Digital twin for rubber seal manufacturing

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This paper describes the latest improvements carried out in terms of material characterization and modelling techniques for uncured rubber required for the development of digital twins of seal compression and injection moulding processes. Much of this work was focused on obtaining the right parameters to be used in the required dynamic viscosity model as well as in the used curing kinetics model.

Moulding simulation results show very good agreement with results like pressure values and melt front displacement obtained experimentally. Based on these results, a new analytical approach was developed giving a rapid indication of the maximum allowable filling or compression time, thus allowing to prevent underfill and scorch in the seal manufacturing process.

1 Introduction

Most seals are moulded and the proper design of the mould and choosing for the right process settings is key to achieving an overall process robustness and efficiency. Here, simulation of the rubber seal production process may support in defining and validating efficient technical solutions to be implemented. However, moldflow simulations for thermosetting materials such as rubber are still in an early phase of their development and thus typically more complex than flow simulations for thermoplastics, particularly because of the involved curing kinetics. Depending on the filler content, also the viscosity curve for thermosetting materials often deviates significantly from the well-known Cox-Merz rule [3], commonly applied for thermoplastic materials. Consequently, the procedure used currently for obtaining the viscosity curve for thermosetting materials requires some modification.

In ensuring process robustness, some intelligence also needs to be added to the overall manufacturing system so that it can autonomously adapt its own parameters to the unavoidable incoming material and environmental variations. Once fully mature, this will be a real step forward. Also, in the process of building such system, a lot will be learned about the manufacturing process itself. The development of an adaptive process and its extension to the concept of adaptive factories hence requires the development of software tools for the specific process. These software tools should do the data acquisition and processing and should make the right decision based on the varying process conditions. A prerequisite for this is the full connectivity and the full connection of all the equipment in the manufacturing plant.

Additionally, rapid and ever-changing material properties require the use of quick material characterization methods. This paper will focus on the used material characterization method and material models that allow for quick yet accurate prediction of moulding outputs and optimization of the used process settings, thereby enabling the digital twin concept for moulding processes.

2 Curing kinetics model

For describing the curing kinetics, use is made of the Kamal's relation. It combines the kinetic behaviour of an n^{th} order chemical reaction and that of an autocatalytic chemical reaction [1]:

$$\frac{d\alpha}{dt} = K_a(1-\alpha)^n + K_b\alpha^m(1-\alpha)^n \tag{1}$$

K_a and K_b are rate constants following Arrhenius law,

i.e. $K_a = Ae^{-Ta/T}$ and $K_b = Be^{-Tb/T}$

with

α the degree of cure

T the temperature in K

t the time in s

Parameters A, B, T_a, T_b, m and n are fitted to measured Rubber Process Analyzer (RPA) cure curves using a nonlinear regression method and by using a corrected thermal response $T(t)$ which depends on the sample thickness and its thermal conductivity. Making use of this corrected thermal response method is of crucial importance for obtaining the correct parameter set. This approach significantly increases the model accuracy, especially when it comes to the predicted scorch time. It is currently used in our digital platforms and now allows for the proper prediction of potential moulding issues related to unexpected rubber scorch.

As an example, Figure 1 shows two measured RPA cure curves, one with the RPA temperature set to 180ºC and one with the RPA temperature set to 200ºC. Also shown are the approximated cure curves using Kamal's relation in combination with the corrected thermal response $T(t)$ of the used rubber sample. As can be seen in the figure, the corrected cure curve, in which an instantaneous temperature increase of the sample is assumed, shows a significant decrease of the scorch time.

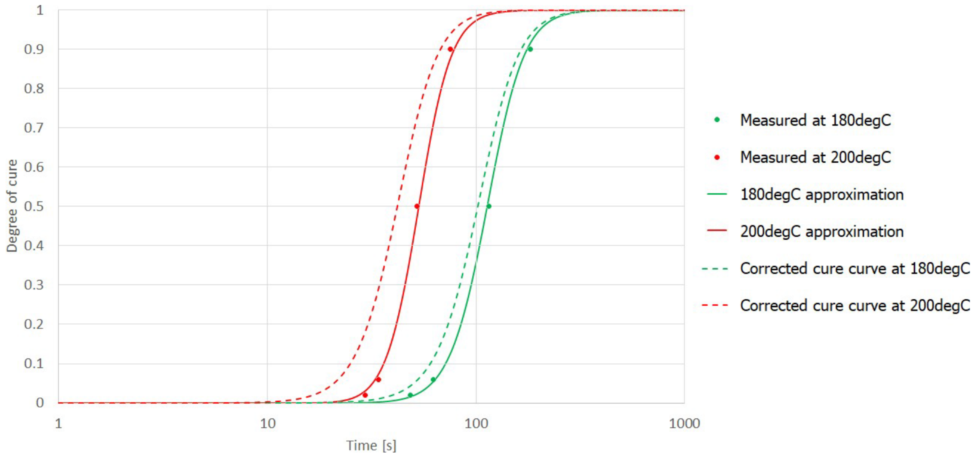

Figure 1: Measured and corrected cure curves

3 The dynamic viscosity model

The dynamic viscosity of a rubber compound depends on both the shear rate and the degree of cure of the used rubber. The dependency on the shear rate is described by the Cross model [2] for which the material model parameters are obtained by using a modification to the Cox-Merz rule [3]. The cure dependency on the other hand is described by the so-called Castro-Macosko model [4]. All used models will be described in the following sections.

3.1 The modified Cox-Merz rule

A modification to the Cox-Merz rule [3] is used to find the dynamic viscosity μ as a function of shear rate by making use of the RPA in the linear regime, i.e. by applying a small amplitude oscillatory strain on the RPA. The Cox-Merz rule states that if one wants to know the dynamic viscosity at shear rate $\dot{\gamma}$, one can measure it as the complex viscosity at angular frequency ω with ω set equal to $\dot{\gamma}$:

$$\mu(\dot{\gamma}) \approx c_\eta |\eta^*(\omega)| \text{ with } \dot{\gamma} = \omega \qquad (2)$$

with

ω the applied angular frequency on the RPA

c_η a material dependent correction factor found from Large Amplitude Oscillatory Strain (LAOS) experiments on the RPA at low frequency

Here, the modification to the standard Cox-Merz rule is in the applied correction factor c_η. For c_η equal to one, Equation (2) reduces to the standard Cox-Merz rule. For thermoplastic materials, this standard rule usually works quite well. For rubber materials however, often a deviation from the standard rule is found, mainly caused by the effect of fillers in the rubber. For this reason, this new rule has been proposed and validated in which a correction factor c_η is applied for reinforced thermosetting materials such as rubber. This material dependent correction factor c_η is found from large amplitude oscillatory strain experiments on the RPA.

As an example, in Figure 2 the solid lines show the measured complex viscosity as a function of the shear rate (which is actually the set angular frequency on the RPA). The dashed lines show the dynamic viscosity as a function of the shear rate as resulting from the modified Cox-Merz rule.

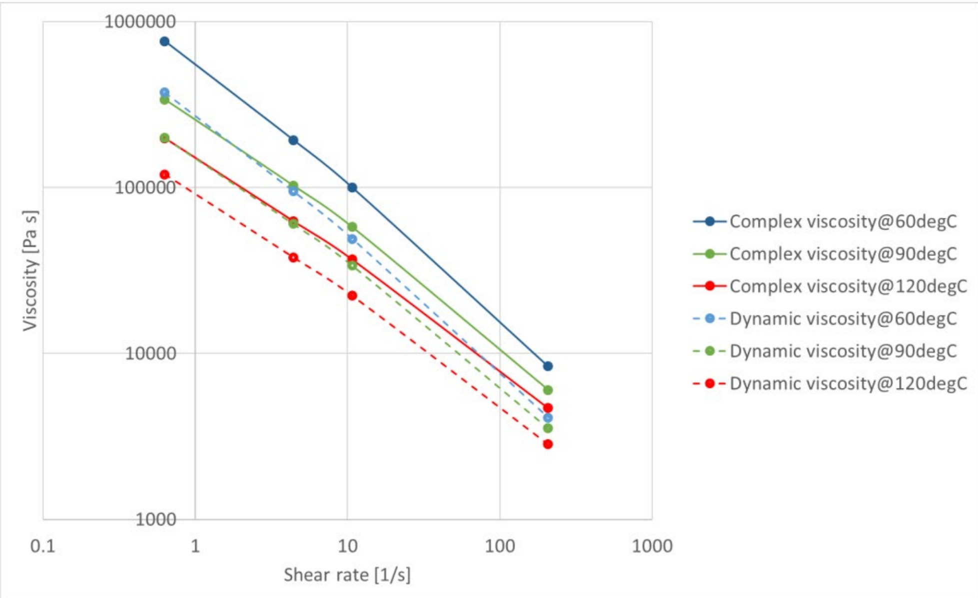

Figure 2: Measured viscosity curves

By using this modified Cox-Merz rule, we are now able to find the dynamic viscosity at higher shear rates than what would normally be possible on the RPA, being limited by a maximum available torque. Therefore, with this novel technique, combined with the fact that the RPA procedure is much less cumbersome and time consuming than using a capillary rheometer for example, the complete viscosity model is built within less than half an hour in our connected material database.

3.2 The Cross model for shear rate dependence

The shear rate ($\dot{\gamma}$) dependence of the dynamic viscosity μ_0 at zero cure is described by the Cross model [2]:

$$\mu_0(\dot{\gamma}) = \frac{\mu_{ZSR}}{1 + \left(\frac{\mu_{ZSR} \cdot \dot{\gamma}}{\tau^*}\right)^{1-n^*}} \quad (3)$$

With μ_{ZSR} the dynamic viscosity at zero shear rate $\dot{\gamma}$ and zero cure given by:

$$\mu_{ZSR} = A exp\left(\frac{T_b}{T}\right) \quad (4)$$

Parameters A, T_b , n^* and τ^* are fitted to measured RPA viscosity curves using a nonlinear regression method.

Figure 3 shows an example of a fitted Cross model. The dashed lines are the measured viscosity curves (as described in the previous section) while the solid lines are the viscosity curves resulting from the fitted Cross model.

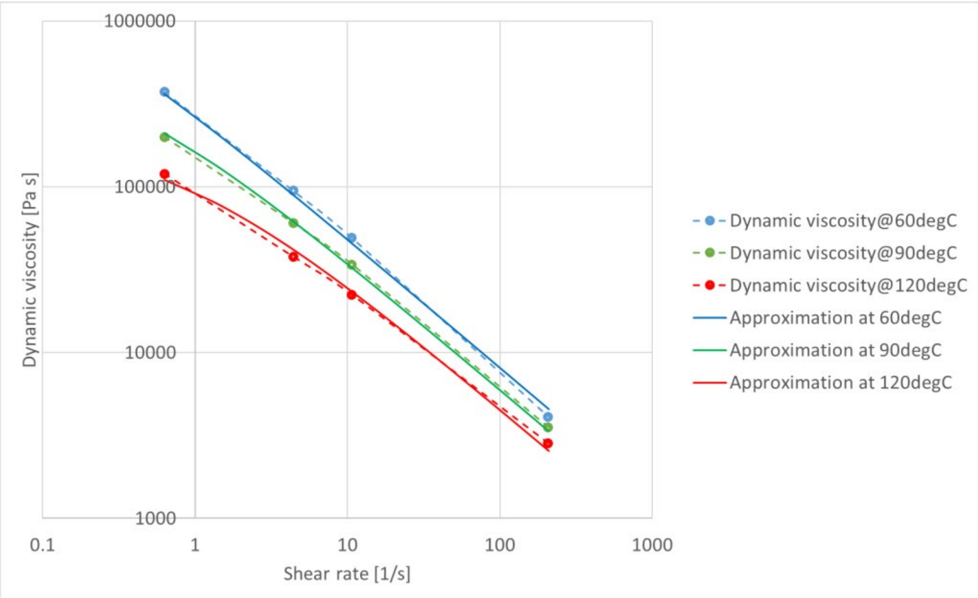

Figure 3: Measured viscosity curves and the fitted Cross model

3.3 The Castro-Macosko model for cure dependence

The cure (α) dependence of the dynamic viscosity (μ) is described by the Castro-Macosko model [4]:

$$\frac{\mu(\dot{\gamma},\alpha)}{\mu_0(\dot{\gamma})} = \left(\frac{\alpha_g}{\alpha_g - \alpha}\right)^{c_1 + c_2\alpha} \quad (5)$$

In which α_g is the so-called gel point. Parameters c_1 and c_2 are fitted to the cure dependence of the measured complex viscosity.

As can be seen in this equation, when the degree of cure α is approaching the gel point α_g, the dynamic viscosity μ will go to infinity. In this way the transition from liquid to solid state is modelled.

As an example, Figure 4 shows the dynamic viscosity μ over the zero-cure dynamic viscosity μ_0 as a function of the degree of cure α. It can be observed that, with the degree of cure α approaching the gel point α_g, the dynamic viscosity μ exponentially raises to infinity. This will prevent the material from flowing. For simulations purposes, as soon as the degree of cure is going above 2% to 3% at the end of filling, one may expect to see some serious quality issues in production such as scorching, bad weld lines or warpage caused by high residual stresses.

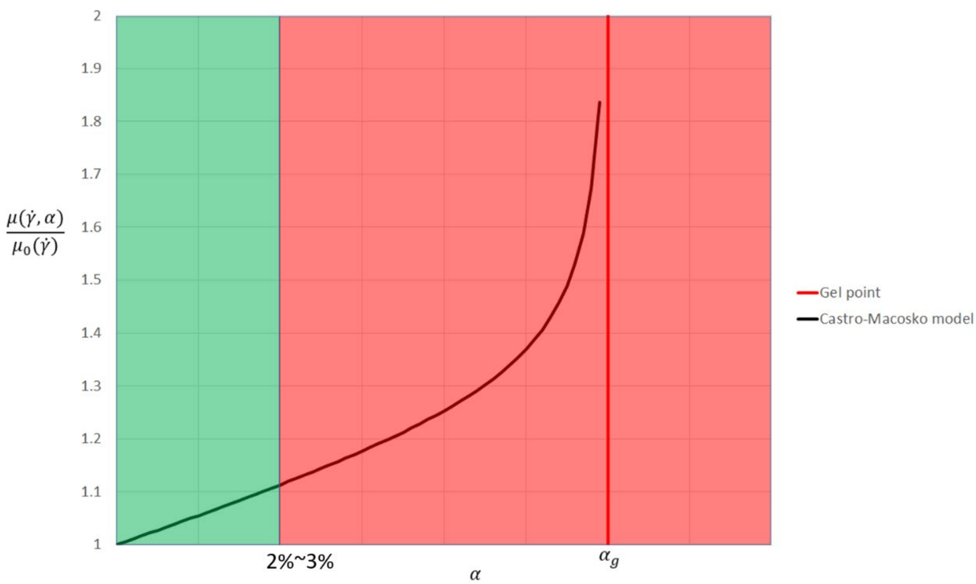

Figure 4: Example showing the increase of the dynamic viscosity due to the effect of curing according to the Castro-Macosko relation

4 Injection moulding simulation results

Figure 5 shows an injection moulding case in which the described material model has been applied for simulation. The used design of experiments is shown in Table 1.

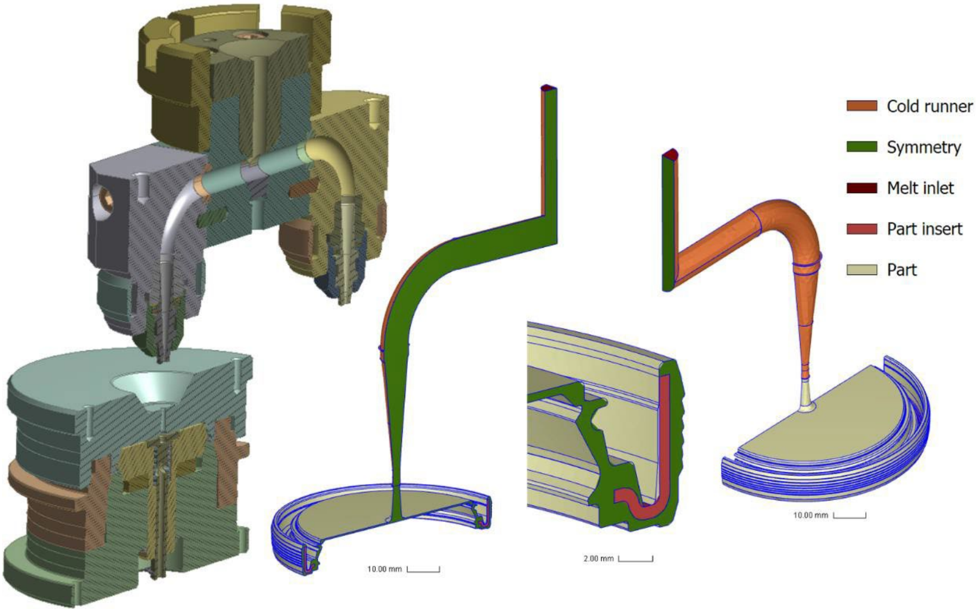

Figure 5: Geometry for the considered injection moulding case

Table 1: Summary of injection moulding design of experiments

Case	Set maximum injection pressure [MPa]	Cold runner temperature [°C]	Mould temperature [°C]	Resulting filling time[s]
1	124.2	70±2	195±2	3.5±0.2
2	106.2	70±2	195±2	5.8±0.2
3	106.2	85±2	195±2	3.5±0.2
4	124.2	85±2	195±2	2.0±0.2

To demonstrate the impact of the used material model, for case 2, Figure 6 shows two pressure profiles, one for the standard material model and characterization method and one with the corrected thermal response profile and corrected Cox-Merz rule applied as described in sections 2 and 3. As can be seen, the corrected characterization method has a significant effect on the resulting injection pressure profile. For the uncorrected standard viscosity model, the maximum injection pressure is reached immediately, resulting in a significant underfill of the part. Figure 7 shows the melt front displacement after 6.1 seconds for the corrected as well as for the uncorrected material model. As can be seen, 98% fill (VP switch point) is already reached for the corrected material model while, for the uncorrected method, there is still a significant underfill. For the corrected method, the underfill is much less significant and corresponds very well with what was found in practice, as depicted in Figure 9.

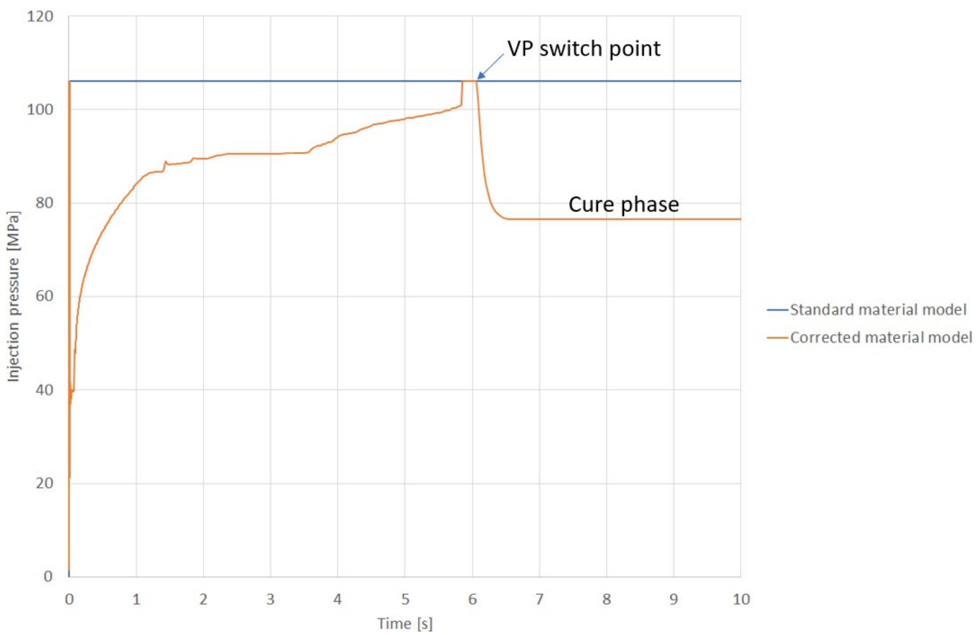

Figure 6: Simulated injection pressure profile with and without the corrected material characterization model

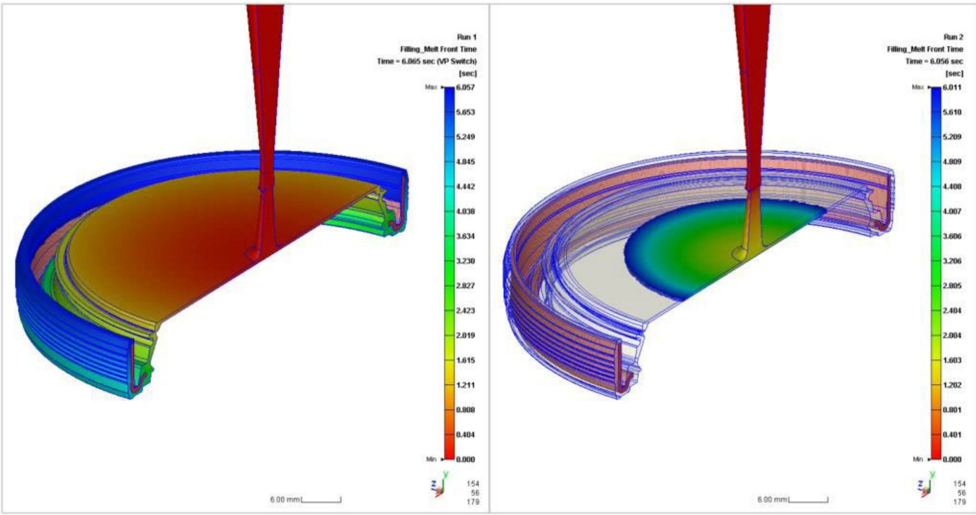

Figure 7: Simulated melt front time contour plots after 6.1s of the injection time for the corrected (left side) and uncorrected (right side) material model

Moreover, as can be observed in Figure 8, for the corrected material model, a very good correspondence is found between simulated injection pressures and actual readings from the used injection moulding machine.

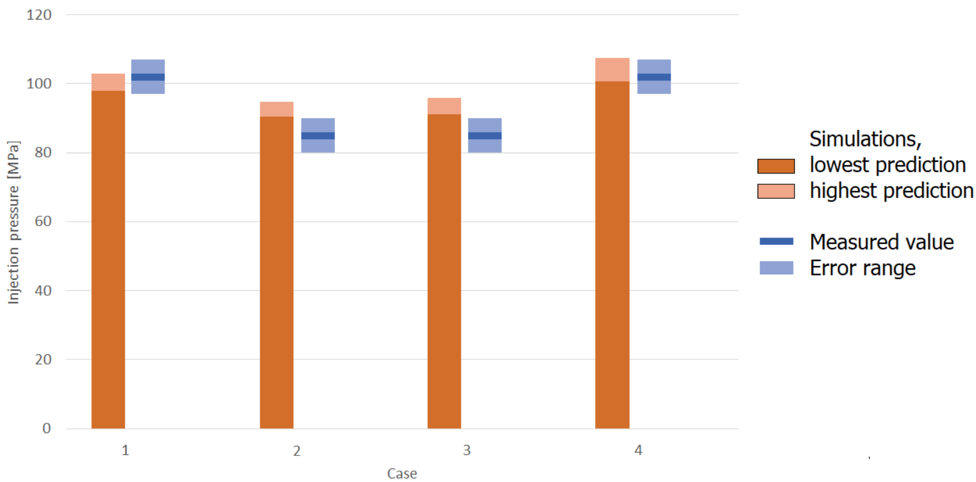

Figure 8: Simulated and measured injection pressures for a number of cases

Finally, the simulation results, provide concurring indicators for defects that were also found in the real product. For case 2 for example, an underfill is predicted in the simulation which was also found in the real product and at the same location, as shown in Figure 9. Similarly, a demoulding damage was found on the real product at the same location where a large gradient in the degree of cure was predicted by the simulation at the end of filling, leading to high residual stresses.

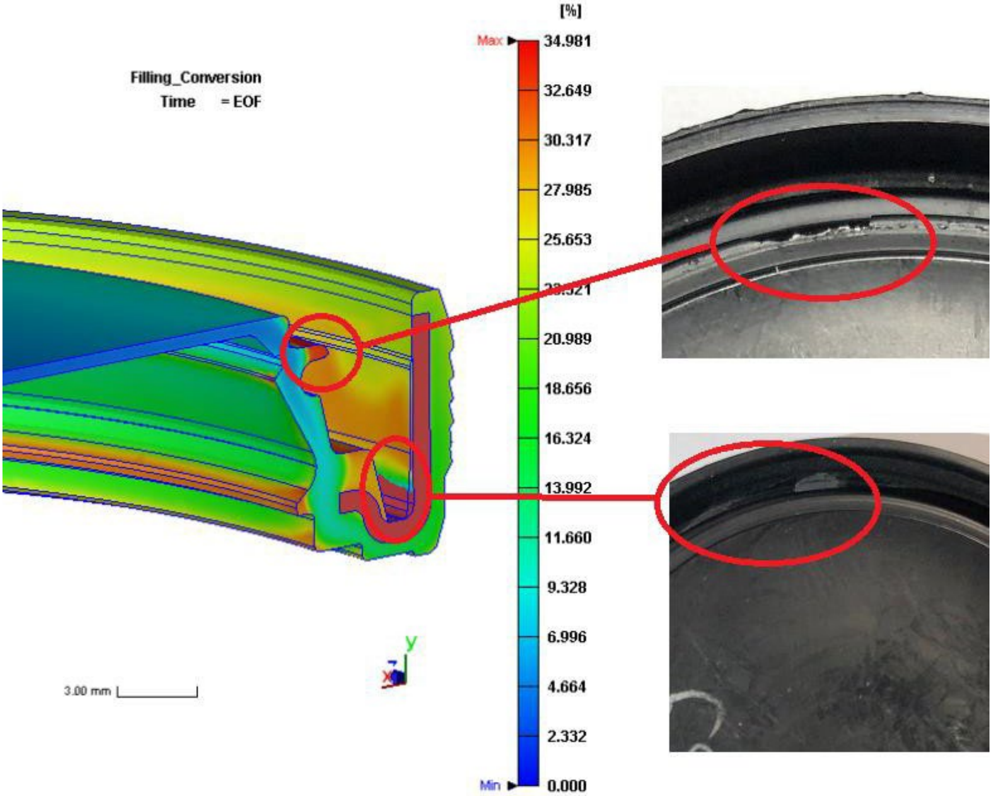

Figure 9: Defects found in the real product as related to high cure degree gradients and underfills found in the simulation

The results shown thereby demonstrate the accuracy and validity of our current numerical prediction method for injection moulding.

5 Compression moulding simulation results

The developed material characterization and modelling procedure described in the previous section is also applicable to compression moulding processes. The learnings from injection moulding have therefore been implemented in our digital twin platforms in combination with advanced compression moulding simulation solvers, leading to the development of a unique virtual compression moulding module for thermosetting materials. For some cases where an initial solid like deformation is relevant, the initial deformation is solved by making use of external FEA software, the results of which may then be imported into the compression moulding module.

Figure 10 shows an example of a compression moulding machine and the used pie section model for the cavity in which the uncured rubber pre-form is initially put onto the mould “shelf” before it is being compressed. As can be seen in the simulation on the right, a good agreement is reached with the melt font displacement obtained experimentally over time from partially compressed parts.

This result partially demonstrates the accuracy and validity of our current numerical prediction method for rubber compression moulding. Future work will focus on the required compression force and compression time required for a complete validation.

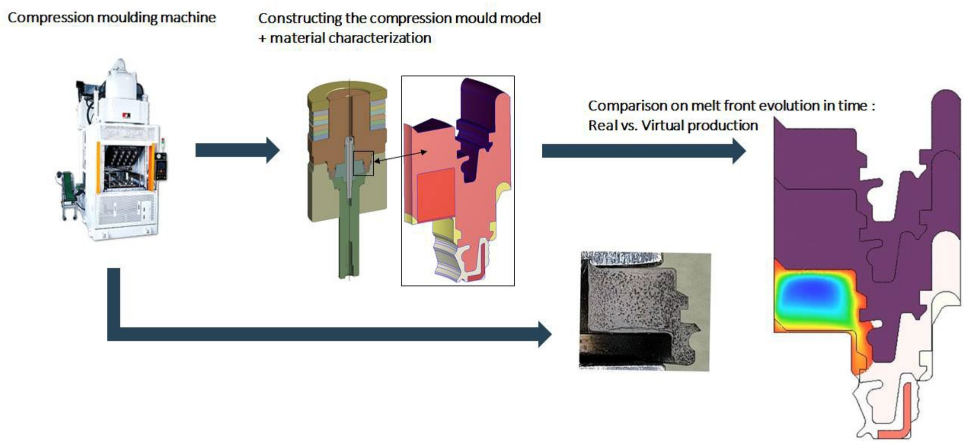

Figure 10: The corrected material model is also being validated for compression moulding

6 Quick analytical tools

By simulating the manufacturing processes and analysing the results, one aims at keeping the scrap rate to an absolute minimum. A reason behind a potentially high scrap rate in seal manufacturing is that rubber batches may show a relatively large variation in material properties. Most moulding machine operators usually ignore what are the specific material properties of the specific rubber batch in use. As a result, an average property value is often assumed. The operator will then adjust the machine settings to that average value, resulting more often than not in a part that is out of conformance. At this stage, trial and error usually takes place in order to identify the optimized machine settings leading to improved part quality. Inevitably, such an approach leads to a very high scrap rate in production.

The next step towards implementation of the digital twin concept is to make use of developed simulation capabilities to quickly adapt to specific process conditions and identify the right machine settings based on these simulation outputs. Although simulation tools could give an operator some indication about which machine settings to use, detailed simulation models are still too cumbersome and time consuming to use in a production environment. Besides, apart from the fact that the setup of a detailed simulation required a lot of time and experience, the run time of such simulation remains quite long. As a result, these advanced simulation tools are not suitable to support machine operators in practice.

To specifically address this challenge, a quick analytical tool has been developed which provides the machine operator with live guidance on how to adjust the moulding machine settings, in real-time, to a specific incoming rubber batch, the properties of which are measured in line via either a Rubber Process Analyzer (RPA) or a Moving Die Rheometer (MDR). The new seal manufacturing workflow then looks as depicted in Figure 11.

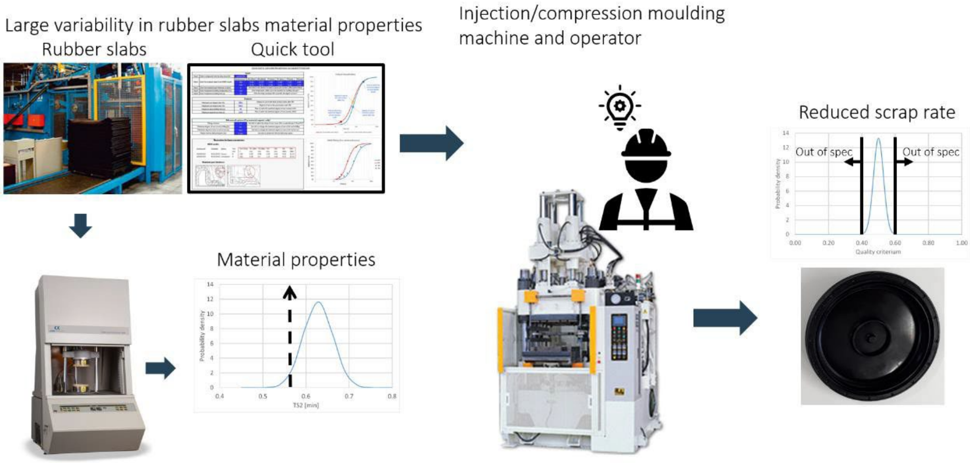

Figure 11: SKF virtual production quick analytical solution

Figure 12 shows the maximum degree of cure values found for the simulated cases discussed in section 4 as compared to the values obtained from this quick analytical tool at the given mould temperature. As can be seen, the maximum degree of cure values obtained from both the advanced simulation method and the quick tool are in very good agreement, thereby validating the analytical approach developed within the quick tool.

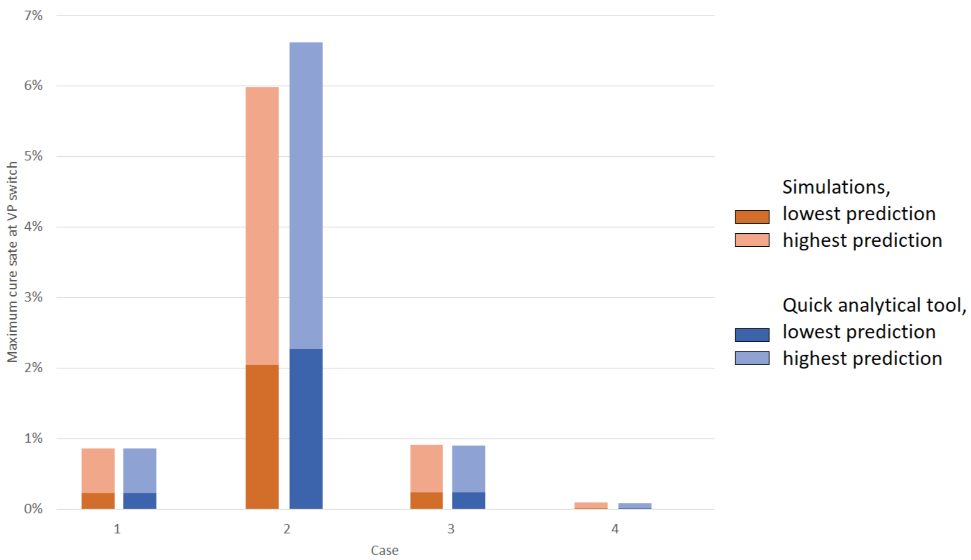

Figure 12: Maximum cure state as simulated for a number of cases and compared to what is found from using the quick analytical tool at the mould temperature

7 Summary and conclusion

A new method for material characterization and modelling has been presented that allows for a quick and improved modelling of the rubber curing kinetics and dynamic viscosity. This method is currently used within our digital twin platforms for seal injection and compression moulding manufacturing processes.

For injection moulding, the material model improvements were demonstrated to have a significant and positive impact on the predicted injection pressure and melt front displacement. Injection moulding simulations in which the corrected material model was applied showed good correspondence between simulated and measured injection pressures. Also, the predicted cure state distribution showed good indicators for underfills, and demoulding defects found in the real product.

Similarly, prediction of the melt front displacement from compression moulding simulations carried out in a newly-developed compression moulding module were demonstrated to be in good agreement with experimental moulding trials.

Finally, an analytical method has been implemented into a quick tool to support our digital twin journey for the seal manufacturing process. Simulated curing results showed that for all times during the process, the maximum cure state was almost identical to that obtained from the quick tool prediction at the set mould temperature.

This tool hence gives an accurate and quick indication of what would be the maximum allowable filling time in order to prevent underfill and scorch in production.

This quick tool, which directly supports increased part quality in production by scrap rate reduction, is one step among many on our seal manufacturing digitalization journey. Following steps are about finding and implementing the right automated connectivity between measured process conditions, simulation tools outputs, and optimized machine settings, to further increase the efficiency and sustainability of our seal manufacturing processes.

8 Acknowledgements

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9 Nomenclature

Variable	***Description***	***Unit***
A	Fitting parameter used in Arrhenius law	[1/s]
B	Fitting parameter used in Arrhenius law	[1/s]
c_1	Fitting parameter used in the Castro-Macosko model	[-]
c_2	Fitting parameter used in the Castro-Macosko model	[-]
c_η	Cox-Merz rule correction factor	[-]
K_a	Rate constant	[1/s]
K_b	Rate constant	[1/s]
m	Fitting parameter used in Kamal's relation	[-]
n	Fitting parameter used in Kamal's relation	[-]
n^*	Fitting parameter used in the Cross model	[-]
t	Time	[s]
T	Temperature	[K]
T_a	Fitting temperature used in Arrhenius law	[K]
T_b	Fitting temperature used in Arrhenius law	[K]
α	Degree of cure	[-]
α_g	Gel point	[-]
$\dot{\gamma}$	Shear rate	[1/s]
η^*	Complex viscosity	[Pa s]
μ	Dynamic viscosity	[Pa s]
μ_0	Dynamic viscosity at zero cure	[Pa s]
μ_{ZSR}	Dynamic viscosity at zero shear rate and zero cure	[Pa s]
τ^*	Fitting parameter used in the Cross model	[Pa]
ω	Angular frequency	[rad/s]

10 References

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