Simulation
of the rubber injection moulding process
Real time or offline - A comparison

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DKT 2018
Nürnberg, July, 5th 2018

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Contents

- Some basic about mechanical properties (quality) of rubber parts and curing rubber
- Offline simulation programs
- Hybrid simulation systems
  - Offline preparation
  - Online results
- Process control by online simulation

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For each type of Simulation

- Main target
- Boundary conditions for the calculation
- Input values
- Variations
- Results

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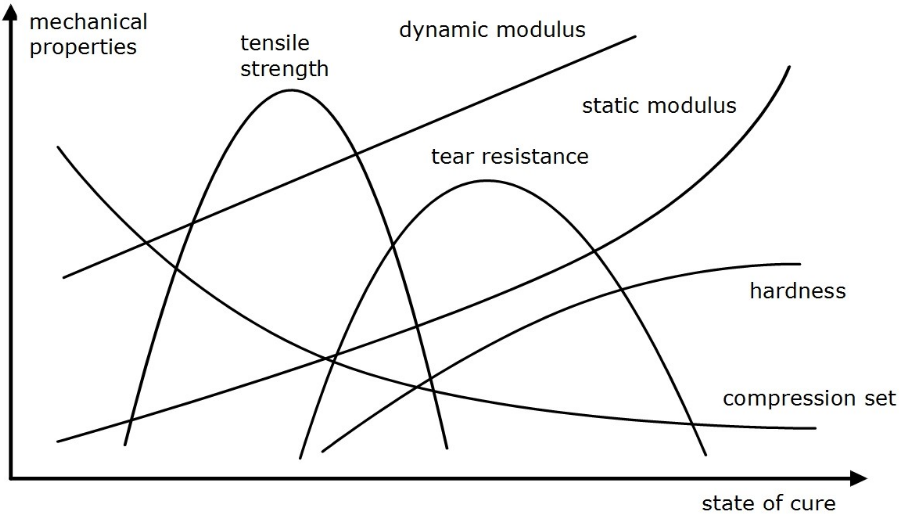
Mechanical Properties by State of Cure



The first goal of production is always to produce parts in required quality.

All the mechanical properties change with state of cure, but in very different ways.

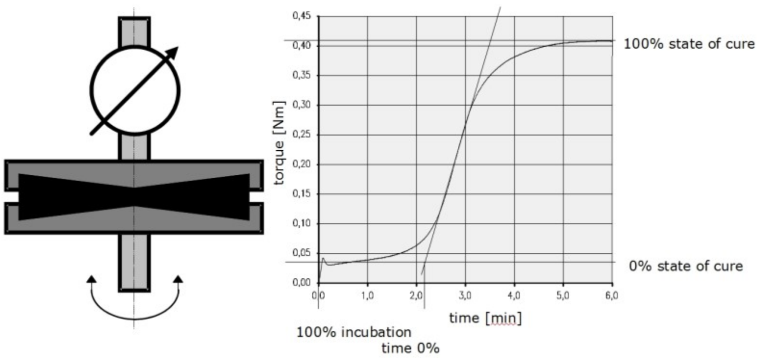
For this reason the mechanical parts quality remains constant in production, when state of cure - or better said, the distribution of state of cure - in the moulding is kept constant.

So systems have been developed, which calculate the curing at the machine by more or less reduced simulation.

But before introducing to those systems, lets have a closer look to curing and influences at the real production.

These dependencies are caused by the fact that the state of cure is not measured by chemical methods, but defined by a mechanical instrument (rheometer).

State of Cure
Principle of Measurement and Definition



The development of state of cure at a nearly constant temperature as a function of time is measured in a rheometer.

For this purpose, a small amount of rubber is pressed and cured in the heated chamber. The lower half of the chamber makes slightly oscillating movements (e.g. 1° deflection). The torque which is required to apply this oscillations is measured and plotted as a function of time (right curve).

The first region, in which the rheometer curve runs nearly horizontally is called incubation phase.

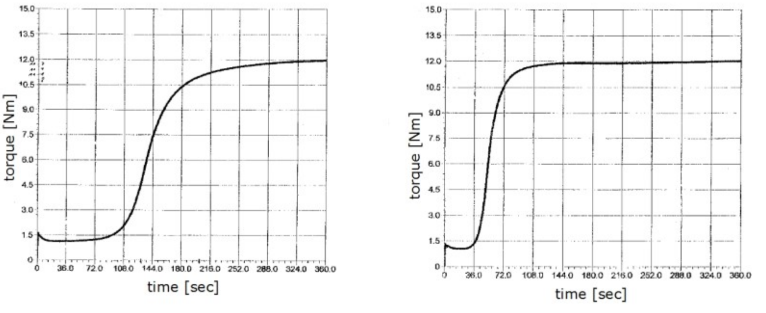
Crosslinking starts after incubation time, when the curve rises.
The last area in which the rheometer curve is horizontal again, called plateau. In this area, all components of the compound, which can form a cross linking, have found each other.

First, the incubation phase runs from 100% (new material) to 0%. After incubation time having come to %0, Cross-linking increases from 0% to 100% (plateau).

Since the measurement in the rheometer is a dynamic torque test, the linear relationship between state of cure and dynamic modulus (previous slide) is quite understandable. Both measurement methods are similar.

The following slides show, which influences act on state of cure and thus to the production goal "quality parts".

Speed of Cure and Temperature



T1 T1 < T2 T2

The comparison of two rheometer curves shows the temperature dependence of cure rate.

At higher temperature, everything goes much faster.

How serious this effect is, can be recognized by a very rough calculation of compound developers:

If temperature is 10 °C higher, the incubation period is about 35 % shorter and curing is about 65 % faster.

For compounds with peroxidic crosslinking systems, this temperature sensitivity is still much more distinctive.

The important factors influencing state of cure are therefore the temperature and the time during which the compound stays in that temperature.

But this is not only mould temperature. It is a temperature development from feeding the material to the screw to the moulded and cooled part. A online simulation should take this into account.

Since the temperature dependency is different for each compound, these characteristics must be taken into account by the evaluation of rheometer curves at different temperatures.

Summary:
Influences to Mouldings Properties

- Mechanical properties depend on state of cure.
- Cure speed depends on temperature.
- Cure speed changes from batch to batch.
- When only minimum values for mechanical properties have to be fulfilled, this can be achieved by an uneconomical long cure time.
- If tear resistance or tensile strength is important for quality or with reverting compounds (NR), this strategy is not successful.

Mechanical properties and thus product quality depend on state of cure.

Cure speed depends on temperature. But due to mould open times, mould cleaning, metering conditions etc. temperature deviation can only be reduced to a certain degree and never eliminated.

Cure speed changes from batch to batch and batch deviations can be up to +/-15% in cure speed.

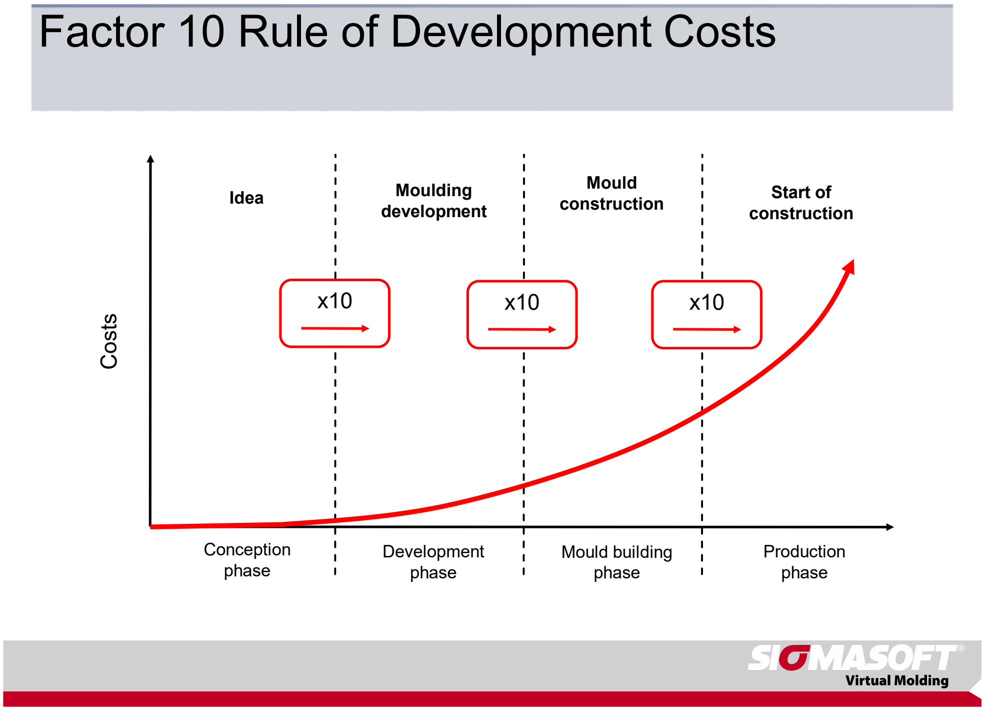
When only minimum values for mechanical properties have to be fulfilled, this can be achieved by an uneconomical long cure time. This long cure time has to take in account the come together of slowest batch, lowest temperatures and lowest viscosity.

If tear resistance or tensile strength is important for quality or with reverting compounds (NR), this strategy is not successful.

Offline simulations
Main Target

- Main target: Mould design
  - Saving Costs by detecting an eliminating production problems before building the mould
  - Optimizing the position of welding lines
  - Optimizing the position of vent pipes to avoide trapped air
  - Analysis for choosing the optimal runner system
  - …

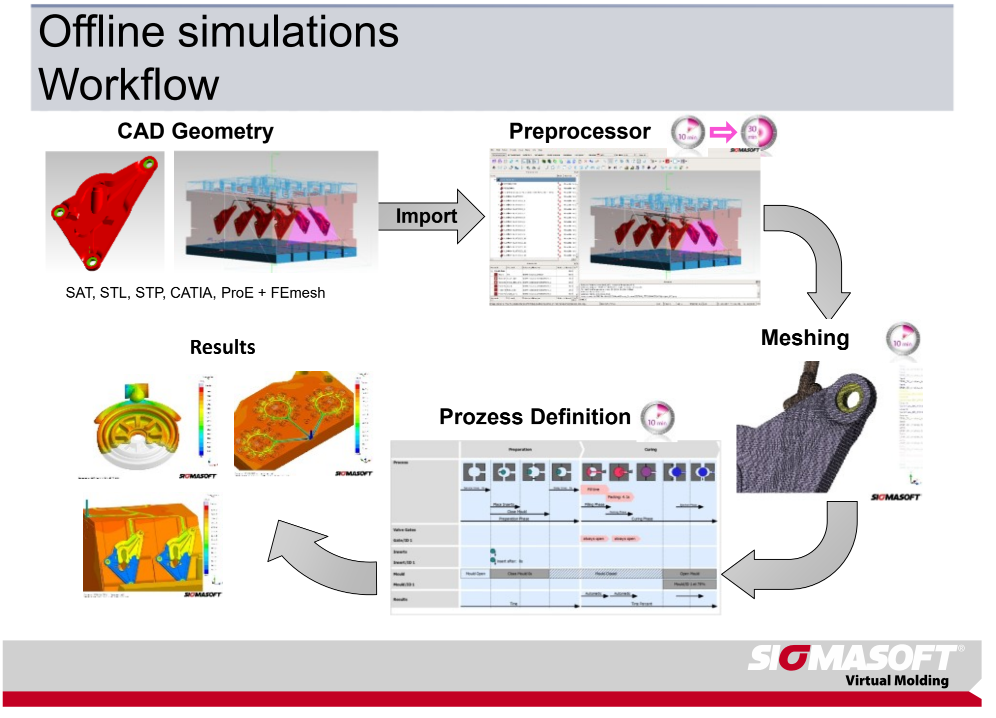
After this basics about curing rubber we start introducing three types of calculations, simulating the rubber injection moulding process.



The development from the idea for a rubber part to the running production can be separated in four phases.

For each step from phase to phase the costs for changes or eliminating errors or problems are rising by factor 10.

So it is advisable to analyse the whole process from the idea to the running production as early as possible.



This slide shows the workflow, using a offline simulation program.

The mouldings **geometry** is imported by file from typical CAD programs, used for mould construction. This import is done for the hot runner and the cold runner too.

A pre-processor program is used to convert the imported geometry to a meshed network, holding a lot of elements. Each element holds information of material (empty, injected rubber, inlay) and the state of the material (temperature, lost incubation time and degree of cross linking).

Material behaviour (Viscosity by temperature and shear rate, thermal data (density, heat capacity, thermal conductivity) and cure speed by temperature and time) is taken from a data base.

Injection speed and cure time is input by the **process definition**. Mould temperature, temperature of (pre-heated) inlays, temperature of the cold runner block have to be input as well as the temperature of the rubber in the injection pot.

Results show the development of mould filling, temperature development of the injected material and based on this, the development of state of cure.

Mould filling also shows the location of weld lines. The location of trapped air helps to find the best location for vent pipes.

Additional results are the required injection pressure and the required clamping force.

A full loop over all steps, shown at the slide, is used to optimize the location of the gate to the mould and vent pipes.

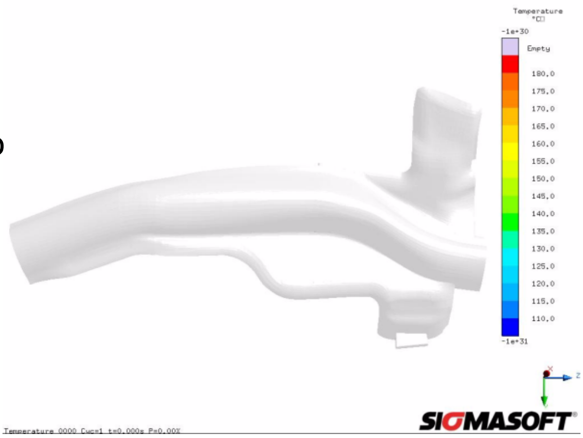
A small loop, over “process definition” and “results” only, can be used to estimate the stability of the production cycle and, if necessary, to improve it by making changes.

Only after these optimizations, the mould will be built.

Offline simulations
Example: Start Condition (1)

Results:

- Unbalanced filling
- High pressure onto right insert
  → starts to move
- Bad weld line position
- Significant trapped air



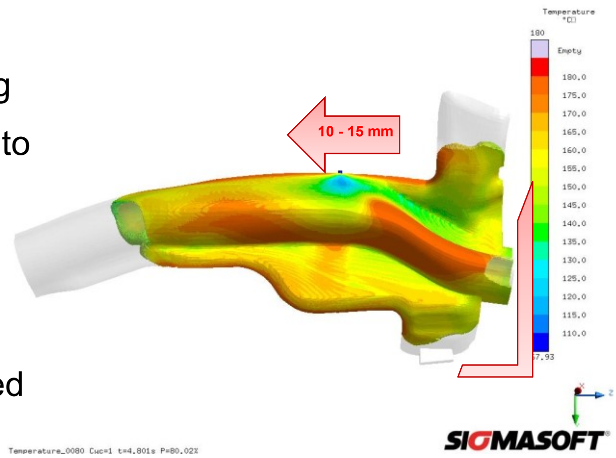
Virtual Molding

This animated slide shows the first simulated filling of the mould directly after the first mould design.

Offline simulations
Example: Start Condition (2)

Results:

- Unbalanced filling
- High pressure onto right insert
  → starts to move
- Bad weld line position
- Significant trapped air



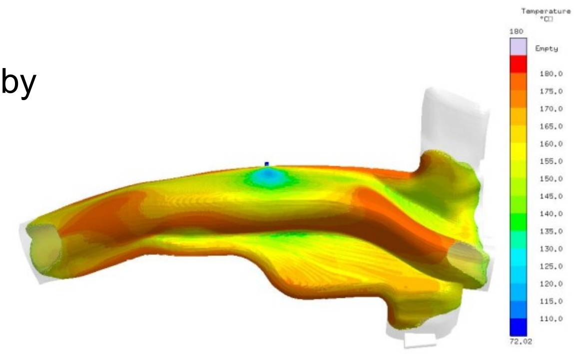
SIGMASOFT Virtual Molding

The mould design can be optimized by changing the position of the gate to the moulding and the position of the vent pipes.

Offline simulations
Example: Optimized Mould Design

Result:

- Gained know-how by doing changes to optimize mould
- Balanced filling
- Uniform load onto inserts
- Less trapped air
- Weld line moved into uncritical area



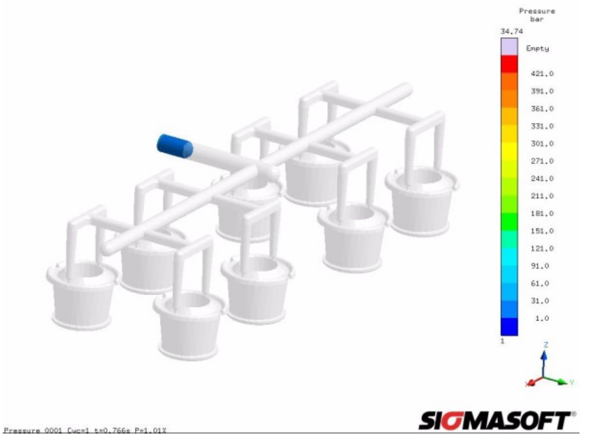
SIGMASOFT Virtual Molding

This slide shows the optimized and nearly filled mould.

All optimizations have been done by simulation. After simulation and building the mould, ideally no or only little corrections of the mould are necessary when starting production.

Offline simulations
Choosing a runner system (Herring bone)

- **-** naturally unbalanced
- **+** small tool size
- **+** lower tool costs
- **-** Bad influence onto part quality
- **-** limited up-scaling to a higher number of cavities



SIGMASOFT Virtual Molding

Offline simulation programs are also useful to compare different types of hot runners or cold runners.

This animated slide shows the filling of a hot runner with herring bone structure.

Different pipe length to the cavities result in different pressure drop and thus unbalanced filling.

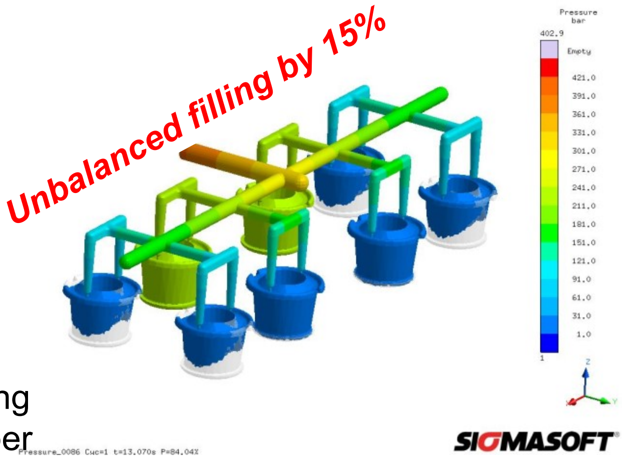
But the small number and length of pipes result in small size and low costs.

Wide variations in quality can be estimated, due to different filling time.

These problems are getting bigger by the number of cavities.

Offline simulations
Choosing a runner system (Herring bone)

- **-** naturally unbalanced
- **+** small tool size
- **+** lower tool costs
- **-** Bad influence onto part quality
- **-** limited up-scaling to a higher number of cavities



SIGMASOFT® Virtual Molding

This slide shows the result of the simulation, shortly before the mould is completely filled.

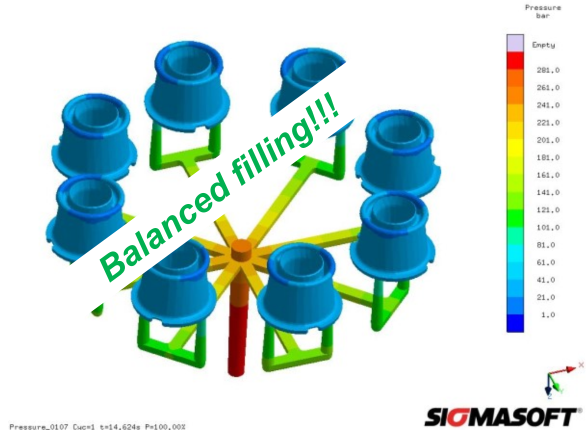
Offline simulations
Choosing a runner system (H-Branching)

- **+** naturally balanced
- **-** larger tool size
- **-** higher tool costs
- **-** good influence onto part quality
- **-** no limits in up-scaling to a higher number of cavities

A runner system with H-branching structure is very much better for a balanced filling, but due to different redirection of the material, a little unbalanced filling remains.

Offline simulations
Choosing a runner system (Radial Star)

- **+** naturally balanced
- medium tool size
- medium tool costs
- **-** good influence onto part quality
- **-** limited in up-scaling to a higher number of cavities



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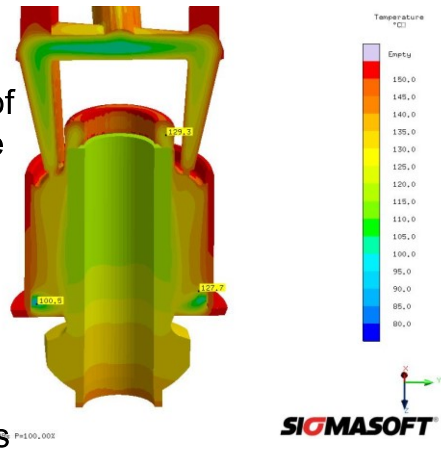
A runner system with radial star structure combines short pipes and a minimized number of branches and redirections.

So a fully balanced filling can be achieved.

Offline simulations
Some additional Benefits

- Transparency to influence of (pre-heated) inlays
- Transparency to distribution of temperature and state of cure
- Hints for setting up the machine
- Estimated cure time and basics for machine selection as input values to pre-production calculation of parts costs



SIGMASOFT Virtual Molding

Processing simulations with variations of input values gives transparency over the injection moulding process.

Offline simulations
Limitations

- Material data are assumed values, but will change from batch to batch
- Process values are assumed values, but these change in real production
- The start condition of the material in the injection pot (temperature and state of cure) is assumed and may change, due to viscosity and metering conditions

But result ranges can be determined with extreme values for the influencing variables mentioned above.

The accuracy of the calculation depends on the accuracy of the input values. This is only theoretical, mostly average description of flow behaviour (changing viscosity by temperature and shear rate (injection speed))

The real rubber injection moulding process will differ because of batch deviation in viscosity and cure speed and deviations in process values (temperature and injection pressure) too.

By simulations over a range of input values, the stability and the limits of the injection moulding process can be analysed.

These limitations are the reason for the development of systems that calculate and control the degree of crosslinking online at the production.

Arguments for online simulations to control cure time

- Material has deviations from batch to batch in viscosity
- Material has deviations from batch to batch in cure speed
- Process values are changing in real production
  - Temperatures of mould, cold runner and injection unit
  - Injection speed
  - Injection pressure
  - Screw speed and metering time

Without cure time controlling, there are variations in quality and cure time at the machine has to be setup for lowest viscosity, slowest curing and lowest temperatures. That uneconomical.

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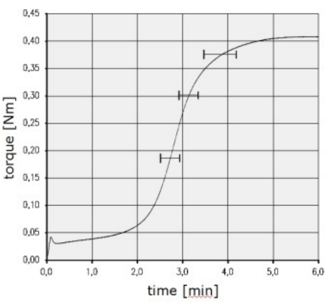
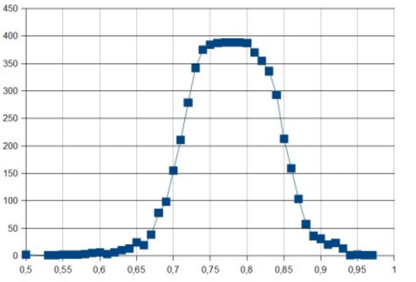
Online Simulation
Batch Deviation





t_{30} (5655 batches)

A rubber compounds are produced in batches. This means that by the smallest errors in

- weighing the individual components,
- fluctuations in the components of the compound (natural rubber, carbon black) and
- fluctuations in the mixing process

each batch has slightly different properties.

To detect these variations and to detect major deviations in time, a rheometer curve is measured from each batch. Only batches that are within a certain tolerances are released for production.

In the left rheometer curve tolerances are exemplary shown.

The diagram on the right shows the result of an evaluation of 5655 batches (NR compound). This are not calculated values. The values are but raw data from the curves (t_{30}).

All (except of 2) batches are within +/- 3 δ (standard deviation) and have been used for production. But +/- 3 δ is +/- 15% here.

So a system, compensating batch deviations can reduce cure time by 15% as an average.

This also shows how much optimization of the quality (uniform degree of crosslinking) and with optimization of economic production (reduction of safety margins in the heating time) are connected.

Batch Compensation makes sense only with online simulations.

Hybrid simulation packages
Offline Simulation – Online Curetime Control

- Development of cure time controllers started more than three decades ago
  - Simulation of the rubber injection moulding process was not too much simpler than today, but computers were less powerful. So long execution times have to be accepted.
  - Machine controllers were even simpler and less powerful too. Unable to compute the rubber injection moulding process in real time.
  - So Hybrid systems have been developed, which calculate complex simulations offline as described above. The results a used as a base for much more simpler calculations at the machine control

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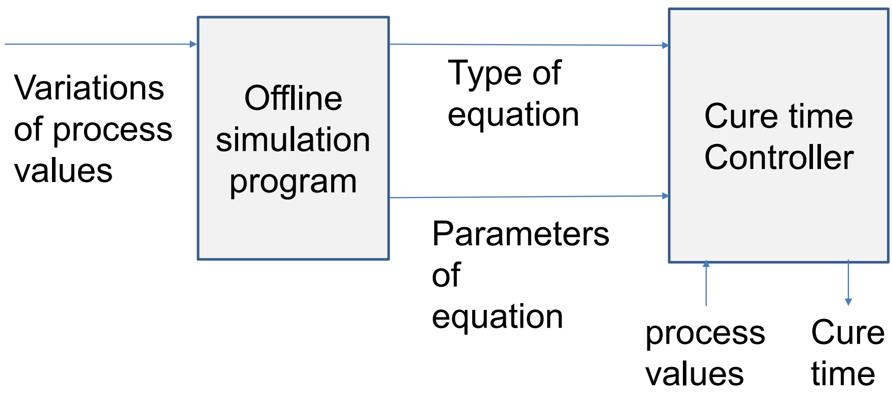
Hybrid simulation packages
Functional Block Diagramm



Hybrid systems consist of two parts

The machine control holds a set of equations which describes the variations in the rubber injection moulding process. Because this formulas is very simple, the machine control can compute it before starting a cycle and make some adjusting at the end of injection phase

A simplified offline simulation program gets the input data and does automatically variations to compute the parameters of the equation. These parameters are transferred from the offline simulation program to the machine control.

Hybrid simulation packages
Benefits

- Most important process values are taken in account.
- Using such systems for cure time control is better than doing nothing to compensate changes in viscosity (measured by injection pressure) and tempertures of mould, cold runner block and injection unit.

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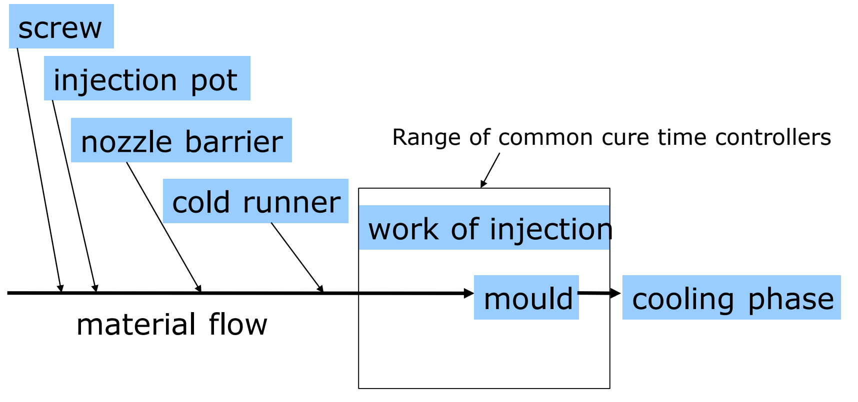
Hybrid simulation packages
Limitations

- Due to simplified simulation and online calculations:
  - Only most important process values are taken in account.
  - Start temperature of the material in the injection pot is assumed and changes, due to changing metering conditions and delay times can't be taken into account.
  - No transparency

This limitations were the reason to develop a process optimization system, simulating the changes in the material (temperature and state of cure) from feeding to the screw to the demoulded and cooled part.

Online Simulation
Batch Deviation

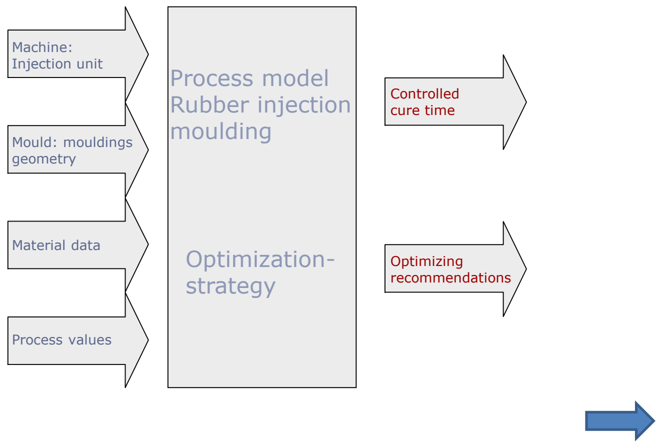


With microprocessors getting stronger, the company CAS developed a Process Optimization System that uses simulation to calculate the injection moulding process in real time, while the production cycle is running.

It takes into account everything what happens to the material from feeding to the screw to the demoulded and cooled product.

This slide shows for comparison, the range of conventional cure time controllers and the whole amount of computation of the CAS Process Optimization System.

Online Simulation
Input and Output Data



The CAS process optimization system uses a process model, which calculates the development of the compounds temperature and cure from feeding to the screw to the cooled moulding.

Data is required for this calculation process.

The description of the injection unit is required to calculate how much material stays in the injection unit and how it is stressed (warmed up) by friction (metering and injection) or heat transfer from screw cylinder or injection cylinder.

The part geometry is needed to calculate the temperature development in the moulding.

The actual process variables (measured temperatures, injection pressure, screw speed, …) are taken online from the machine control.

The system always works with the loaded current batch data.

All calculations are done online in real time.

When the desired state of cure has been reached, a signal for termination of the cure time is given to the machine control.

A cycle log is generated at the end of the cycle for optimization of the process and for documentation too.

Online Simulation Machine Data

- Type of injection unit
- Screws geometry
  - Diameter of screw
  - Number of screw zones
  - For each screw zone
    - lenght
    - channel height at beginnig and end of zone
    - screws modulus
    - thickness of screw flight
- Diameter of injection pot
- Pressure amplification factor
- Length and inner diameter of nozzle barrier

The description of the injection unit is needed for the calculation of material flow through the machine and for conversion of friction work (metering, injection) into temperature changes.

The material flow inside the machine is calculated as an online real time simulation of reality.

At all locations where material stays or moves in the machine, the state of the material and it’s changes (volumetric, thermal, reaction kinetics) is calculated. By this calculations, the residence times of the material are taken into account, even if the time changes due to different shot weight, different cycle time or downtimes.

The machine data also include the conversion factors for the measurement of all process variables.

All the data, describing the injection unit come from the machine manufacturers and are input to the system only once while setting up.

Online Simulation
Mould Data

- Mouldings data
  - Geometry (plate, rectangle, cuboid, cylinder)
  - Type of heat transfer for each surface
- Cold runners geometry
- Set point values
  - Set point for state cure
  - Adjusting values for temperatures
- Tolerances

Mould data is the description of mould and cold runner. Set point values for the distribution for state of cure, adjusting values for temperatures and tolerances belong to mould data too.

Heat transfer from the mould to the moulding and inside the moulding is made by the finite difference method. The moulding is geometrically described simply by four basic geometry types.

Due to the selected geometry type, there are 2 to 6 surfaces. For each of these surfaces, one of three measured mould temperatures (clamp side, injection side, intermediate plate) can be selected with or without insert.

The heating up characteristics of inserts is determined in advance by an experiment, in which the temperature of the insert at the time, the mould is closed and the temperature of the insert some time later is measured.

The description of the cold runners geometry is shown at the next slide.

Online Simulation
Cold Runner Geometry

- Assuming a full balanced cold runner system
- For each runner section on one path from machines nozzle to cold runner nozzle:
  - length of tube
  - diameter of tube
  - inner diameter (needle valve section)
  - percentage of mass flow through the tube

The description of the cold runner is required for several reasons:

- The volume of the cold runner has an influence on the residence time of the material in the process.
- The geometry of the tubes has an influence on the temperature history during the time the material stays at the cold runner.
- The branches, are described by the flow rate factor, and the geometry of the tubes has an impact on pressure loss, and thus on heating up the material in injection phase.

Online Simulation
Compound Data (only once per Recipe)

- Caloric Data
  - density
  - heat capacity
  - thermal diffusivity
- rheological Compound Data
  - viscosity at a certain temperature
  - flow exponent to calculate viscosity in relation to material flow
  - flow activation energy to calculate viscosity in relation to temperature
- Cure characteristic
  - Evaluation of three rheometer curves at three different temperatures

The compound data is determined once per recipe.

The caloric data is used for the calculation of heat transfer and for calculating the conversion of mechanical work (injection, metering) to temperature changes.

The rheological compound data is required for the calculation of pressure losses in screw, nozzle and cold runner.

Since the calculations of the process model is calibrated by measured process variables, it is allowed to work very well with empirical values for the caloric and rheological data. This data is stored as a function of polymer type (NR, EPDM, ...), filler, hardness Shore A and density at the CAS Material Data Program LAB, supplied with the CAS Process Optimization System.

The cure characteristic needed to calculate the rising state of cure in dependency of the changing temperature.

The determination of reaction kinetical data is done by evaluating three (minimum 2, maximum 5) rheometer curves at three different temperatures with the CAS Material Data Program.

Online Simulation
Batch Data

- Evaluation of the usual batch curve measured by a rheometer
- Data transferred automatically from the rheometer computer to the CAS material data program and automatically evaluation of the batch curve.

- ➔ No additional efforts necessary for batch evaluation.

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Online Simulation
Interface to Machine Control

Input from machine control

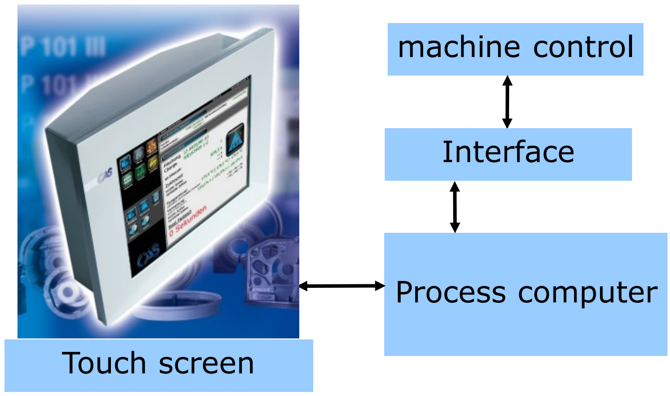
- stroke position
- injection pressure (hydraulic)
- screw speed
- temperatures
  - screw cylinder
  - injection pot
  - cold runner block
  - Up to 4 mould temperatures (clamp side, center plate, injection side, changing plate)
- “mould is closed”

Output to machine control

- “stop cure time”

All values are measured online continuously in the current cycle and are used for the real time calculations.

Online Simulation
Block Diagram Process Optimization System



The CAS optimization system as a retrofit kit can be connected to any (older) injection molding machine. A data acquisition unit is the interface between machine control and process computer. Entering the machine data is done during setting up by CAS.

It is operated via a touch screen and a simple, intuitive user interface iCure.

By integrating the system into the local area network, an easy data transfer is guaranteed. In addition, this integration allows the remote control of the system.

OEM Versions are available at DESMA (Propter and Propter light) and Maplan (Cure^2 and Cure^1)

Online Simulation
Workflow

- Input all mould data (mouldings geometry, adjusting values for temperatures, …).
- Load batch data from data base.
- Run cycles with different cure time as usual.
- Wait for feed back from the quality department.
- ==> Choose set values for distribution of state of cure.
- Switch on controlling cure time.

Working with the system is easy.

After entering the mouldings geometry and possibly the cold runners geometry, the correction values for the mould temperatures (difference between temperature, measured at the sensor and temperature measured with a hand-held thermometer at the surface of the mould) batch data has to be loaded from the data base. With this data the system is ready for use and calculates the evolution of the materials state from feeding to the screw to the cooled moulding. This calculations are always done. No matter if controlling cure time is switched on or off.

Now the machine setter runs cycles with different cure time as usual. Each cycle is documented by the system automatically. The set values for state of cure can be read from this cycle reports, after feed back of the quality department, having checked the mouldings.

After input of these values for state of cure, controlling cure time can be switched on. From now on, the system controls state of cure and thus the mouldings quality.

Slower batches, lower temperatures and lower injection pressure lead to longer cure times. Faster batches, higher temperatures and higher injection pressure results in a faster cure times. But mouldings quality is controlled by state of cure.

As a result the safety margins in cure time can be reduced. An average cure time reduction of 10% to 20% can be achieved by controlling state of cure and taking into account batch deviations and variations of process values.

Online Simulation
Restrictions and Expectations

- Simpler modelling to be processed in real time.
- Inaccuracy due to rougher calculations can be compensated by measured process values.
- Targets are not exact values.
  Target is a value, that corresponds to state of cure (Quality) and to hold this value constant.
- Compensation of fluctuations in process values
- Compensation of batch deviations

A simpler modelling is necessary, because all calculations have to be processed while the production cycle is running.

This results mainly in a rougher description of the moulding. Finite Differences an used instead of Finite Elements. All elements have larger dimensions and the same type of geometry.

The Inaccuracy, due to this simplifications will be compensated by measured process values. E.g. calculated pressure loss is adjusted by measured injection pressure.

The main target of online simulation is process control. The result is giving signals to the injection moulding machine to hold state of cure, that corresponds to mechanical properties (quality) constant. To accomplish this goal, these simplifications are allowed.

On the other hand, online simulation offers new advantages:

Because all calculations are done, while the production cycle is running, all fluctuations in process values (temperatures, injection speed, injection pressure, screw speed, metering time, …) can be taken in account.

Batch deviations in viscosity is taken in account by measured injection pressure. Batch deviations in cure speed is taken in account by bringing the evaluation of the batch test to the machine.

Online Simulation
Additional Benefits

- Simulation gives transparency and is thus gaining process knowledge.
- This transparency is internally used to offer recommendations to optimize the machine settings.
- Depending on
  - Mouldings geometry (thick or thin)
  - Shot volume, cold runner volume, size of injection unit
  - Type of curing system (regular, reverting, peroxidic)

  The “right” recommendations for machine settings are offered to reach same state of cure in shorter cycle time.

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Thank you for your attention

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I thank you for your attention.

And I have to thank Tobias Mansfeld from Sigmasoft and Dr. Wolfgang Kroener from CAS for their help, making this presentation.