Simulation of distortion and residual stress in high pressure die casting – modelling and experiments

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Abstract. Two individual high-pressure die-casting geometries were developed in order to study the influence of process parameters and different alloys on the distortion behaviour of castings. These geometries were a stress lattice and a V-shaped sample tending to form residual stress due to different wall thickness respectively by a deliberate massive gating system. In the experimental castings the influence of the most important process parameters such as die temperature and die opening time and the cooling regime was examined. The time evolution of process temperatures was measured using thermal imaging. The heat transfer coefficients were adapted to the observed temperature distributions. Castings were produced from the two alloys AlSi12 and AlSi10MnMg. The distortion of the castings was measured by means of a tactile measuring device. For the alloy AlSi10MnMg thermo-physical and thermo-mechanical data were obtained using differential scanning calorimetry, laser flash technique, dilatometry and tensile testing at elevated temperatures. These data were used for modelling the material behaviour of the AlSi10MnMg alloy in the numerical model while for the alloy AlSi12(Fe) literature data were used. Process and stress simulation were conducted using the commercial FEM software ANSYS Workbench. A survey on the results of the comparison between simulation and experiment is given for both alloys.

1 Introduction

Increasing computing power of modern hardware systems opens new possibilities of simulating complex phenomena in the casting process as well as the overall simulation of the casting process. While the simulation of filling and solidification can be considered as state of the art, in numerical process simulation, the simulation of residual stresses and distortion needs to be improved in order to make more accurate predictions. This is due to a number of reasons; these include a lack of accurate input data for numerical simulation or still difficult to handle mechanical contact problems. A model approximating real casting conditions has to be chosen carefully in order to make accurate predictions. In this work trial castings with reproducible distortion behaviour were designed and produced in high-pressure die-casting (HPDC); the distortion of the final products were measured by tactile methods.

Thermo-physical and thermo-mechanical material properties were measured over a wide temperature range for the aluminium alloy AlSi10MnMg. Simulation models considering the process parameters and the material behaviour were developed.

These simulation models only contain parameters which were measured directly or were derived from measurements and are perfectly free from fit parameters without any physical meaning. The

results of the simulations are compared to the distortion of the trial castings. A critical review of the model assumptions used in this work and a short preview on research tasks to further improve the experimental design and the simulation techniques are given.

2 Theory of stress prediction in casting processes

Stress simulation in casting processes is a highly complex problem consisting of several tasks. The correct prediction of temperature and solidification, as well as an accurate material model is the basis to simulate stress and distortion. These phenomena are induced by shrinkage constraints in the mould as well as the geometry of the casting part including the gating system. The thermal, mechanical and material models are not independent but can show strong interaction.

Temperature T as a function of time t is calculated by the solution of the heat transfer equation

$$\frac{\partial}{\partial t}\left(\rho c_p T\right) = \nabla \cdot \left(\lambda \nabla T\right) + \Delta h_f\left(\frac{\partial f_s}{\partial T}\right)\left(\frac{\partial T}{\partial t}\right) \tag{1}$$

where ρ is density, c_p is heat capacity, λ is thermal conductivity, Δh_f is latent heat of fusion and f_s is solid fraction [1, 2].

As thermal strains are calculated from the thermal model, every stress and distortion simulation can be only as accurate as the calculated temperature distribution. The mechanical model describes the evolution of thermal (and mechanical) strains due to thermal (and mechanical) forces. The components of the total strain $\vec{\varepsilon}^{tot}$ are described by *Eq.(2)*, the relation between thermal stress and thermal strain is given by *Eq.(3)*,

$$d\vec{\varepsilon}^{tot} = d\vec{\varepsilon}^{el} + d\vec{\varepsilon}^{(visco-)plas} + d\vec{\varepsilon}^{th} + d\vec{\varepsilon}^{E(T),\nu(T)} \text{, and} \tag{2}$$

$$d\sigma = (\vec{D}^{el} - \vec{D}^{plas})\left(d\vec{\varepsilon}^{tot} - d\vec{\varepsilon}^{th}\right) - d\sigma_0, \tag{3}$$

where $d\vec{\varepsilon}^{el}$, $d\vec{\varepsilon}^{(visco-)plas}$, and $d\vec{\varepsilon}^{th}$ are elastic, (visco-)plastic, and thermal components of strain. The component $d\vec{\varepsilon}^{E(T),\nu(T)}$ is caused by the temperature dependence of Young's Modulus and the Poisson ratio. In *Eq.(3)* stress σ and strain are connected via the stiffness and plasticity matrix $\vec{D}^{el}, \vec{D}^{plas}$; σ_0 is a virtual component that takes into account the temperature dependency of the yield stress in the work hardening model [1].

3 Experimental

The geometry of the stress lattice and the V-shape for the trail castings were designed using a commercial numerical casting simulation tool (MAGMAsoft) in order to optimize filling, solidification and the evolution of reproducible distortion before machining the high-pressure die-casting tool. The stress lattice consists of a thick middle bar and two thin side bars which are connected by two beams perpendicular to them. The V-shape consists of a thin-walled symmetric lid and an arbitrarily massive gating system, in order to induce well measurable distortion in the lid. Because of the different cooling rates due to differences in wall thickness between certain casting areas (stress lattice) or between casting and gating (V-shape), the geometry is deformed plastically which leads to residual stress and global distortion of the casting part. Photographs of a stress lattice and a V-shaped Lid are shown in figure 1.
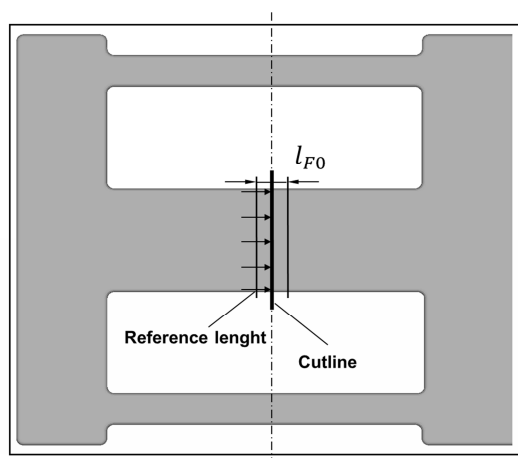
All experimental castings where performed using a commercial HPDC-machine (Bühler SC D/53, 530 kN closing force). In a series of experimental castings the die temperature, the closing time (the time between the injection of the melt and the ejection of the casting) of the die and the cooling regime of the sample after ejection (water quenching or natural convection) were varied systematically. Two alloys AlSi12(Fe) and AlSi10MnMg were used in order to compare results for different alloys. A list of the selected parameters is given in Table 1. The process parameters were measured and logged for the use in process modelling.

Figure 1. Stress lattice (left) and V-shaped (right) casting produced by high-pressure die-casting.

Table 1. List of varied parameters in experimental castings

Alloy	Die temperature [°C]	Stress lattice		V-shape	
		Closing time 20 sec.	Closing time 30 sec.	Closing time 5 sec.	Closing time 8 sec.
AlSi10nMg	160	x		x	x
	180	x		x	x
	200	x			
	230	x	x		
	260	x	x		
	140	x			
AlSi12(Fe)	160	x		x	x
	180	x		x	x
	200	x		x	x
	230	x	x		
	260	x			

Figure 2. Evaluation of the distortion of a stress lattice by cutting of the middle bar.

Both the tool and the casting temperatures were obtained by thermal imaging using an infrared camera system (FLIR ThermaCam E45). The cooling curves of the castings (after applying a thin graphite layer in order to achieve an emmitance close to one) were measured by an infrared camera system (FLIR ThermaCam A320). The temperatures of the castings at the time of ejection were obtained by extrapolation using a polynomial fit function.

After cooling of each individual casting to ambient temperature its distortion was measured. A sketch of the stress lattice is given in figure 2. Global distortion of the stress lattice was measured by comparing the differences of a defined reference length l_{F0} before and after cutting the middle bar of the stress lattice. The residual stress was obtained by applying a simple elastic material behaviour according to Hooke's law. A similar stress lattice produced in sand casting was analysed by Fendt [3].

In figure 3 a sketch of a V-shaped lid is shown. Global distortion was evaluated by determining the distance between two selected points of the geometry. The procedure of the evaluation can be described as follows: The distance a_0 is the distance of the reference points at the die at room temperature. The distance a_1 is the distance of the same reference points at the casting at room temperature. As T_{die} is the die temperature set by the oil tempering system and T_a is room temperature, the distance of the reference points in the die at the time of ejection is given by:

$$a_{die,ej} = a_0 \cdot [1 + (T_{die} - T_a) \cdot \alpha_{die}], \tag{4}$$

where α_{die} is the coefficient of thermal expansion the die material. As the casting shrinks to the die during cooling and the distance of the reference points of the casting $a_{cast,ej}$ is equal to the distance of the reference points in the die $a_{die,ej}$. As T_{cast} is the temperature of the casting at the time of ejection and α_{cast} is the coefficient of thermal expansion the casting material, the shrinkage of the casting Δl_{cast} can be calculated by:

$$\Delta l_{cast} = (T_{cast} - T_a) \cdot \alpha_{cast}. \tag{5}$$

The elongation of the distance between the reference points Δa_{0-1} is the global distortion of the geometry caused by the residual stress and can be calculated be *Eq. 6*

$$\Delta a_{0-1} = a_1 \cdot (1 + \Delta l_{cast}) - a_{die,ej}. \tag{6}$$
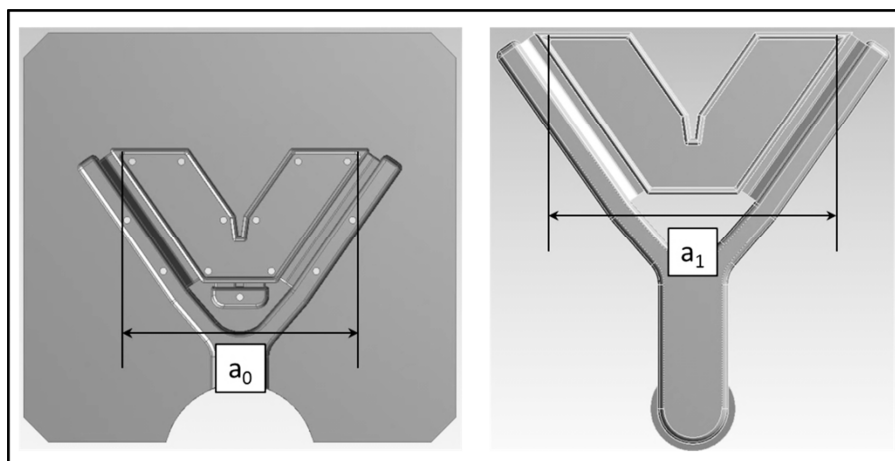
Figure 3. Evaluation of the elongation of a V-shaped bowl

Figure 4 shows a sketch of the V-shape before and after cutting the casting system. The elastic recovery of the lid is calculated by *Eq 7*:

$$\Delta a_{ela} = a_1 - a_2. \tag{7}$$

The quality of numerical simulation depends strongly on the accuracy of the input data. For the alloy AlSi12(Fe) existing literature data were judged to be sufficient. The alloy AlSi10MnMg had to be fully characterized by thermo-physical and thermo-mechanical measurements using differential-scanning-calorimetry, laser-flash technique, dilatometry and tensile testing at elevated temperatures.
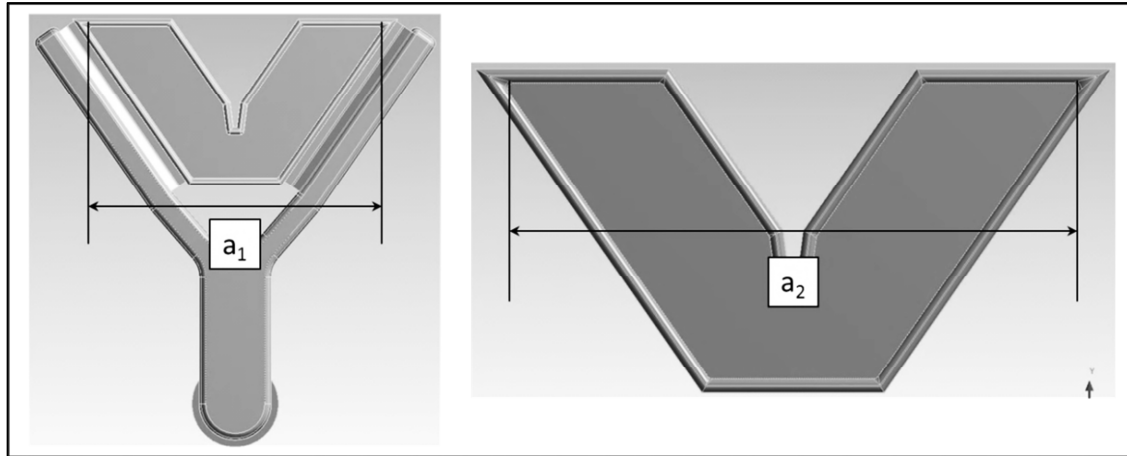

Figure 4. Evaluation of the elastic recovery of a V-shaped lid due to machining.

4 Modelling and Simulation

The transient temperature distribution, the displacement and the thermal stress were simulated with a commercial software package (ANSYS Workbench 11.0 SP1) using an FEM code. Boundary and initial conditions were taken from process data acquired during the production of the castings. The heat transfer coefficients between casting and die as well as between casting and cooling medium were obtained by adjusting the temperature simulation to the results of thermal imaging. The heat transfer coefficient between die and casting as well as the heat transfer coefficient between casting and air were considered to be temperature-dependent. The temperature loss during mould filling and the thermo-mechanical interaction between casting and mould (gap formation) had to be disregarded for the reasons of the complexity and stability of the contact modelling as well as computing power restrictions. As the friction coefficient between die and casting has been unknown the mechanical contact between die and casting was modelled as frictionless contact; there is no shear stress on the contact surfaces. The ejection forces were not taken into account for the same reasons.

The material behaviour was considered to be isotropic and homogeneous over the entire casting. For the plastic material behaviour a work hardening (multilinear-isotropic) model was used. The start of plastic flow was estimated by analysing the stress-strain curves. The plastic flow was considered to start when the stress-strain curves shows a deviation of more than one percent from linear slope. This tends to be more accurate than the yield stress ($R_{p0,2}$) which has no physical meaning. The die was modelled elastically, because plastic stress components in the die are restricted to a very thin surface layer.
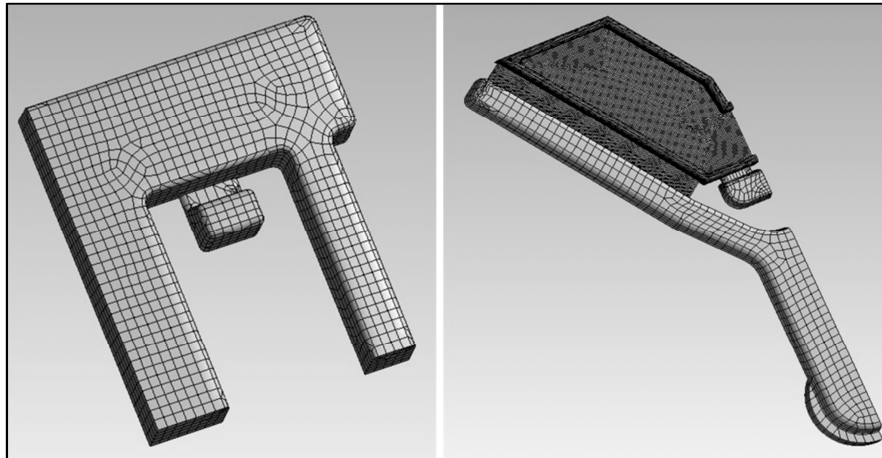
Figure 5. Geometry and enmeshment of the stress lattice (left) and the V-shape (right) for the calculation of the temperature and displacement fields.

The calculated temperature fields were applied as thermal loads in the mechanical simulation. In order to achieve finer enmeshment the stress lattice was cut along its two symmetric planes (neglecting the influence of the gating system, which is very small according to initial simulation results). The V-Shaped lid was cut along the axis of symmetry along the middle of the geometry. Figure 5 shows the meshed geometry of stress lattice and V-shape.

5 Results

Figure 6 shows the comparison between the measured and simulated strain of the stress lattice for different cooling regimes as a function of die temperature for both cast alloys. As the differences in the distortion values for different closing times (due to the low thermal conductivity of the mould material restraining the heat flow) are not significant the results in figure 6 are only shown for a closing time of 20 seconds. However the solidification of the casting is completed within 12 to 15 seconds for the whole range of different die temperatures. Experiments with incomplete solidification of the casting at the time of ejection could not be performed for technical reasons. The strain in air cooled castings shows a minimum at a die temperature of 230° C. This might be due to the relation of the average temperature level of the casting at the time of ejection and the temperature difference between the middle and the side bars. The influence of the cooling regime after ejection is high and leads to strains about twice as high for samples quenched in water than cooled by natural convection to ambient temperature. Comparing the results of AlSi10MnMg and AlSi12(Fe), the sensitivity for distortion is highly influenced by the material properties of the cast alloys. As the AlSi12(Fe)-alloy has a lower thermal expansion and a higher yield stress than the AlSi10MnMg-alloy, the measured and calculated strain values are significantly lower.

Figure 7 shows the comparison between the measured and simulated strain of the V-shaped lid for different closing times as a function of die temperature for both cast alloys. The elongation shows a slight increase according to the temperature of the die and a slight decrease according to the closing time for both alloys. The influence of the cooling regime after ejection (not shown) is smaller than for the stress lattice. The elongation values for both alloys are in the same range. Figure 8 shows the comparison of the elastic recovery of the V-shaped lid for different closing times as a function of die temperature for both cast alloys. For the alloy AlSi12(Fe) there is only little influence for both, the closing time and die temperature in the measurements. For the alloy AlSi10MnMg this influence is higher. The elastic recovery for AlSi10MnMg is higher than for AlSi12(Fe). This might be due to the higher yield stress and the lower temperature at the time of ejection.
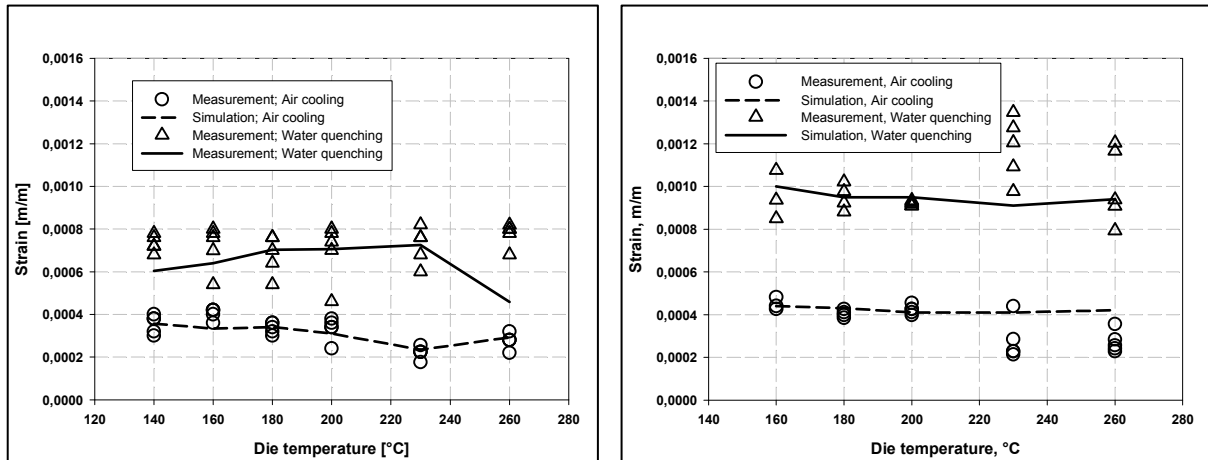
Figure 6. Comparison of measured and calculated elastic strain in the middle bar of a stress lattice cast in HPDC (20 seconds closing time) for the alloys AlSi12(Fe) (left) and AlSi10MnMg (right).
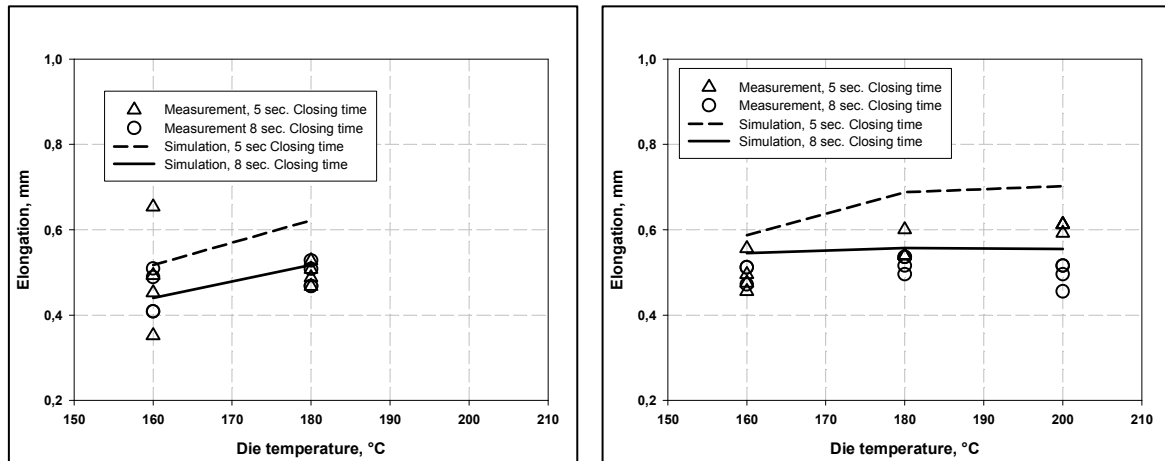
Figure 7. Comparison of measured and calculated elongation of a V-shaped lid at cast in HPDC (air cooled after ejection) for the alloys AlSi12(Fe) (left) and AlSi10MnMg (right).
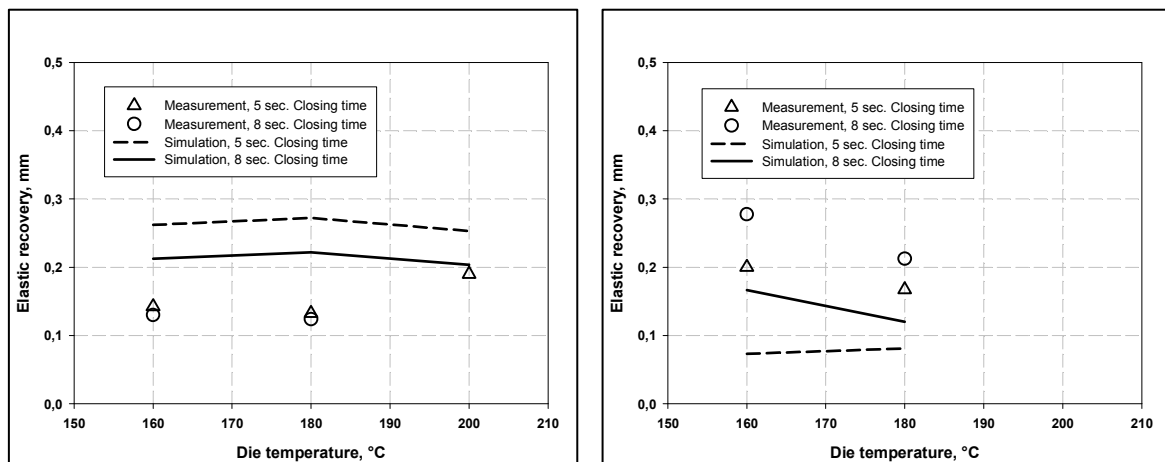
Figure 8. Comparison of measured and calculated elastic recovery of a V-shaped lid at cast in HPDC (air cooled after ejection) for the alloys AlSi12(Fe) (left) and AlSi10MnMg (right).

6 Discussion

The results of the experimental castings show that there are differences between the distortion behaviour of the stress lattice and the V-shape according to the chosen process parameters. The stress lattice is more sensitive to the cooling regime after ejection than the V-shape because of the increase of temperature difference between side and middle bars caused by water quenching. This temperature difference is the most important driving force for the distortion of the stress lattice. As cooling in the die is restricted by the relatively low thermal conductivity of the die material and because of the large thermal mass of the stress lattice, the influence of the die temperature pre-set by the oil tempering system is quite small. The V-shape is more sensitive to the die temperature and the closing time. High die temperatures and short closing times lead to higher temperatures at ejection which lead to higher deformation due to a lower yield stress. An influence of the alloy was obtained for both the stress lattice and the V-shape.

The simulation of the distortion in the stress lattice shows a good agreement between simulation and measurements for all process parameters and for both alloys. The results of the simulation of the elongation for the V-shape show also good agreement with the measurements. The agreement of the simulated and measured elastic recovery is quite poor. The reason seems to be the estimation of the start of plastic flow especially at elevated temperatures. A parameter study showed that a variation of twenty percent in the yield stress in the simulation model leads to an increase of about twenty percent in elastic recovery but only three percent in the elongation before machining. Further investigations are presently carried out to elaborate these phenomena.

Although the simulation of residual stress shows a good agreement with the results from experimental castings further research is needed. This is due to the following reasons:

- all material properties were considered to be homogenous over the entire casting
- mechanical and thermal contact has to be improved
- the mould was not considered to be deformed plastically
- the mechanical material behaviour in the initial solidification range had to be estimated due to the lack of data for that range.

The results of this work can be used for the process simulation of more complex castings. The identification of critical process parameters can help foundrymen for better planning the casting process of castings which tend to the formation of distortion.

Acknowledgement

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