Simulation of a Thixoforging Process of Aluminium Alloys with Flow-3D

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Abstract

Thixoforming allows to produce complex parts with good mechanical properties in a few process steps. When simulating the die filling, the moving upper die as well as the thixotropic properties of the work material have to be considered. The work material is described by a shear rate and shear time dependent viscosity. The die filling of a simple part, calculated with different viscosity parameters, is compared with the experimental results. Within these simulations, the forming forces were calculated and compared with the experimentally measured forces. The simulation is verified with these quantitative data. With a proper choice of the viscosity parameters it is possible to fit the results of the simulation to the reality. When comparing the results of simulation and experiment, it is possible to advise proper values for the thixotropic parameters. Finally, some results found by simulating a serial produced part are discussed. This steering knuckle is a part of the suspension of a sports vehicle. The simulation was used to improve the mold filling in an early stage of the die design.

1 Introduction

Thixoforming is a method of forming technology, where a semi-solid-slug is formed to a near-net-shape part. Thixoforming can be subdivided into thixocasting and thixoforging. Thixocasting is done on slightly modified die casting machines. In this forming variant the inductively reheated and partly molten billet is set into the shot sleeve. The semi solid material is pressed into the closed die by the shot ram (s. Fig. 1).

Thixoforging is done on hydraulic forging presses. The reheated billet is taken into the opened forging die. While closing the die, the work piece is formed. Thixoforging in closed dies can be realized using double action presses. The slurry is taken into the open die. After the die is closed, the work piece is formed by the press piston. On single action presses a closing tool is necessary to perform this forming variant /1/.

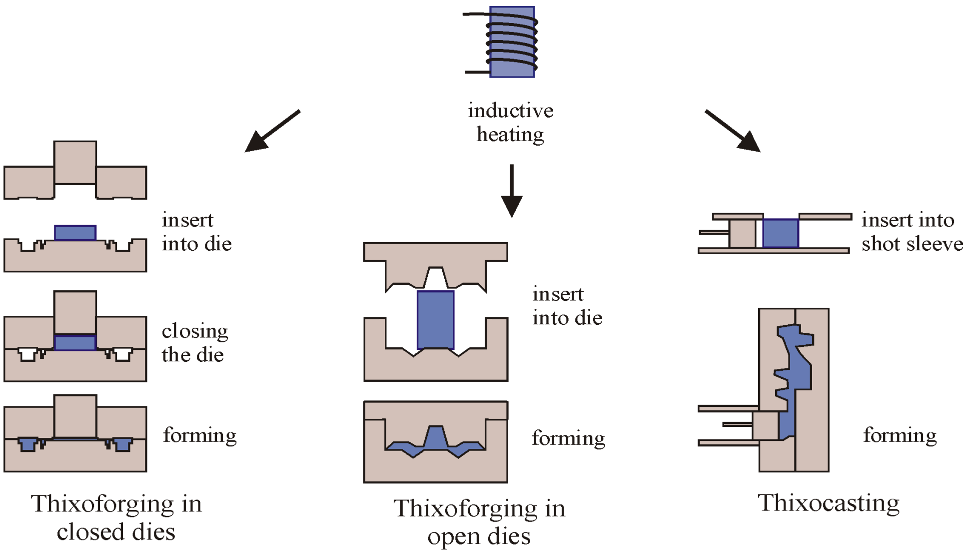

Fig. 1: Thixoforming variants

When thixocasting or thixoforging in closed dies, the filling of the die takes place through a gate with a constant cross-sectional area. The simulation can be performed with a constant inlet profile and an appropriate velocity distribution. Therefore, forming the part and closing the die occurs at the same time when performing thixoforging in open dies. That means, moving dies must be modeled, when simulating thixoforging. The CFD program Flow-3D was used to investigate the form filling when thixoforging. It enables to model any moving objects in the calculating region /2/.

In most cases the development of new production processes forces to improve an optimum between work pieces quality and its production costs. Thixoforging enables to produce work pieces with complex geometry and good mechanical properties such as high fracture elongation and high ultimate tensile strength. Producing such parts becomes more and more important while forcing light weight constructions.

When developing thixoforging, the production costs should be competitive compared with rival processes such as forging and high pressure die casting. The total costs of work pieces are strongly influenced by the quality and costs of the moulds or forging dies. There is a common use of computational process simulation to avoid major mistakes when designing such dies. The results of such simulations lead to a improved die design. Especially when beginning new production processes the use of a simulation is recommended to compensate the missing practise.

2 Basics of the material model

The relevant equations of the fluid flow (continuous, momentum and energy equation) are solved using a langarian description in finite differences. The deformation stress of the material is described by an apparent viscosity value /5/. Using this basic approach it is possible to calculate the high deformation rates, occurring while thixoforming.

The thixotropic behavior of aluminum alloys is described by an apparent viscosity, which depends on the fraction solid f_s, the strain rate $\dot{\gamma}$ and the shear time t.

$$\eta_{ap} = f(f_s, \dot{\gamma}, t) \qquad \text{Eq. 1}$$

The fraction solid is calculated using the well-known Scheil-equation.

$$f_s = 1 - \left(\frac{T_F - T}{T_F - T_L} \right)^{\frac{1}{k-1}} \qquad \text{Eq. 2}$$

In Eq. 2, T_F is the melting temperature of the pure metal (e.g. T_F=659°C in the case of aluminum alloys), T_L is the liquidus temperature of the used alloy (T_L=615°C in the case of A 365), k is the partition ratio.

The equilibrium viscosity, i.e. the viscosity occurring after continuous shearing at constant shear rate is described by Eq. 3. This equation was arranged by Joly and Mehrabian and verified by Quaak /3/ /6/.

$$\eta = A \cdot \exp(B \cdot f_s) \cdot \dot{\gamma}^m \qquad \text{Eq. 3}$$

The equilibrium viscosity of the alloy A356 in dependence of the temperature and the shear rate, calculated with Eq. 2 and Eq. 3 is show in Fig. 2.

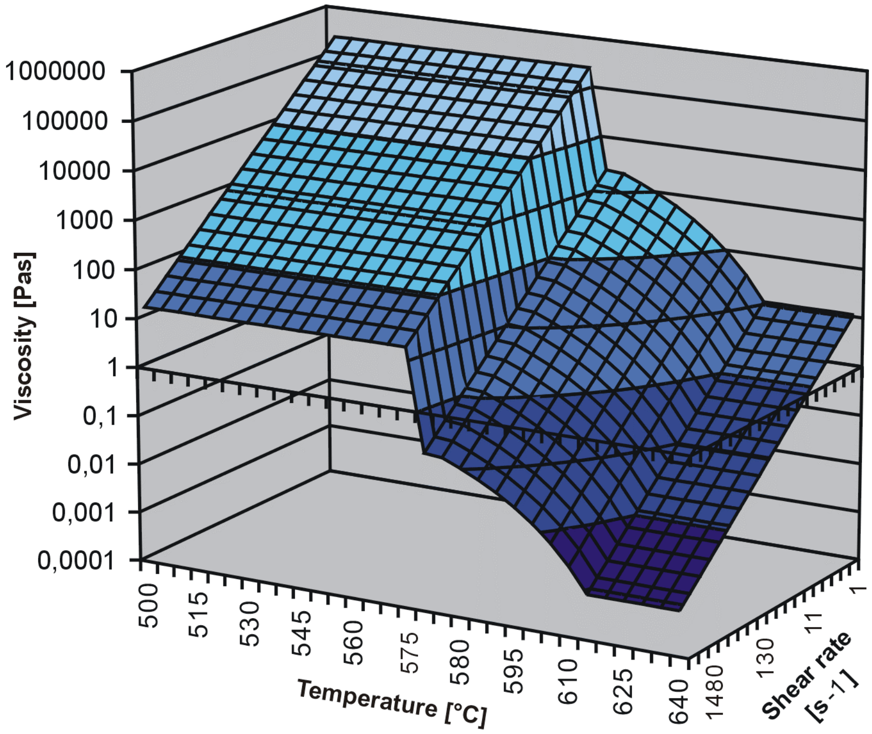

Fig. 2: Viscosity in dependence of the temperature and shear rate, calculated with Eq. 2 and Eq.3.

The time dependant thixotropic effects are considered in a transport equation which describes the evolution of the apparent viscosity η_{ap}.

$$\frac{d\eta}{dt} = \frac{1}{\lambda} \cdot (\eta_{\infty} - \eta) \qquad \text{Gl. 4}$$

where t is the shear time, λ is the relaxation time and η_{∞} is the equilibrium viscosity. In Flow-3D the reciprocal value $\beta = 1/\lambda$ is used instead of the relaxation time. Where β is called thinning rate.

3 Elementary work piece

3.1 Axissymmetric model

The mold filling of an axis symmetric workpiece called “Cup” was investigated. For this reason various calculations were performed before the experimental work. In these calculations the initial viscosity and the thinning rate were varied.

Calculation	Initial Viscosity [Pas]	Thinning rate [s^{-1}]
1	1300	40
2	1300	20
3	1300	10
4	1300	1
5	2600	20
6	13000	20

Fig. 3: Viscosity parameters

The simulations showed good correspondence with the experimental results, obtained by step-shootings. When performing these step-shootings, the press punch is abruptly stopped before the complete filling of the die is finished. This enables visualization of the form filling process. Fig. 4 shows the good correspondence between the simulation and the experiment. The colors show the pressure distribution in the work piece. The form filling showed only few differences in the different calculations. The differences in the form filling obtained in the simulation with different viscosity parameters can not be valued due to the strong influence of small variations of the process input parameters, such as the temperature of the slurry. The shape of the die cavity mostly determines the mold filling. Therefore the small differences in the viscosity evolution are not significant. Thus it is not possible to fix proper viscosity parameters. But due to the axis symmetric model the calculation times where short.

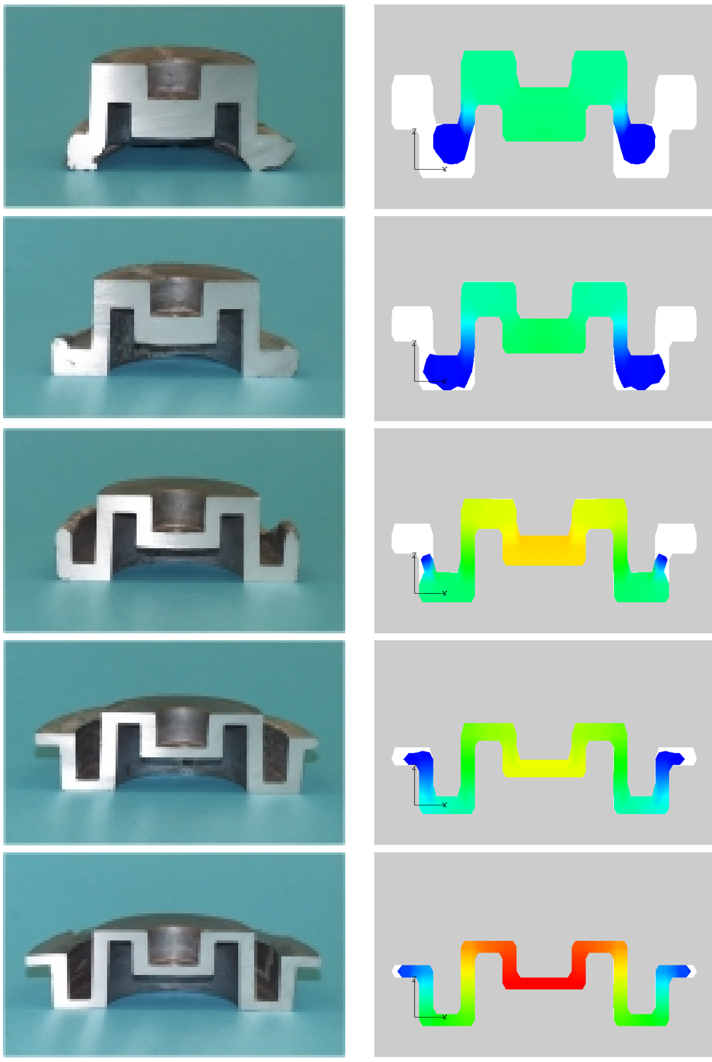

Fig. 4: Experimental results compared with calculated results, colored by the pressure.

3.2 Force Calculation

The simulation program Flow-3D allows to calculate the interacting forces between fluid and die. When calculating the force, normal forces due to fluid pressure as well as tangential forces due to velocity gradients are considered. In Fig. 5 the progression of the forming forces, calculated with various viscosity parameters listened in Fig 3 are shown.

The numbers indicate the calculation number. The influence of the viscosity parameters can be seen clearly. After an initial slow rise, the force increases to higher values at a forming stroke of about 55mm. At the end of the forming process, the forming force, measured on the lower die, increases rapidly. The measured forming force, averaged from several experiments is also shown in Fig. 5. The force lead can also be seen. At the end of the forming process, the force increases up to the maximum press force of the hydraulic press. In this stage the pressure is loaded for a solidification free of shrinkage cavities.

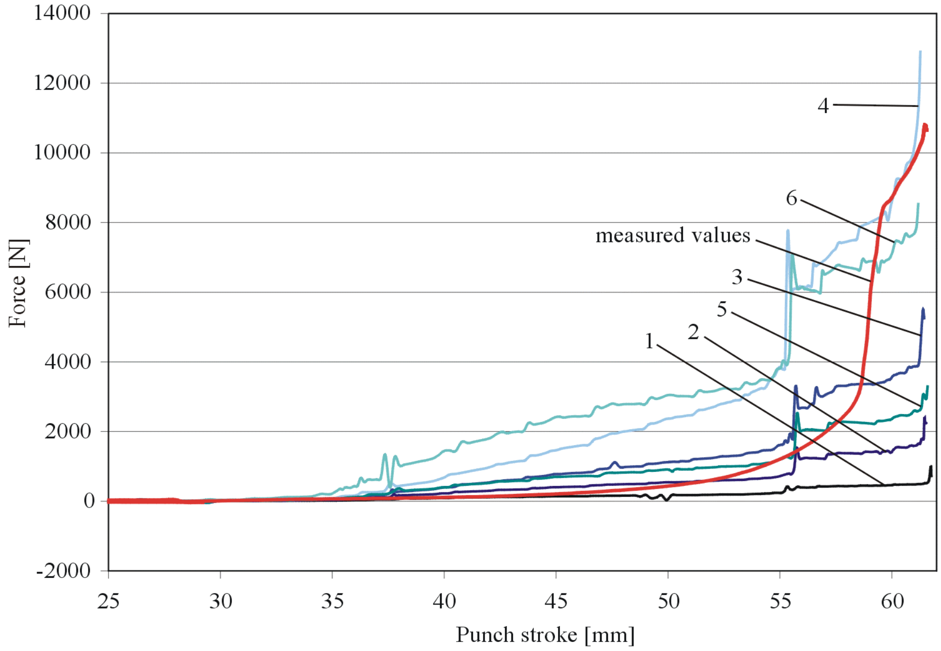

Fig. 5: Calculated and measured forming forces (The numbers indicate the different calculations specified in Fig. 3)

The forming forces measured at the end of the punch stroke corresponds well with the simulated forces, calculated with the parameters *initial viscosity mui=1300 Pas* and *thinning rate muthn=1* s^{-1}. However at prior punch strokes there are significant differences. In this range the measured force corresponds with force curves calculated with higher thinning rates. This results confirm the statements in /3/ and /5/, which express the shear rate dependent thinning with two different characteristic thinning times. The breakdown of the combinations (contiguity) between the different primary aluminum globules is a fast process. This results in a fast decrease of the viscosity. The rounding of the primary aluminum globules is a process about 10 times slower. This results in a lower decreasing rate of the viscosity. When calculating with a constant average thinning rate it becomes obvious that at the beginning of the forming process too high forces are calculated, while at the end the calculated forces are lower than the measured values.

3.3 Elementary work piece with rib

The geometry simulated in chapter 3.1 and 3.2 could be specified as an axis symmetric problem. The die was modified to verify the form filling behavior of a three dimensional problem. Two slots were machined into the upper die to enable a material flow in tangential direction. In the three dimensional simulation the influence of different viscosity parameters on the form filling was investigated. The simulation results were compared with the experimental step-shootings.

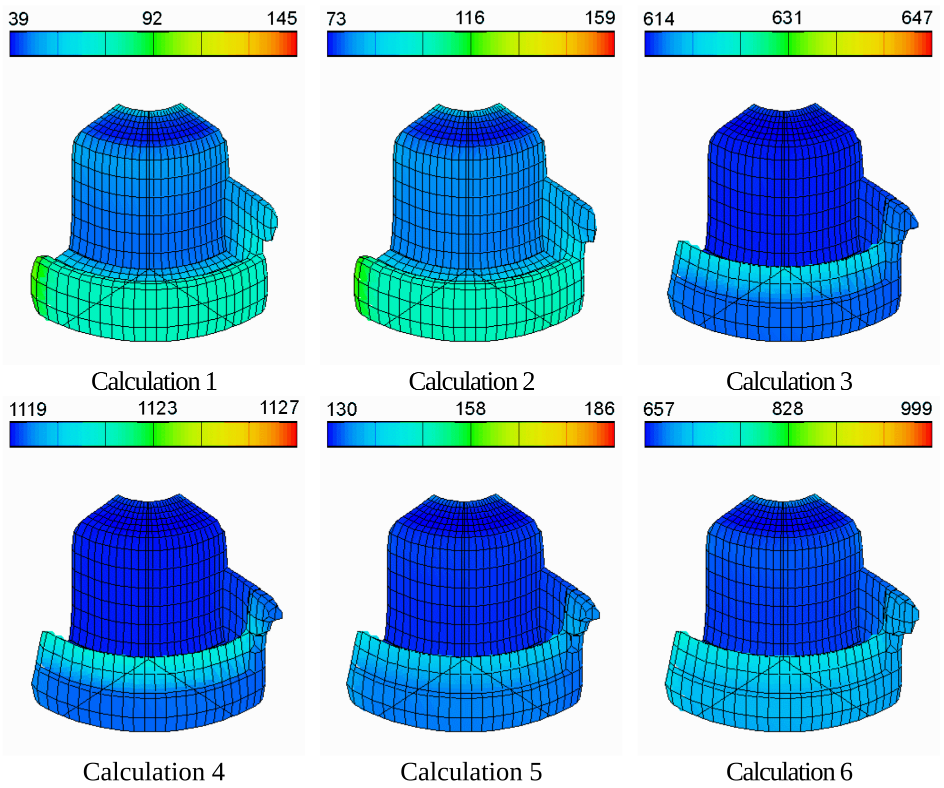

Fig. 6: Form filling, calculated with different viscosity parameters, colored by the viscosity in Pas.

When comparing the mold filling stages calculated with the viscosity parameters shown in Fig. 3 it becomes obvious, that the thinning rate has a stronger influence than the initial viscosity. The initial viscosity primarily influences the absolute value of the stress. The influence on the viscosity distribution, which has an effect on the material flow is low (s. Fig. 6).

To verify the simulations, step-shootings were performed. A partly formed workpiece is shown in Fig. 7.

Fig. 7: Form filling of the elementary work piece. The punch stroke was equal to the simulation shown in Fig. 6

Comparison of the various simulations show that the calculation number 1 matches best with the experimental results. Therefore the results made in chapter 3.2 are verified. In the early stages of the forming process the material can be modeled with high thinning rates. This means, the forming force as well as the form filling can be simulated. There are few differences between simulation and experimental results. These differences can be explained by the viscosity approach.

4 Suspension Part

Serial related parts are formed in cooperation with industrial companies. The work piece “Steering knuckle” is presently produced by an conventional forging process. A lower material consumption and a near-net-shape when forming the part by thixoforging should save costs. For example the ratio of the mass of the raw material and the mass of the pre-finished work piece is about 1.05. Because of the fraction liquid, two material flows can pour around a core and weld at the opposite side. For this reason, it is possible to form the bore pre-finished (s. Fig. 8). Rubber suspensions are pressed in these bores. The work

piece has good mechanical properties such as high yield strength and fracture elongation comparable with conventionally forged parts.
The simulation tool Flow-3D was used at the Institute for Metal Forming Technology to ensure the mold filling of the die. For this reason, the correct positioning of the wasters and the effects of the insertion point of the slurry were investigated.
The three dimensional calculation gave a good overview of the filling behavior. Therefore critical areas of the work piece could be identified.

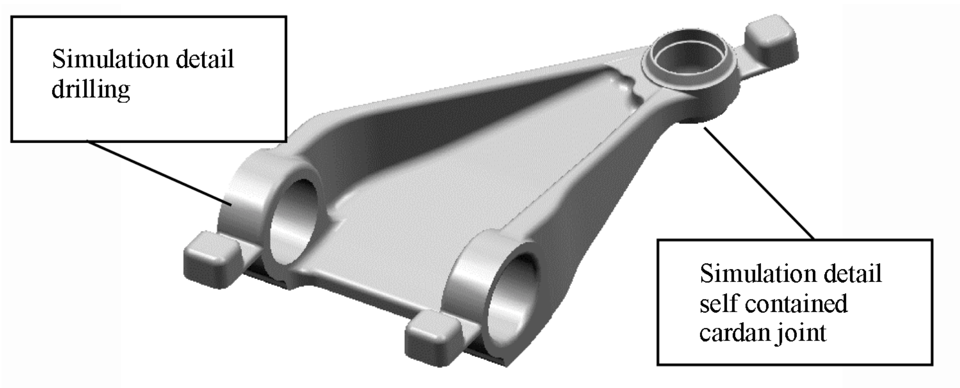

Fig. 8: Work piece Suspension Part

The mold filling, calculated with the viscosity parameters verified in chapter 3 is shown in Fig. 9. The mold geometry, used in this simulation was designed to ensure a uniform material flow into the overflow areas. When shifting any oxides or lubricant entrapments into the overflows high strength weldings of two concurring material flows can be performed.

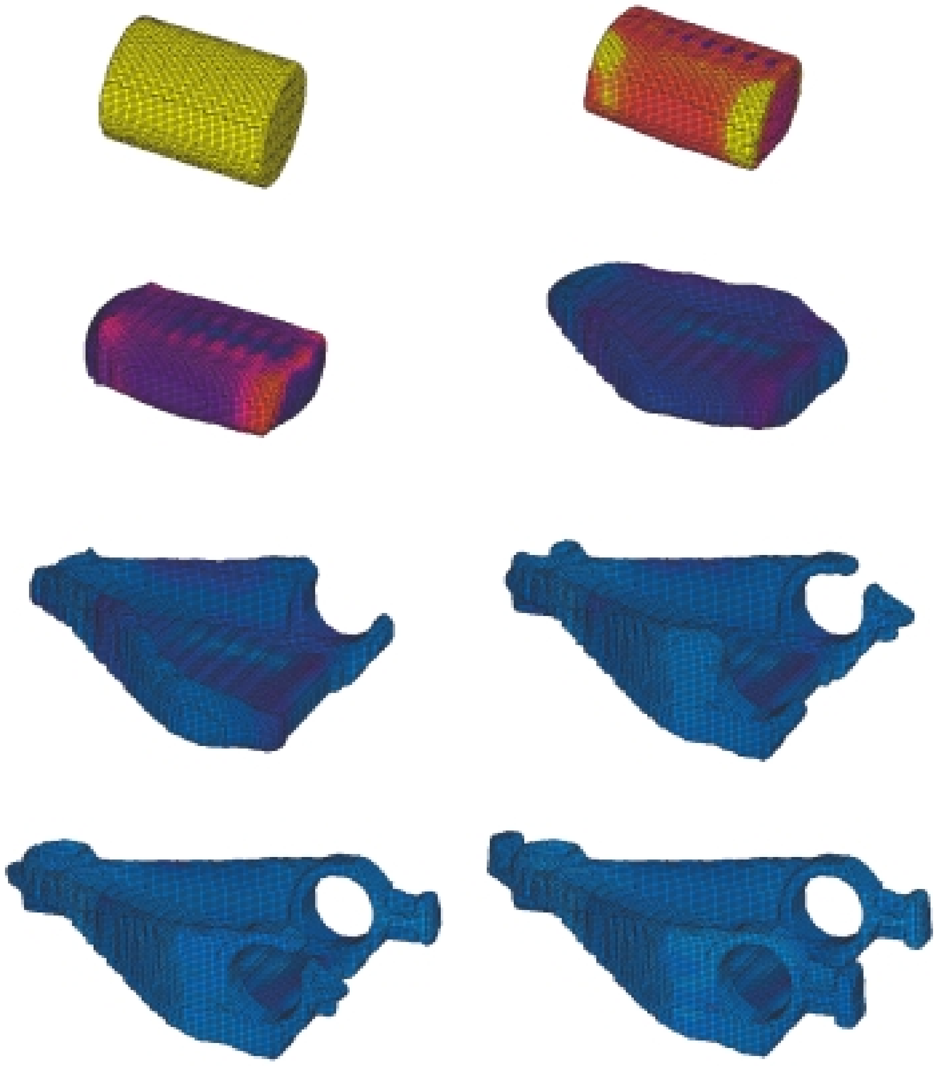

Fig. 9: Mold filling of the work piece Steering knuckle ,Alloy A356, slug geometry ∅ 65 mm x 62,5 mm; slug temperature 580°C; die temperature 300°C; punch speed 400 mm/s, colored by the viscosity.

As shown in Fig 9, the material flow does not coincidence in the area of the overflow inlet. At this time the overflows are almost completely filled. The form filling could be improved modifying the cross-section of the overflow inlet. Fig. 10 shows the microstructure in this area. The uniform material flow from both sides into the overflow is obvious.

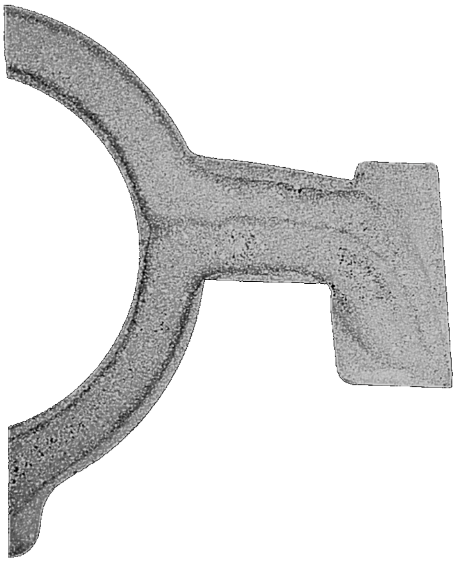

Fig. 10: Microstructure in the area of the inlet of the overflow

As shown above the simulation of the thixoforging process in the early stage of the die design leads to a modified mould design. The production reliability was improved and the time from designing to high quality work pieces was reduced /7/.

As shown in Fig. 11 the material flow around the self-contained cardan joint coincidence in the area of the overflow inlet. Therefore the welding in this area should show high mechanical strength.

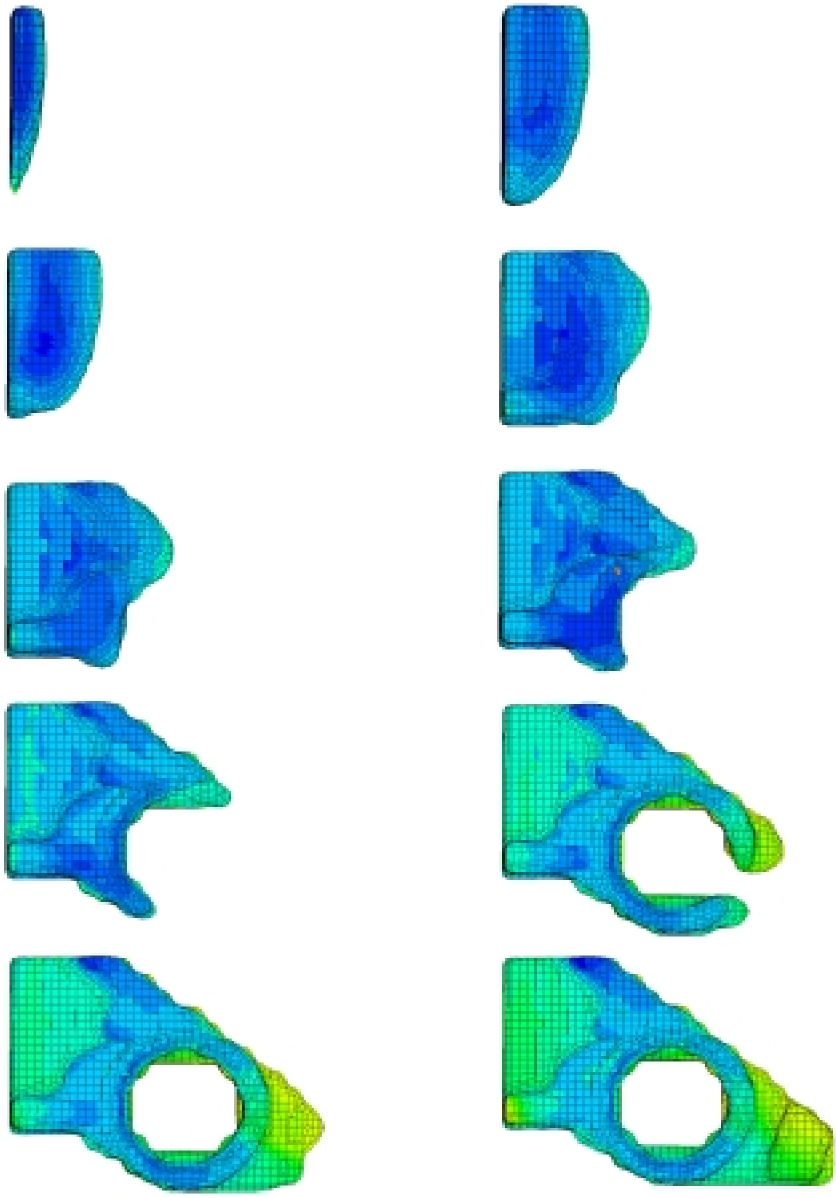

Fig. 11: Simulation detail self-contained cardan joint, alloy A356, slug geometry ∅ 65 mm x 62,5 mm; slug temperature 580°C; die temperature 300°C; punch velocity 400 mm/s, colored by the viscosity

5 Conclusion

The simulation of the flow behavior of semi solid materials during thixoforging shows good correspondence with the experiments. In this work the authors attempted to start with simple elementary parts and proceed with more complex shaped work pieces. The simulations were compared with the experimental results. When simulating the mold filling, the influence of the fraction solid and the influence of the cooling of the material can be considered by an combined heat flow calculation. The material model allows to consider the influence of shear rate, shear time and temperature on the viscosity evolution.

When using a second parameter for thinning time, the correspondence with reality could be further improved. At present the discontinuity in the diagram of fraction solid vs temperature (eutectic) cannot be considered. Additionally further basic experiments are necessary to get the required input parameters and material properties of semi solid alloys in the range of f_s=50-80%. In the future the simulation of the filling behavior of semi solid metals will be an important step when developing new work pieces. The die development time can be reduced and cost savings can be achived by simulating the mold filling behavior when thixoforging.

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