Operating Window in Injection Molding with 9 Experiments

Dr. Hans-Joachim Graf,
TechnoBiz-Group (H-JG Consulting)
J. Leistenschneider Str.27, 63628 Bad Soden-Salmuenster, Germany
Phone: +49 60656 209428, Fax: +49 3222 1520721, e-mail: hjgraf@cyg.net

Introduction:

The analysis and optimization of the Injection Molding Process in Rubber Manufacturing started in the late 70ties with some papers and publication about the Operating Window (**1,2,3**). Based on then analysis of the injection molding process and a clear definition, what is a process factors and what a response according statistic experimental design (DoE) procedure (**4,5**), it is possible to construct the operating window for the molding process within nine experiments.

The factors important for part performance are the heat history of the compound through all stages of the injection molding process, the mold temperature, the injection speed and the heating time [**Figure 1**]. The higher the cavity entrance temperature of the rubber the shorter the vulcanization time (**6**) [**Figure 2**]. This before mentioned process factors determining the vulcanization and finally the crosslink density (**7**). Almost all physical properties correlate with this term (**8**).

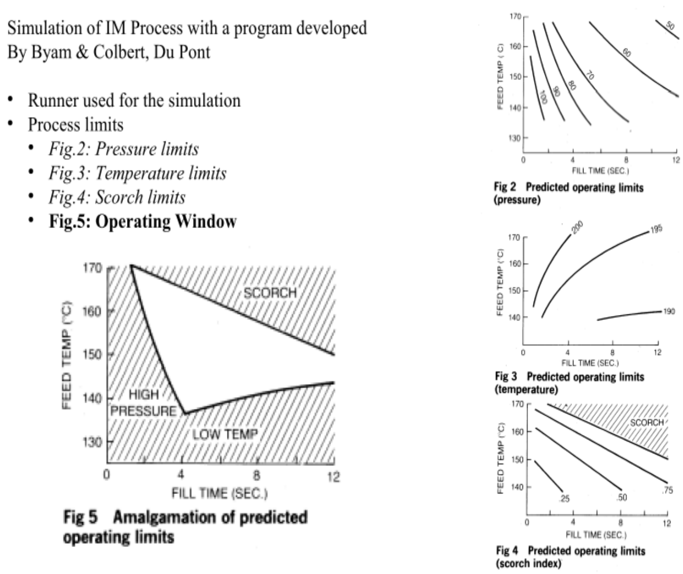

Fig. 1: Operating Window Simulation according Byam & Colbert

The operating window describes the boundaries of the injection molding process on mold temperature over time with the third factor: compound temperature. One limit is pressure (short time) the other is the scorch index (long time). The scorch index is the scorch time consumed and is taken mostly as 50% reduction of scorch. The operating window constructed in this way becomes smaller with increased compound temperature, while the vulcanization time has the same slope as the scorch index line but shifted to longer time.

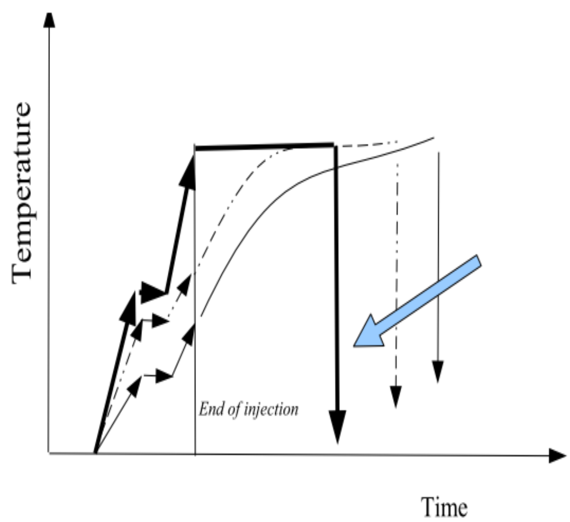

Fig. 2: Influence on Cavity Entrance Temperature on Vulcanization Time

The the injection molding process steps as well as the the whole process can now be described with regression equations. As a result of some mathematical operations finally the vulcanization time is correlated with three factors: temperature of the mold, the compound temperature at start of the injection and the injection speed [**Figure 3**]. With this four factors in mind it is possible to perform an experiment according the statistic experimental design (DoE) procedure.

Experimental Strategy

The DoE procedure of this kind needs a starting point meaning the lowest limits of four factors. This point can be evaluated with step wise increase of heating time at the lower limits the other factors using the correlation between none porous point and crosslink density. The evaluation is necessary only to determine the lower limit of the heating time. The crosslink density on the part produced under this conditions can be measured via

$$t_{vulc} = f\,(T_{Mold},\ V_{cure}, V_{inj},\ V_{Sc},\ P_{Stau},\ T_{cyl})$$

In case that the T_{mold} is a constant as well as the compound (V_{cure}) vulcanization time depends on four [4 !] factors.

The difficulty is, to determine the vulcanization time which corresponds to the mold temperature

$$t_{vulc} = f\,(T_{Mold},\ V_{inj},\ T_{cmpd})$$

with $T_{cmpd} = f\,(V_{Sc},\ P_{Stau},\ T_{cyl})$

Fig. 3: Regression Equations to describe the injection Molding Process

equilibrium swelling for example and correlated to part performance criteria like compression set, spring constant and any other property. A fractional factorial design with the above mentioned four factors allows the evaluation of the operating window for a given compound and it dependency on compound and mold temperature. Nine experiments are needed if no replicas are taken into account. While the independent factors are linear correlated with the the responses, the vulcanization time is not independent (temperature time relation of vulcianzation). Therefore the correlation can be expected as none linear. In a fractional factorial design the factors are confounded, but this influence can be neglected. The experiments are done with an NR-compound on a LWB - injection molding machine with 250 to clamping force. This machine has a EFE injection unit. This unit allows to manipulate the compound temperature with the position of a nozzle. The position of the nozzle is directly correlated with the compound temperature. In the experiment the nozzle position is taken a factor synonym for compound temperature. The mold used was a 4 cavity mold. The overlay plot shows the size of the operating window in yellow color, where all properties specified are met [**Figure 4**]. With increase of the compound temperature – respective the nozzle position: half closed and then almost closed – the operating window becomes smaller and finely disappears. The optimum process settings can now be identified based on the knowledge of process repeat-ability including process variations and compound batch to batch variations.

Conclusions

The compounding window can be identified with a fractional factorial DoE in nine steps. A precondition is the knowledge of the influence of the plastification conditions on compound temperature, the repeat-ability of the machine and the batch to batch variations. This experimental procedure is needed to every compound. The starting point – in other words the lower limits of all factors has to be evaluated in a separate experiment.

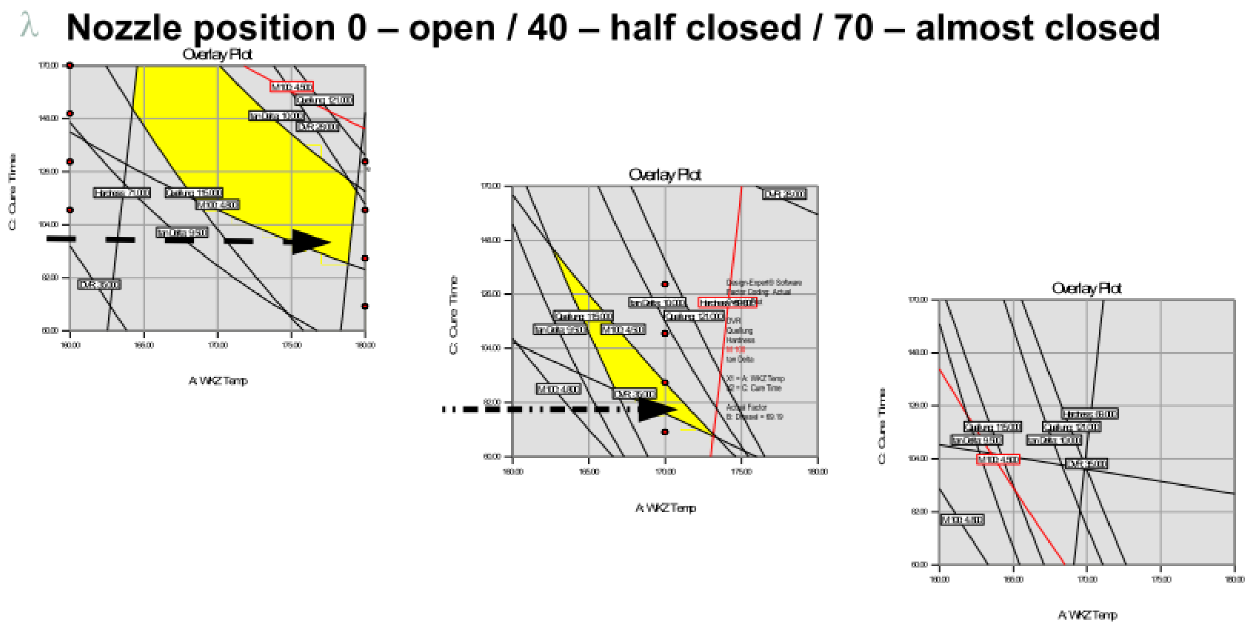

Fig. 4: Resulting Operating Window for a NR-75°ShA Compound at Different Compound Temperatures (Injection Unit: LWB-EFE) through differetn Nozzle Positions as indicated in the drawing.

Literature:

(1) JD Colbert, GP Byam, Applying Science to Processing – Profitability PartI : Injection Molding, Paper presented at the 111. RDofACS Meeting, May 3-6, 1977, Chikago, IL, USA
(2) JD Byam, RD Souffie, KD Ziegel, The Route to lower Processing Costs, European Rubber Journal, Nov. 1981, page 27 – 32
(3) RF Karg, CE Boozer, RE Benefield, Injection Molding of Elastomers, Rubber World, July 1987, page 14 - 23
(4) RJ Del Vechio, Understanding Design of Experiments, Hanser Publishers, 1997 Munich
(5) WM Putera, Dependency of Network Homogeneity on the Process Parameters of Injection Molding of Elastomers, University of Allied Sciences Darmstadt, Germany, Thesis 2007 (GE)
(6) HJ Graf, Determination of the Shortest Possible Vulcanization Time in Rubber Injection Molding, Paper presented at Rubber Molding Asia, 2014, Bangkok, Thailand
(7) DE Hertz JR, Theory and Practice of Vulcanization, Elastomerics, November 1984
(8) T Lochner, Influence of Different Injection Units on the Properties of Molded Parts from Rubber Compounds,University of Applied Science Würzburg/Schweinfurt, Thesis 2014 (GE)