Evaluation and modelling of chemical segregation effects for Thixoforming processing

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Abstract:

Aachen University of Technology, Germany investigates intensively on Thixoforming. This work is supported by Deutsche Forschungsgemeinschaft (DFG) within a collaborative research center. Thixocasting and -forging are modern "soft forming" processes in which semi solid slurries -comparable to the stiffness of "butter"- can be formed at substantially lower pressure and temperature than used for conventional forming processes. The process gains an increasing interest. The automotive industry is focused on process technologies which combines complex parts with improved mechanical properties. A significant potential of energy- and costs-savings can be expected.

Although the process basics were already developed in 1972 by MIT (Massachusetts Institute of Technology, Cambridge) the required improvement of process stability and the introduction of suitable quality management systems are still to be enhanced. The technology is applied especially for near net shape forming of complex structures with good mechanical properties.

This paper evaluates macro-segregation using computer modelling tools. Macro-segregation takes place at the forming step of Thixoforming and is defect, because the component quality can be reduced. Due to this macro-segregation simulation was developed and confirmed by metallurgical tests.

The chemical segregation is calculated for a prototype component by means of a diphasic model for the liquid and solid phase of the slurry. The calculation is confirmed by chemical analysis of prototype components and Thixoforming defects can be minimized.

1 Introduction

Thixoforming is an innovative process for semi-solid alloys, which have to be shaped into complex geometries resulting in improved mechanical properties. The near net shape processing leads to a significant reduced number of process steps. Especially automobile companies, demanding numerous components with high quality, are strongly interested in this technology. Components with high-quality mechanical properties can be manufactured. Using Thixoforming technology new applications for commercial alloys are expected. It opens new perspectives for processing critical alloys by conventional casting and forging /Kiehne00/. Although the process fundamentals have been investigated in 1972 by the Massachusetts Institute of Technology in Cambridge (MIT), a strong demand on semi-sold processing know-how exists still today. In order to improve the component quality and process stability an intense study of defect avoidance is needed.

The different departments of the collaborative research centre in Aachen, are focusing on raw material development /Noll02, Noll00-1/, Thixoforming processing by Casting and Forging, Determination of typical Thixoforming defects (e.g. chemical segregation), quantifying the influence on mechanical properties /Noll01/ and development of recycling strategies /Noll00-2/.

The aim of this investigation is to determine the driving force for chemical segregation during the process in the semi-solid state. The results are used to define the optimal process parameters. Chemical segregation was made predictable and a practical guidelines was developed in order to reduce the influence of detrimental effects on the component quality.

2 Driving forces for chemical segregation for Thixoforming - Overview

Segregation of alloy components usually takes place during solidification. Differences in chemical composition in dimension of a grain size ($\leq$ 100µm) are called micro-segregation. Chemical segregation in expanded regions ($\geq$ 100µm) is called macro-segregation, which can affect the component quality quite negatively.

Macro-segregation in cast components may be initiated by /Engh92/:

(1) different solute content of solid and liquid phase, combined with

(2) separation of solid and liquid phase.

A difference in the solubility of an element in the liquid and the solid phase is the normal situation during solidification. The segregation between solid and liquid phase can essentially be induced due to:

- temperatures gradients
- concentration gradients
- thermal contractions
- convection in the bulk melt caused by temperature or concentration gradients, thermal contraction, or by electromagnetic stirring.

The compression of the slurry has an additional effect on the phase composition /Sommer01/, which has special importance for thixoforming.

Two different process routes for Thixoforming, which fundamentally vary from each other in temperature control are established /Noll02/. Segregation in the semi-solid state can be associated to the traditional process, which is defined by three process steps: raw material production, reheating into the semi-solid state and forming (see **Tab. 1**).

Process step	Segregation phenomenon thesis
Raw material production (solid feedstock) by continuous casting	inhomogeneous micro structure and distribution of grain size due to inverse segregation (1).
inductive reheating of a billet into the semi solid condition	temperature differences at surface and core areas of the billet, e.g. “edge overheating“(2), may lead to billet-bleeding, metal loss and decreased alloy content.
Forming / Casting	a.) flow behaviour of inhomogeneous slurry, leads to segregation of suspensions, especially occurring at different cross-section areas, due to varying properties of solid and liquid fraction (3). b.) tools- and component geometry, leads to different cooling conditions e.g. effected by gating system and tool geometry (4)

Tab. 1: Important effects on segregation phenomena in the semi-solid state for different thixoforming process steps

In order to discuss possible effects for segregation phenomena and to give new impulses on thixoforming development the SFB 289 (collaborative research centre in Aachen has formed a task group.

Raw materials can fundamentally be described by chemical composition and micro-structure. Differences of grain size distribution between surface and centre was be proven in commercial Thixoforming ingot material (A356), whose structure is grain refined by magneto-hydraulic dynamic stirring (MHD) /Noll01/. A separation of different grain sizes by “stream classification” is known from processing technology. /Kelly95/. During the moulding at semi-solid condition a similar sorting process can be expected, if particles of the primary phase are dissociated due to the flow of the eutectic phase. Different chemical compositions in solid phase and liquid matrix during the Thixoforming caused by this sorting process must lead to chemical enrichment of such phases in critical component areas. This type of segregation is already predestinated in the raw material production step.

Also during the inductive reheating process step the grain size distribution in the solid phase is affected. A growth is favoured thermodynamically for larger particles (explanation 2). This must increase the inhomogenity of the micro structure in the billet. Therefore attention has to be paid to the melting of initial silicon crystals of the eutectic phase. Remaining crystals would otherwise influence the flow properties and lead to process difficulties.

Even if the influence of the mixture of solid and liquid in the raw material and the distribution of grain sizes is neglected (explanation 3), a relative movement between solid particles and liquid phase can occur. If the deformation velocity is low, the liquid phase is pressed out between solid particles even before the mixture is flowing homogeneously. This mostly takes place at the beginning of the shaping process right before the network structure of dendrites is broken /Neudenberger01/. If the deformation velocity is high, the flow condition of the slurry becomes turbulent and a tendency of porosity defects exists.

Comparable to manufacturing of conventional casting components, a segregation process is caused by the different cooling velocities in several areas of the component during the forming process (explanation 4). A description of this process is complicated, because equilibrium will never be reached due to high technical cooling velocity. Today a forecast of segregation by using thermodynamic calculations is only possible with certain compromises. An interaction of the influences is expectable as well. Due to this, practical tests have to be done in order to determine the significant segregation mechanism.

3 Forming tests of a prototype component

The overview of segregation thesis for Thixoforming indicates that the complete process chain from ingot material to the finished component has to be considered carefully. Today a detection of individual segregation effects is not possible. An integral consideration, which allows the comparison of calculated simulation and experimentally observed effects, is striven.

The following experimental investigation is realized by forming tests using the conventional three step process of Thixoforming. The solid feedstock, continuously casted and grain refined by MHD, is warmed up with an inductive heater in vertical position into the semi solid state and subsequently formed by Thixocasting.

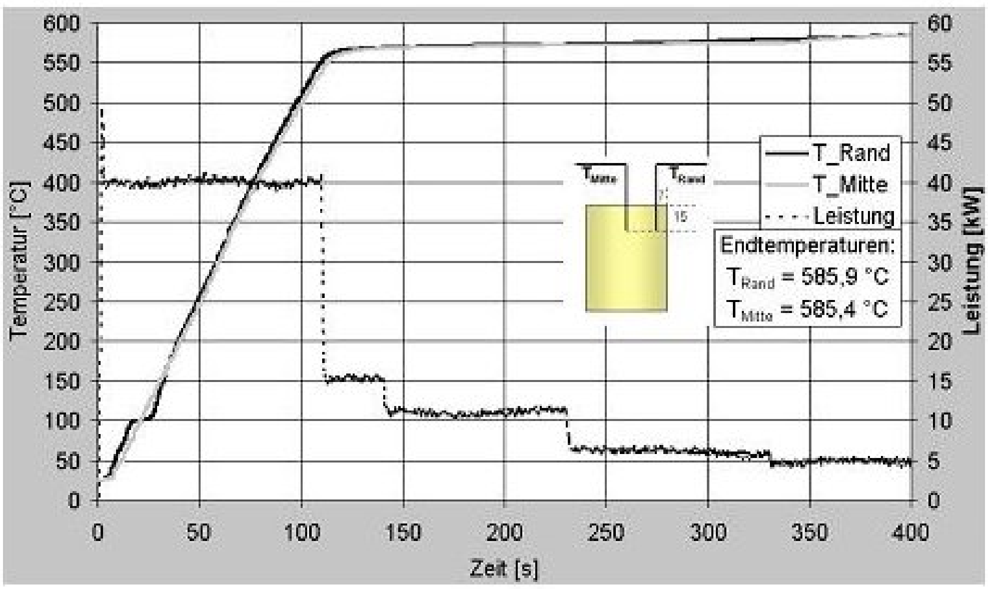
The test material is a commercial A356 (AlSi7Mg0.3) ingot with 3“-diameter. The reheating of the 180 mm high billets (weight 2,22 kg) is realised by using a power-time program (energy input per billet = 6089 kJ = 1,69 kWh). The metal loss by bleeding is in average 190 g (8,6 % of input raw material weight) at a temperature of 585 °C ± 1 °C (see **Picture 1**).

A chemical analysis of reheated billets indicated a chemical homogeneous raw material. The average content of silicon in the raw material was decreased approximately to 1% due to metal loss. In consequence the average content of silicon in the reheated billet was nearly 6%.

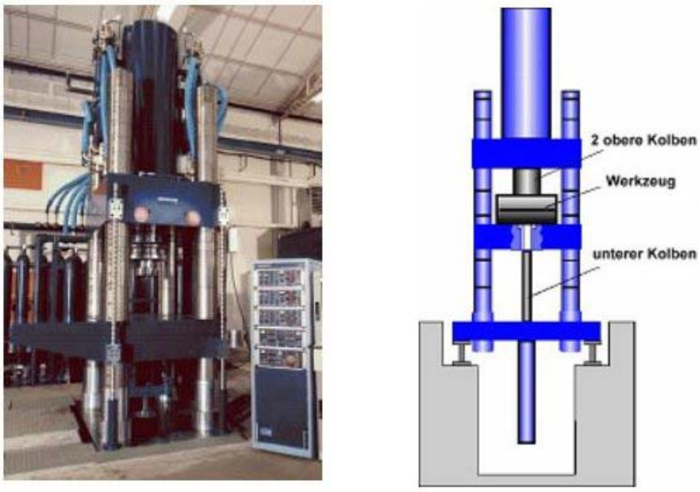
The forming tests are realised by means of a vertical servo-hydraulic press (see **Picture 2**). The press disposes three adjustable pistons to:

- bring up the clamping force of the tool (upper ring piston),
- press the billet (lower piston), and
- form the component (upper middle piston).

Against the usual practise a vertical billet position was chosen for this tests in order to prevent the deformation of the reheated billet. This takes place in horizontal casting chambers, if the ratio of height / diameter is not process conform.



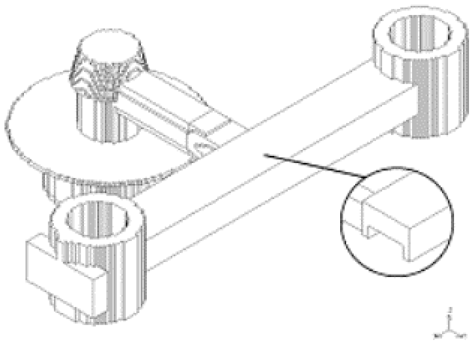
Picture 1: Inductive billet heating procedure (ingot material A356 (MHD); 2,2kg; dT~5 °K/s)



	F_{max}	v_{max}
upper ring piston	4.000 kN	0,8 m/s
upper middle piston	2.000 kN	0,8 m/s
lower piston	1.000 kN	3,0 m/s

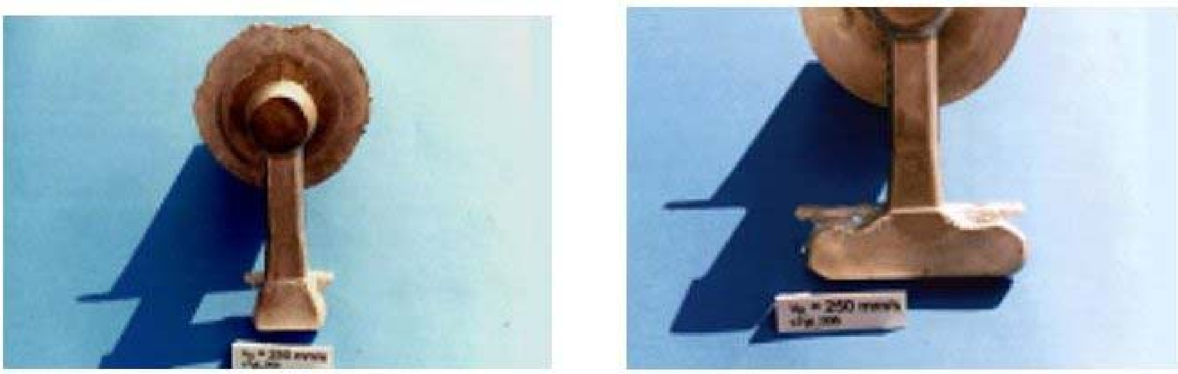
Picture 2: Servo-hydraulic press of the EFU GmbH

A prototype component is chosen for forming tests (see **Picture 3**). The component is a C-profile (length 350 mm x width 40 mm X height 15 mm, cross-section = 480 mm²). The gating system is located at the centre of the component.

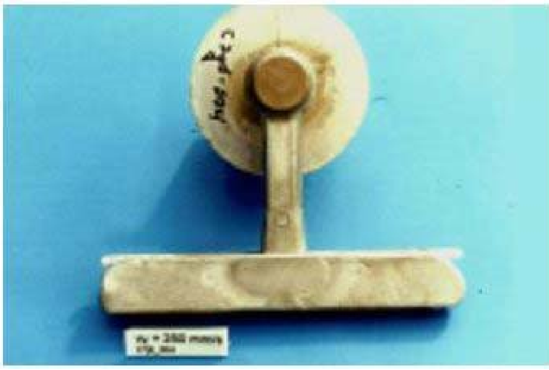


Picture 3: Prototype component for Thixoforming tests

Step shot tests were accomplished at a constant piston velocity of the caster (volume flow = 1385 cm³/s) in order to investigate the flow behaviour and possible segregation phenomena. The used tool was preheated at a temperature of T_{Tool} = 200 °C. **Picture 4** shows the manufactured step shot components. A laminar material flow, which prevents the input of oxygen, was maintained.



step1 step 2



step 3 step 4

Picture 4: Step shot samples of the thixoformed prototype component (A356)

Several tests where made subsequently in order to isolate segregation phenomena relating chemical composition and to compare the results with simulated calculations.

4 Diphasic calculation of segregation

The step shot tests were simulated computer aided. By using the conducted calculations the segregation caused by flow phenomena (Tab.1, thesis (3)) has been pre-calculated and areas of individual phase and/or chemical component enrichment have been forecasted.

4.1 Establishment of a diphasic model

The entire mobility of each particle and the particle interaction in liquid phase have been calculated for a flow simulation of a dual phase mixture. This leads to a high expenditure of computing time. In order to reduce calculation time both phases of the alloy are calculated separately. The liquid phase is described as a Newtonian viscosity fluid and the solid one as a pseudofluid./Mod01/. The conservation of momentum equations have to be solved for both phases to simulate the forming process. Impulse exchange between solid and liquid are described by using Darcy's law:

$$f_l \left(\underline{v}_l - \underline{v}_s \right) = -\frac{k_p}{\eta_l} \nabla p \qquad \text{(Equ. 4.1)}$$

f_l is the quantity of liquid phase, v_l is the vector of velocity of the liquid phase and v_s of the solid phase. k_p is the permeability of the solid phase and p the isotropic pressure. The permeability can be described by the capillary model of Carman-Kozeny:

$$k_p = \frac{f_l^3 \cdot d_p^2}{72\mu \left(1 - f_l\right)^2} \qquad \text{(Equ. 4.2)}$$

μ is determined by experimental data and varies between 2 and 2.5. d_p is the medium particle diameter of the solid phase. The viscosity of the semi-solid alloy η_b is calculated by superposition of the viscosity of liquid phase η_l and the pseudofluid η_s:

$$\eta_b = \eta_l + \eta_s \qquad \text{(Equ. 4.3)}$$

η_b has to be determined by rheometer tests. The relationship of tension and deformation of the agglomerated particle network is described by the viscosity η_s. In the simulation the viscosity of solid phase is described by:

$$\eta_s = \left(\frac{S_0(f_s)}{\dot{\gamma}_s} + k(f_s) \cdot \dot{\gamma}_s^{m-1} \right) \cdot \kappa \qquad \text{(Equ. 4.4)}$$

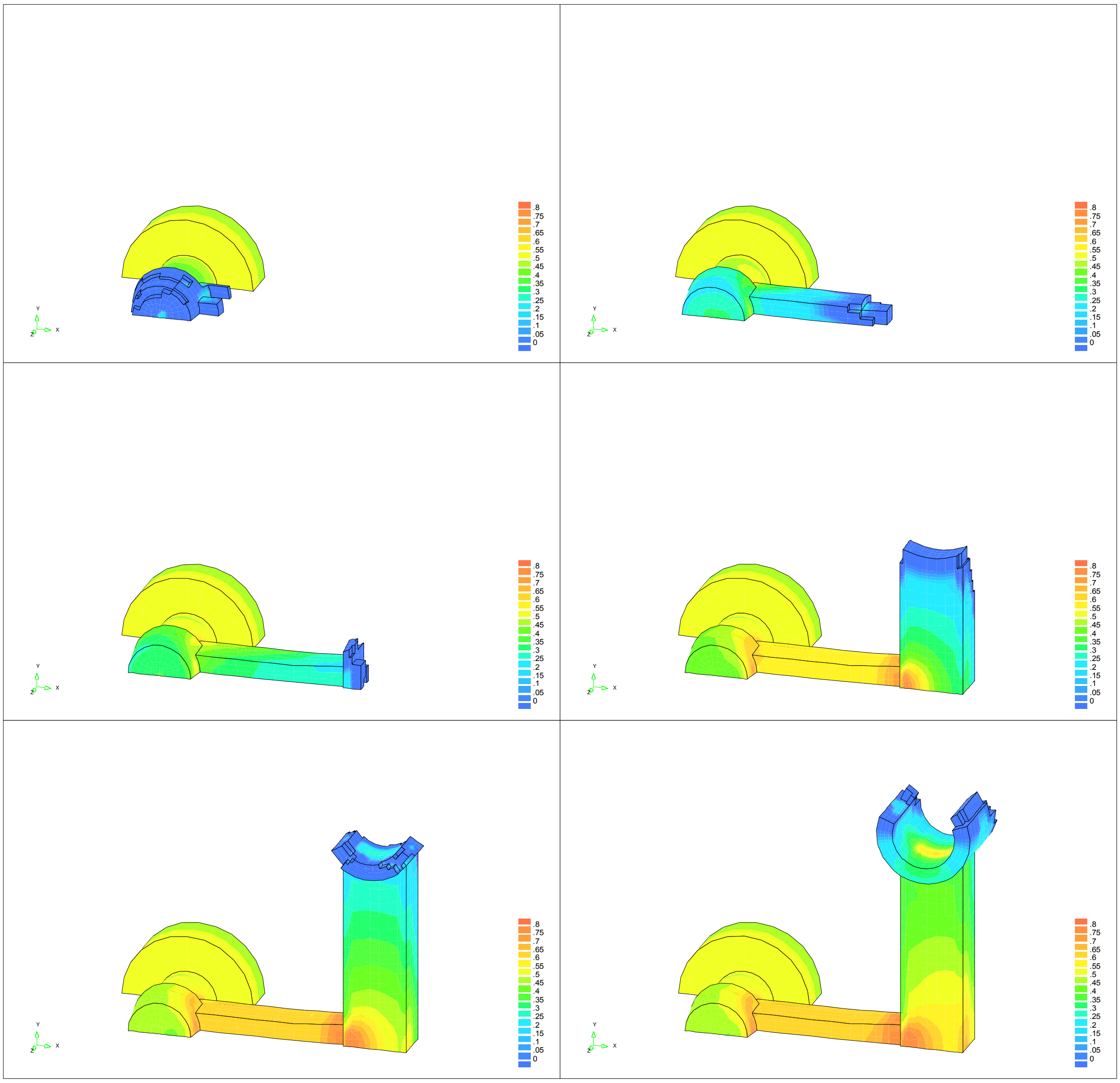
$S_0(f_s)$ is the yield stress, $k(f_s)$ is the strain rate and m is a flow exponent. $\dot{\gamma}$ is the rate of shearing. All parameters have to be determined by rheometer tests /Mod99/. The time rate of change of the structure parameter κ is described by a equitation:

$$\frac{D\kappa}{Dt} = c(\dot{\gamma}_s) \cdot \left(\kappa_e(\dot{\gamma}_s) - \kappa\right) \qquad \text{(Equ. 4.5)}$$

The structure parameter κ describes the agglomeration of solid phase, its value varies between 0 and 1. A value of 1 is corresponding to complete agglomeration, and 0 is total distribution of particles. At the beginning of the simulation a complete agglomeration by the particles is estimated ($\kappa = 1$). κ_e is the equilibrium structure parameter, adjusted at a certain rate of shearing and the variable c describes the speed of achieving this parameter. These variables have to be determined by rheometer experiments as well. The model describes the disphasic structure in first approximation. However, the influence of the distribution of grain size remains unconsidered so far. Also a fitting with structure characteristics shape factor, contiguity etc. is still to be done.

4.2 Results of the diphasic simulation

The model was implemented into a flow simulation program, developed by Petera at the technical university of Lodz (Poland). By using this (CFD-) software the step shot of a prototype component was simulated. A solid phase content of 50% was set as starting value. **Picture 5** shows the simulation of the segregation at a piston velocity of 250 mm/s. An increased solid fraction content corresponds qualitatively to a decreased alloy content of silicon and vice versa. These results fit very well with experimental results of forming tests, which indicate a low rate of solid phase at the front of the slurry while form filling. This can be explained by using thesis (3), which includes the compression of the particle network of the billet at the beginning of the step shot. In consequence this results in bleeding of liquid metal and is corresponding with an increased solid fraction in the remaining gating area.

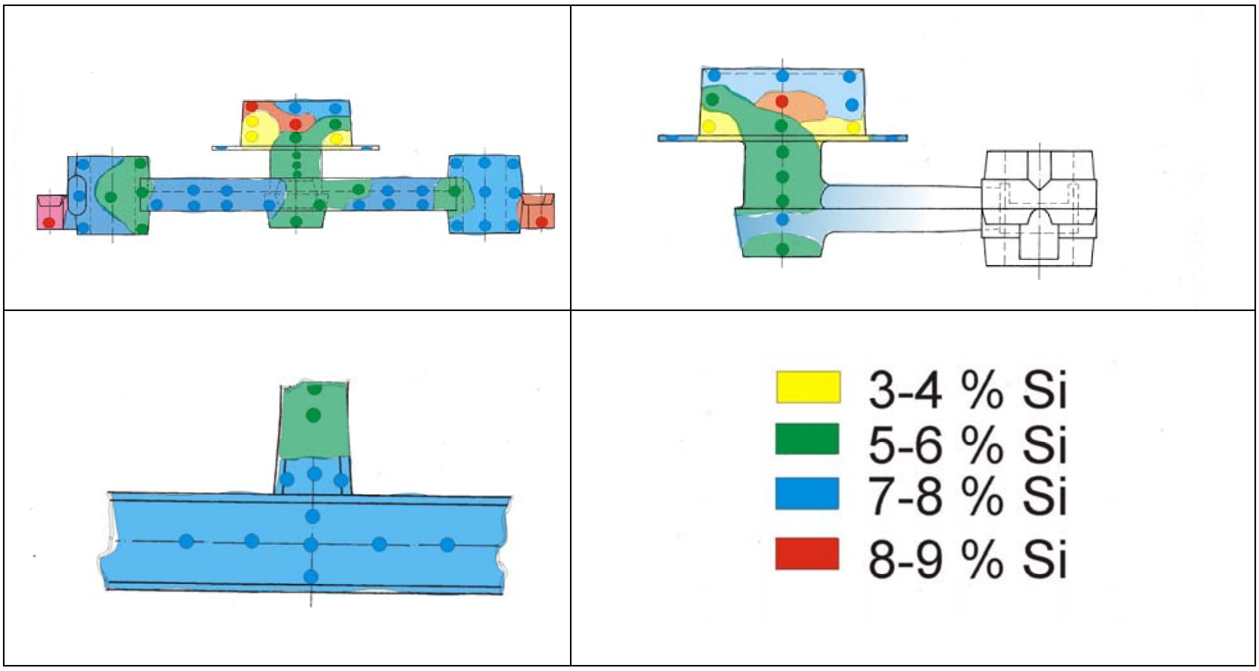


Picture 5: Simulation of segregation during the step shot process. Piston speed 250 mm/s.

The amount of solid phase increases from blue to red; corresponding with high silicon content (blue, ~7 - 9 mass. % Si) / low silicon content (red, ~3 - 6 mass. % Si), (compare with **Picture 6**)

5 Chemical analysis and evaluation of the diphasic model

Drilling chip samples of the component were investigated regarding their chemical homogeneity. By means of ICP (inductive coupled plasma) technique results of the evaluation are fitted with the simulation. **Picture 6** shows the silicon content distribution of the component.



Picture 6: silicon content distribution of the component after step-shot tests (Spots: samples for ICP-analysis)

The results of the simulation can qualitatively be proven by the chemical investigation. The silicon content in the component and the calculated content of elements are nearly identical. A high silicon content is corresponding with low solid fraction and vice versa. This indicates, that the optimal process parameter settings defined by e.g. ingot quality, raw material temperature, phase content, tool temperature, tool coating, gating system, forming velocity and clock time have to be investigated more exactly in order to prevent segregation.

6 Summary

Metallurgical effects, which lead to segregation during the shaping process at semi-solid condition are identified in this study. The segregation leads to inhomogeneity of Thixoforming components and will affect the quality.

The computer simulation of a prototype filling process fits with the results of chemical analysis tests. An increased silicon content corresponds with an increased liquid fraction. This segregation is forecastable by diphasic simulation.

In future an adaptation of established raw material characteristics e.g. grain size distribution, shape factor of the dendrites, contiguity and morphology of the eutectic phase has to be implemented.

7 Acknowledgments

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