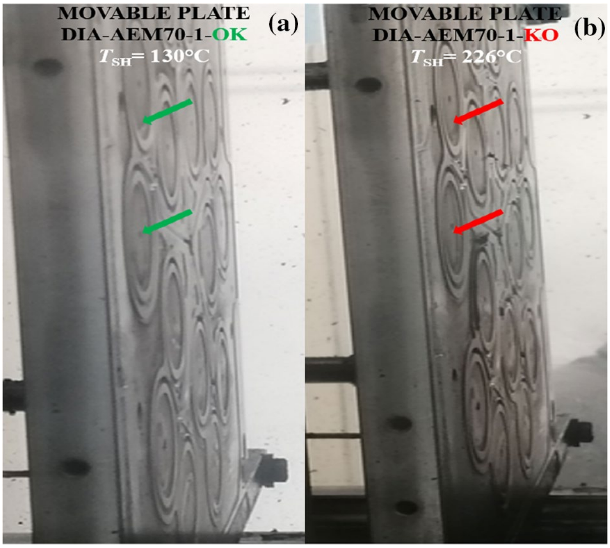

Fig. 7 **a** Cavities of movable plate during the DIA-AEM70-1-OK production run. **b** Cavities of movable plate during the DIA-AEM70-1-KO production run. Green arrows indicate clean cavities, and red arrows indicate some fouled cavities

significant fouling, even after 2 days of production run, was found, as pointed out by red arrows in the figure.

About the DIA-AEM70-1-OK production run, an average T_{SH} of 130 °C was measured during the daily process control and, after injection molding, stabilization, deburring, and post-cure of 4 h at 175 °C, no relevant quality issue of final parts was found, including IRHD M hardness value of 71.1 ± 0.1 points according to *ISO 48* (70.0 ± 5 required specification).

Whereas in the case of DIA-AEM70-1-KO production run, an average T_{SH} of 226 °C was measured during the daily process control and, after injection molding, stabilization, deburring and post-cure of 4 h at 175 °C, some surface hardened and cracked parts, 0.2–0.3% of the overall production (about 110,000 O-rings), were obtained. This amount of scraps, and especially this type of defect, is relevant because the automotive industry requires "zero defected" parts. A IRHD M hardness value of 82.4 ± 0.1 points was measured, thus out of the required specification.

The effect of exceeding rubber shelf life produced an increase of T_{SH} by 96 °C, which largely outcomes the effects produced by the variation of process setup parameters, at least within the range explored in this work. This suggests that the rubber properties have the significant effect on T_{SH}.

The significant increase of T_{SH} was the first indicator of DIA-AEM70-1 processability change due to its shelf life variation. Another relevant indicator was the quick mold fouling increase in the DIA-AEM70-1-KO production run (after only 2 days of production). The last condition obviously has negatively affected the productivity of DIA-AEM70-1-KO, thus subjected to extraordinary cleaning.

Furthermore, even modifying the process parameter setup such as injection pressure, injection speed and screw rotation speed, no reduction in this excessive shear heating was found.

Therefore, T_{SH} is already a useful parameter to guarantee a very fast online process control, that is, to collect information concerning the risk of scorching and thermal degradation, leading, for example, to the diffusion of compound ingredients (low volatile chemicals), stickiness, mold fouling and also color variation.

Moreover, monitoring also η_{SH} allows to get a more quantitative and precise indication of the quality of molded parts: By introducing η_{SH} of a new production run into the data of η_{SH} vs M_L correlation, the processability of the newly introduced production run can be inferred from the coefficient if determination R^2, as shown in the details in [19]. Moreover, η_{SH} and the use of the roadmap could provide information also about new compounds, whose T_{SH} limit for the obtainment of good quality parts is not known a priori, unless process trials are performed. Therefore, logη_{SH} was introduced to allow the comparison of process outputs between DIA-AEM70-1 and the other rubber compounds.

Figure 8 shows the relationship between logη_{SH} at 10 s^{-1} and M_L from 12 min at 177 °C by MDR for the eight rubber compounds with very stable industrial production runs, and the DIA-AEM70-1-KO run (R^2 of 0.797).

In more detail, new curve was created, starting from the roadmap reported in Fig. 6, by introducing the values of logη_{SH} at 10 s^{-1} and M_L of DIA-AEM70-1-KO, while keeping the values of the other eight productions runs constant.

By introducing the point of DIA-AEM70-1-KO, a relevant deviation from the previous proportional trend was observed, with decreased R^2 from 0.936 to 0.797, according to the power regression model.

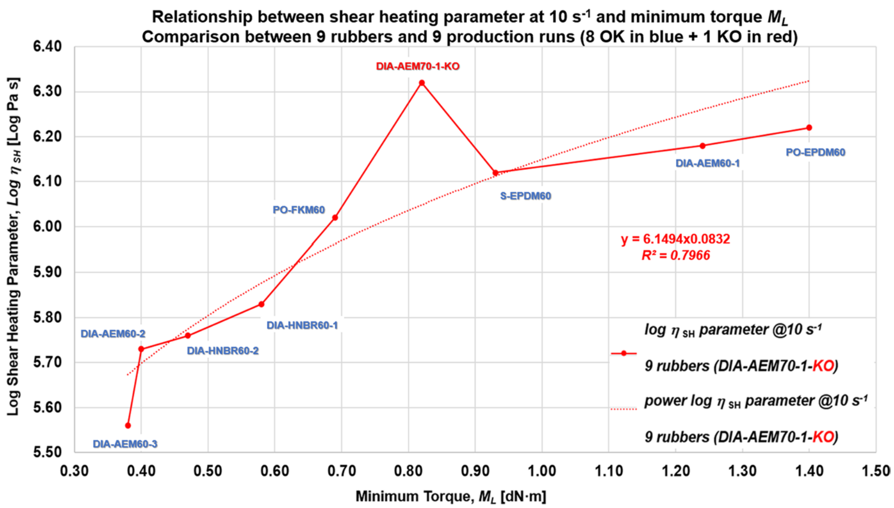

Fig. 8 Relationship between shear heating parameter η_{SH} at 10 s^{-1} and minimum torque M_L, comparison between 9 rubbers and 9 production runs: 8 OK runs and 1 KO run

Therefore, the coefficient of determination of $\log\eta_{SH}$ vs M_L curves provides a good indication of process stability of DIA-AEM70-1 runs.

Accordingly, the DIA-AEM70-1-KO run, out of the material shelf life, with M_L of 0.84 ± 0.07 dN·m, an average T_{SH} of 226 °C (+96 °C) and $\log\eta_{SH}$ at 10 s^{-1} of 6.32 ± 0.33 Pa·s, did not allow a stable production cycle, where hardened and cracked parts, 0.2–0.3% of final scraps, were produced.

Figure 8 clearly shows how $\log\eta_{SH}$ values of a production run, combined with M_L values, give indication of the "real output" of the injection molding process by comparison of this data with a well-established roadmap, obtained from stable production runs of different rubber compounds and process conditions. This monitoring has the advantage of being fast and provides information about the stability of the process, while it is running, well before completing the production run.

Conclusions

This work aimed to get new insights about the "process monitoring tool" proposed by authors for the online monitoring of the shear heating phenomenon to guarantee an optimal injection molding of technical rubber parts. The online monitoring is based on direct measurement of the surface rubber temperature (T_{SH}) by an infrared thermal camera at the nozzle outlet of the injection molding machine extruder. Therefore, a very fast process control is proposed and applied to an industrial case to investigate the processing behavior of AEM rubber compounds. The first investigation regards the rubber properties variation due to exceeding the shelf life (for the DIA-AEM70-1), and the second one regarding the process parameters setup (for the DIA-AEM60-2). Therefore, the relationships between T_{SH} vs injection pressure, vs injection speed, vs screw speed rotation and vs *L/D* ratio were investigated. The setup level of the four parameters is varied close to the limit of the operativity range, by ensuring the rubber compound processability without relevant cycle time variation.

About DIA-AEM60-2, T_{SH} is mainly influenced by the screw *L/D* ratio, followed by injection pressure and screw speed rotation (especially if set to higher levels), whereas the injection speed is the least effective parameter to reduce T_{SH}.

This measured T_{SH} led to the calculation of a technological parameter designated shear heating parameter, η_{SH}, which also takes into account physical material properties (density and specific heat capacity) and process conditions (*L/D* ratio). The authors compared this parameter with the previously found robust correlation between the shear heating parameter (η_{SH}) and the minimum torque measured in rheometric laboratory tests (M_L). The correlation is valid for different rubber compounds (based on AEM, EP(D)M, HNBR and FKM elastomers) and different injection molding machines (300 Ton Engel, 450 Ton IMG and 190 Ton MIR) and process parameters setup [6, 19].

About DIA-AEM70-1, the introduction of η_{SH} vs M_L values in the previously found robust correlation showed a significant deviation from the proportional trend, when the AEM rubber compound exceeded it shelf life. Therefore, the coefficient of determination of $\log\eta_{SH}$ vs M_L curves provides a good indication of process stability of DIA-AEM70-1 runs.

The monitoring of T_{SH} has the advantage of being fast and provides information about the stability of the process, while it is running, well before completing the production run.

Moreover, the robust correlation between the shear heating parameter (η_{SH}) and the minimum torque measured in rheometric laboratory tests (M_L) can be used as a tool for process control and allows to predict the process parameter setup useful for molding of a new rubber compound.

Finally, the possibility to use T_{SH} and η_{SH} in the setup of computer-aided engineering simulations, useful for mold design and injection molding process optimization, will be investigated in future works.

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