# Influence of Process Conditions on Segregation Behavior in Twin-Roll Casting of an AlFeSi-Alloy

Christian W. Schmidt, Dag Mortensen, and Kai-Friedrich Karhausen

**Abstract**

In twin-roll casting of aluminium the content of alloying elements is limited due to the formation of segregations mainly at the centerline and the surface of the strip. Their appearance, size and localization have a major influence on the final product quality. AlFeSi alloys are well suited for this investigation as they are alloyed with iron far beyond solubility. In casting experiments, casting speed is altered stepwise while all other casting parameters are not actively changed. Naturally roll and strip temperatures are increasing while separation force and strip thickness are reducing when casting speed is increased. Basically with increased casting speed the liquid and semi-solid sump is growing and contact time of the strip with the water-cooled roll is reduced. Hence both factors influencing segregation behavior, namely solidification conditions and deformation of the sump, are changing during the experiments. Experimental investigation is supported by process simulation in Alsim.

**Keywords**

Twin-roll casting • Aluminium • Segregation • AlFeSi

## Introduction

Although strip casting technologies like twin-roll casting are very resource efficient processes, the spectrum of alloys cast via these technologies as well as the range of products produced thereof is limited to low alloyed products with medium surface requirements. The limitation in alloying content mainly bases on two points. With increasing content of eutectic forming alloying elements, the solidification range widens considerably and especially the solidus temperature decreases clearly. This implies that rather low temperatures have to be achieved in the casting process to solidify alloyed materials in time and this can only be reached by relatively low casting speeds. The second limiting point are segregations, typically either located in the strip center, close to the surface or within a central band of strip gauge. The formation of segregations in twin-roll casting is based on a rather complex interplay of metallurgical, thermal and mechanical causes and as a direct experimental observation of the solidification process is impossible, simulations are used to support experimental investigation of process parameter and material properties.

## Segregations in Twin-Roll Casting of AlFeSi Alloys

The origin of segregations in twin-roll casting of AlFeSi alloys is the directed solidification with high cooling rates in this process in general as well as the high content of iron in these alloys in special, which is far beyond maximum solubility in aluminium and makes them well suited for such an investigation. Caused by the very high cooling rates, a

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higher concentration of alloying elements remain in solid solution compared to thermodynamical equilibrium [1]. Nevertheless, when the alloy solidifies, the alloying elements partition in a certain relationship between the liquid and the solid phase depending on actual temperature and cooling rate. In the case of iron and silicon the concentration in the remaining liquid phase is higher and hence the residual melt is steadily enriched in these elements while solidification proceeds. In the usual case of symmetric strip cooling, the location where material solidifies last is the centerline of the strip. Here the enriched interdendritic liquid finally solidifies and eutectic colonies and large localized pre-eutectic precipitates can be formed depending on composition of the alloy and parameter of the casting process. Because of the mechanical pressure on the semi-solid sump during twin-roll casting also other segregation patterns are observed in case of rather hot casting conditions and thin strip. The segregation patterns in twin-roll casting are categorized in surface segregates or surface bleeds, centerline segregates, among which channel and deformation segregates can be distinguished and banded structures [2, 3].

## Surface Bleeds

Surface bleeds are pockets of solute-rich material on strip surface containing a clearly increased concentration of intermetallic precipitates. The structure can either appear eutectic or very fine dendritic. Lockyer et al. [2–4] propose that surface bleeds are a result of a small gap opening up between the roll and the semi-solid sheet. This space gets partially filled by solute-rich liquid, which immediately solidifies when it contacts the roll. During solidification, initially a thin semisolid film forms on roll surface. This film is pushed towards the roll gap by metallostatic pressure. As it approaches the roll gap, it meets material that is moving at lower speed owing to backward slip, and the resultant difference in velocities causes the thin semisolid film to buckle. The compressive forces acting on the semisolid material in this region squeeze solute-rich liquid from in between the solidified dendrite network into the gap now formed on the surface, where it immediately solidifies in contact with the roll in droplet shape. Throughout the following hot deformation the surface bleed gets its typical saucer-like shape [5]. The mechanism of surface segregate formation was confirmed by Forbord et al. [6] investigating stop samples in connection with simulations. That study revealed that at relatively high casting speeds a low pressure zone develops close to the roll providing the driving force for enriched interdendritic liquid to flow towards strip surface. High casting speed or low separating forces, thin strip thickness, alloys with freezing ranges of 10–30 °C and reasonable amount of liquid present prior to completion of solidification promote the formation of surface bleeds [4].

## Centerline Segregates

Centerline segregates are a major problem in twin-roll casting of long freezing range alloys. This, together with reduced casting speed and high separating forces, makes twin-roll casting of such alloys unattractive. Centerline segregates are distinguished by their formation mechanism and appearance in channel segregates and deformation segregates [2, 3]. Channel segregates are cylindrical regions with strongly enhanced content of eutectic forming alloying elements and hence reduced melting point. They are aligned in casting direction and occur at the plane in strip thickness, were both solidified aluminium layers meet. In the usual case of symmetric solidification they are positioned exactly at the centerline. Their formation is related to deformation of the mushy zone, which contains a network of solid dendrites and enriched melt in interdendritic locations. When casting conditions are comparably hot, meaning e.g. thin strip thickness, high strip speed or poor cooling conditions, the sump or solidification length grows and the mushy zone is deformed by the pressure of the rolls. As the solid portion deforms, the liquid portions are pushed back from the relatively cold mushy zone upstream towards the hotter melt zone. When liquid metal flows from a colder to a hotter area, the liquid must change its composition and re-melts already solidified material. The forced flow of liquid created by roll pressure causes melting, that causes further flow and finally channel formation. Usually the channels have an almost constant spacing. When casting conditions become even hotter, the appearance of centerline segregates becomes more equiaxed and they are then distributed within a certain band of the casting gauge [3]. This happens when in the mushy zone solid and liquid are co-deformed rather than liquid being squeezed back upstream, leading to the name deformation segregates. Enhanced heat transfer, e.g. by the use of copper shells, generally leads to a reduction of centerline segregation [7].

## Banded Structure

At very low separating forces, the structure does not anymore vary continuously from the surface to the strip center. There is a rather sudden change in dendrite arm spacing (DAS) midway through the sample. Then a clear distinction between a central band and two outer bands can be made. The inner band has an extremely small DAS, while some coarser areas can be found. Yun et al. [3] propose that the base of the sump becomes more U-shaped and hence the interface between mushy zone and solid zone becomes flat. As soon as there is solid throughout the casting thickness in the mushy zone, pressure builds up by the rolls and considerably increases heat transfer between strip and rolls. Due to the flat U-shaped interface between mushy zone and solid zone, there is a steep localized gradient in cooling rate and hence in temperature.

## Experimental

### Alloy

For this investigation an AlFeSi alloy with the chemical composition as shown in Table 1 was used, because the high alloying level of iron in such alloys allows a comparably easy observation of segregation effects. The melt interval of this alloy of approximately 31 K is considered as comparably large for twin-roll casting of aluminium. During solidification of this alloy first α-AlFeSi and then β-AlFeSi phases form.

### Setup of the Casting Trials

The casting trials were performed on a SCAL 3CM Caster with 956 mm outer roll diameter under standard production conditions at the end of a production campaign. The casting process was in a stable steady-state process and the only active change to the process was in roll speed. After each change, the casting process proceeded for 15 min until manual measurements of roll surface temperature and strip surface temperature were undertaken. For each casting speed stable process data, strip profile measurement and temperature measurements were recorded.

### Alsim Model for Twin-Roll Casting

Alsim is a finite element model including heat and fluid flow coupled with stresses and deformations. A Coulomb friction law is applied and by iterations on the mechanical conservation equations the parts of the cast surface that are either in slip or sticking mode against the roll shell are determined and tangential forces are calculated. The results include the roll force, the forward slip and the momentum on the rolls. A 2D finite element approach is applied, as the heat flow in the width direction is assumed to be insignificant and a plane strain-approximation is assumed to be valid for a large part of the strip. More details about the model can be found in [8], including the Arbitrary Euler Lagrangian (ALE) formulation for the moving mesh. In this study the model has been used also for segregation analysis. In that case a volume-averaged two-phase model approach is used for the flow. The model accounts also for the solidification shrinkage (shrinkage flow). The flow of both phases (liquid and solid) is calculated separately and coupled with interfacial terms, more details about this model formulation can be found in [9]. The weakest part of the model are perhaps the assumptions on heat transfer coefficients between the strip and the roll shell. As direct temperature measurements are difficult to obtain, the only validation of this approach is the temperature on the strip some distance away from the roll gap. The heat transfer coefficients are tuned to fit against one of the experiments and then the same heat transfer coefficients are used for all cases. An ad hoc choice for the increase of the heat transfer coefficients (HTC) was made—the HTC's vary from 10,000 to 40,000 W/m$^2$ K in the centre where the pressure is highest.

## Influence of Casting Speed on Other Parameter of the Twin-Roll Casting Process

Although apart from roll speed no other casting parameter was actively changed during the trials, of course as a reaction to this, other parameter like e.g. strip thickness and process temperatures change as well to a certain extent. The influence of casting speed on those parameter is shown in Fig. 1. Direct reaction to increasing casting speed is a shift of the solidification front downstream, identical to an increase in sump length because of a reduction of contact time. This leads to a higher share of liquid metal in the roll gap and hence to a reduction of separating force (see Fig. 1a). These hotter casting conditions also directly lead to a slight increase in roll surface temperature of 8 °C and increased strip surface temperature at roll exit by 22 °C in total. Besides these process parameter, the geometry of the strip changes as well. Strip thickness as well as profile height reduce with increasing casting speed. Forward slip does not show a clear trend, most probably due to lack of precision in the indirect measurement taken.

**Table 1** Chemical composition of the applied alloy in wt%

| Si | Fe | Cu | Mn | Mg | Ti | Al |
|---|---|---|---|---|---|---|
| 0.858 | 0.759 | 0.001 | 0.042 | 0.006 | 0.011 | 98.329 |

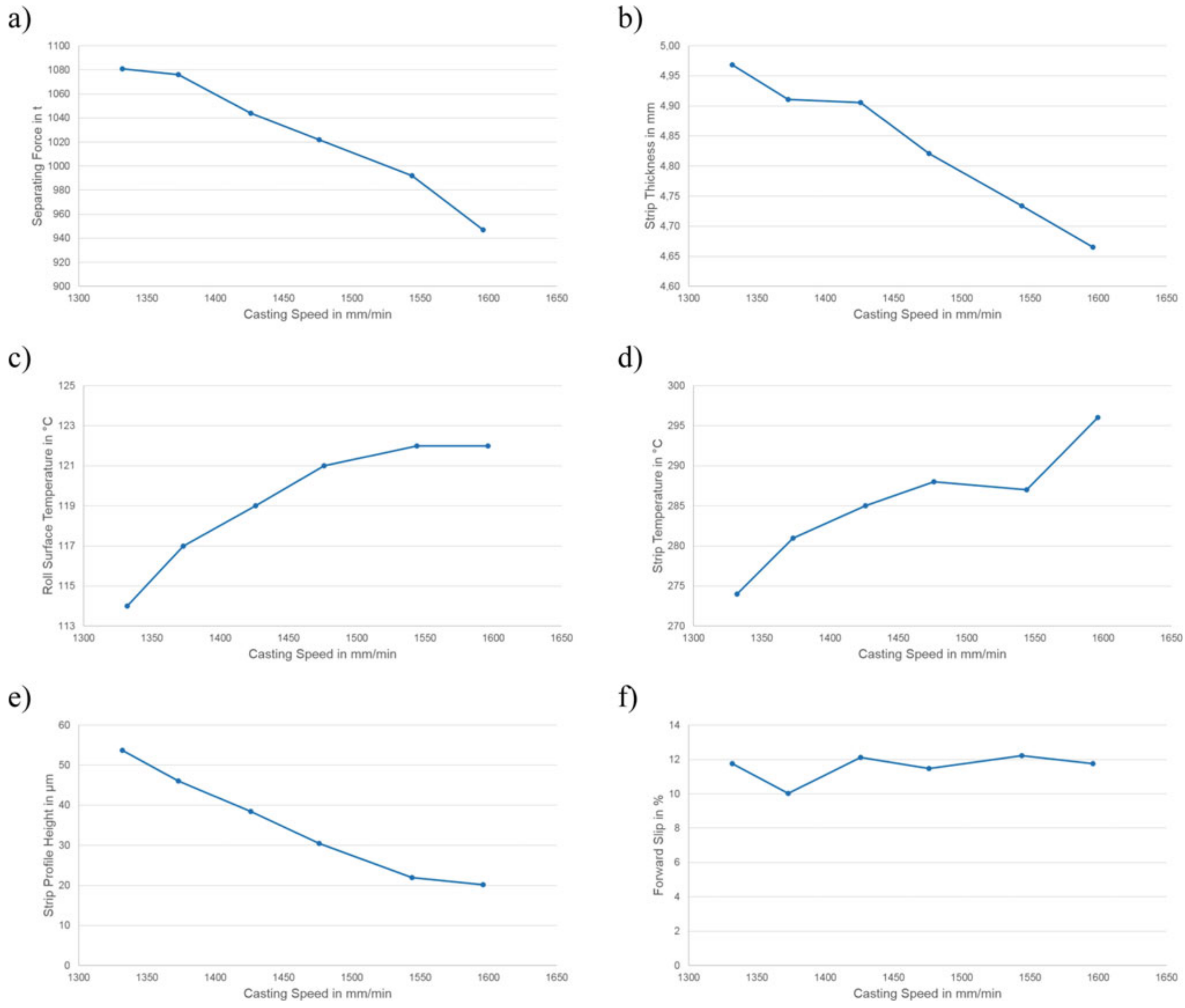


**Fig. 1** Influence of casting speed on other process parameter during the trial

## Influence of Process Conditions on Microstructure and Element Distribution

The microstructure of all specimens regardless of casting speed shows a strongly deformed surface layer typical for twin-roll cast material without any surface bleeds. Proceeding towards strip center, there is a rather sudden transition in the structure from elongated, deformed grains oriented in a low angle to casting direction to rather equiaxed ones. In bright field mode (see Fig. 2) it becomes obvious, that at this transition a comparably high amount of intermetallics is found, indicating a preferential segregation to this transition area at low casting speed. With increasing casting speed, the segregation becomes more and more dislocated in a band around this transition from sheared grains to rather equiaxed ones, while the transition between those bands becomes increasingly pronounced in terms of grain size and orientation (see Fig. 3).

Measuring the relative thickness of the two outer and the central band (see Table 2) reveals that with increasing casting speed the relative thickness of the central band grows. The proportion of top and bottom band stays rather constant, while the bottom band is always a bit thicker. The thickness of the outer bands is decreasing with increasing casting speed because of the shorter contact time between strip and roll. Besides, with increasing casting speed the depth of the sump increases and its shape transforms from an arrow to a lying U [3]. Hence, the geometry of the boundary between semi-solid and solid becomes flat and causes the relative thickness of the central region to grow in accordance with to the mechanistic argumentation of Yun et al. [3].

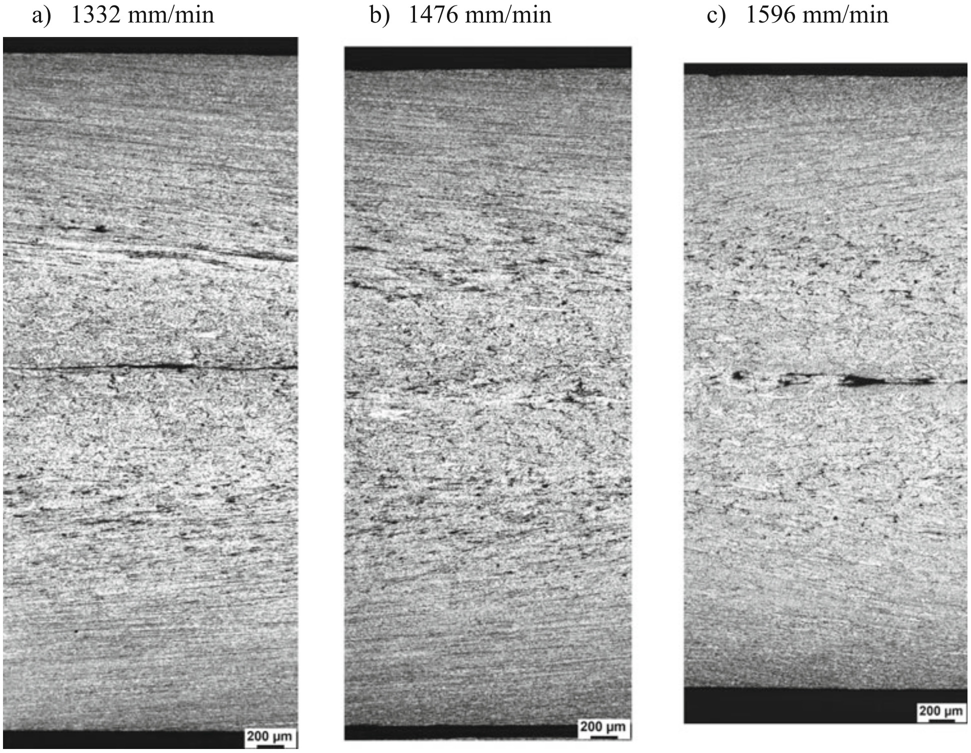


**Fig. 2** Longitudinal sections of as-cast material in bright field mode

While there are no surface bleeds on any of the samples and there is a mild form of a banded structure with slightly different appearance in each sample, there is also a distinct centerline segregation in each sample. Both, appearance and frequency of large centerline segregates requires a certain amount of statistics. A clear trend cannot be identified from the limited volume of metallography samples investigated (see Fig. 3). At low casting speed, the centerline segregates are present in form of channel segregates with a rather constant width. At higher casting speeds, both, deformation segregates as well as channel segregates are observed.

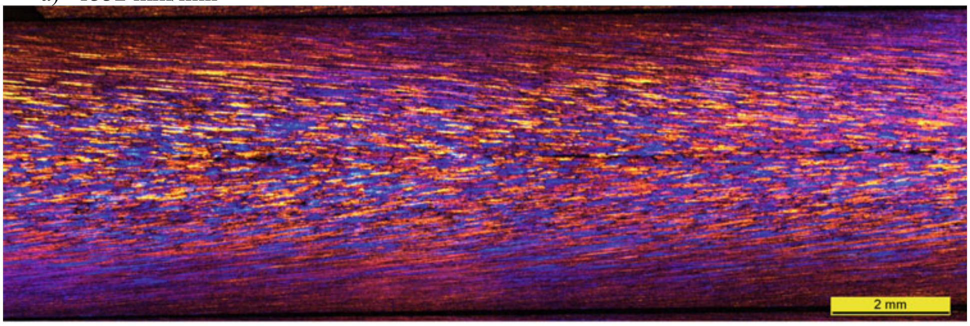
While in metallographic investigation the macroscopic distribution of large precipitates was revealed, the distribution of the main alloying elements iron and silicon is mapped with WDX. The maps in Fig. 4 show the macrosegregation pattern caused by directed solidification with systematically changing high cooling rates from strip surface to strip center. The images show a longitudinal section from strip surface (top) to centerline (close to bottom). Clearly visible are the centerline segregations with large channel-like areas with very high concentration of both elements. While close to the surface, the distribution seems rather homogeneous, it becomes more and more heterogeneous within the central band.

A more detailed analysis is shown in Fig. 5, where the recorded maps were aggregated to line profiles perpendicular to strip surface by averaging across width of the maps. These profiles show clearly that iron and silicon are distributed in a proportional way, as it is expected knowing that mainly α-AlFeSi and β-AlFeSi phases are found in this alloy. Close to surface the concentration of both elements is slightly enriched although no large precipitates were detected in metallographic examinations. This is a result of the very high quenching rate in this surface-near regions of about 100–1000 K/s leading to enhanced solubility of iron [1] and very fine precipitates. From surface onwards, the concentrations of both elements decrease steadily with low scatter until the zone boundary with the inner band. Here both, average concentration and local scatter of element distribution increase. This is in good accordance with the observation of large precipitates in this area. At lower speed this area is found at larger distance to the surface and the scatter is clearly higher, indicating a more severe tendency to segregation towards this zone boundary. Within the central band the absolute minimum of alloying element concentration is observed until the centerline segregates are found.

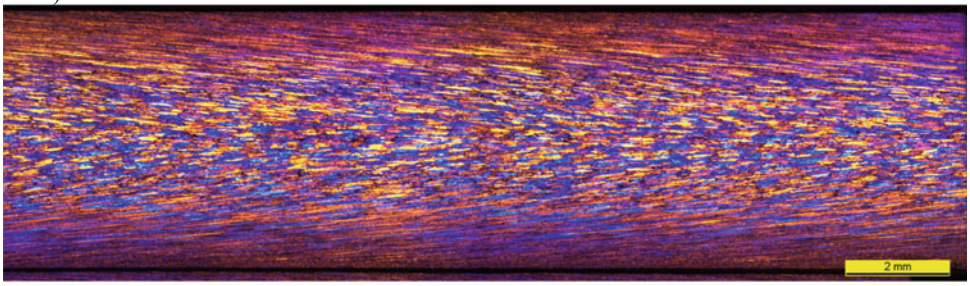
## Comparison of Experimental Results with Alsim Simulations

Figure 6 shows the comparison of Alsim results with measured separating force and forward slip. The model captures the trend in separating force although for the highest speeds

a) 1332 mm/min



b) 1476 mm/min



c) 1596 mm/min

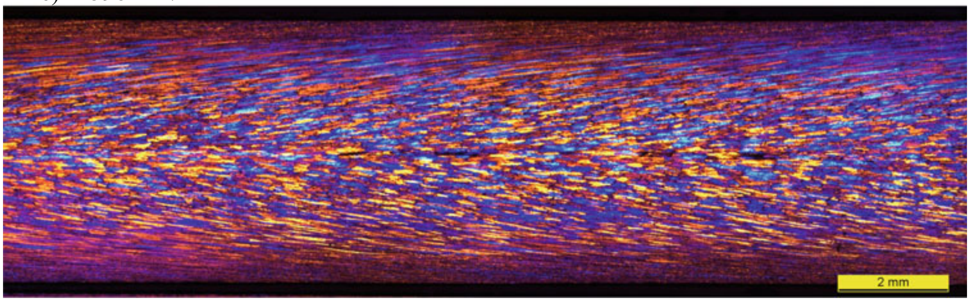


**Fig. 3** Longitudinal sections at casting gauge at slow, medium and high casting speed

**Table 2** Relative thickness of the respective bands at casting gauge

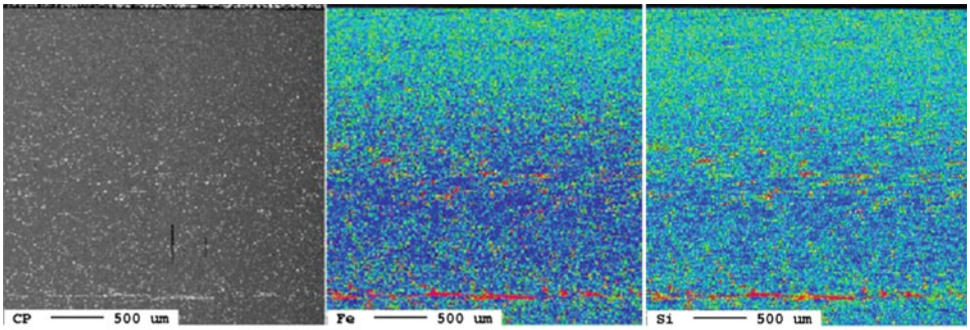
| | 1332 mm/min | 1476 mm/min | 1596 mm/min |
|---|---|---|---|
| Top band (%) | 32.2 | 29.6 | 21.7 |
| Central band (%) | 32.5 | 38.5 | 55.1 |
| Bottom band (%) | 35.3 | 31.9 | 23.2 |

the simulation results show too high forces. This might be related to the variation in strip thickness—the strip gets thinner as the speed increases (see Fig. 1b), while this effect is not included directly in the model. The experimental forward slip is generally higher than the simulated results. This is also related to the ad hoc choice of friction coefficient in the simulation (0.4 was used).

Figure 7 shows the normal stress component and the shear stress component for the case with the lowest roll speed of 1192 mm/min, identical to 1332 mm/min experimental casting speed.

For the macrosegregation results a Scheil microsegregation model was used. The results will be strongly affected by the local heat conditions in part of the strip close to the meniscus and in the part where there is no large pressure against the roll. The heat transfer coefficients are unknown and the results must be interpreted as qualitative results capturing the trends from observations. Figure 8 shows results from the case with casting speed 1332 mm/min. The segregation is oscillatory. The shrinkage contribution causes a depleted centre (as is observed in extrusion ingots and sheet ingots) but the inwards movement of mushy zone

a) 1332 mm/min



b) 1596 mm/min

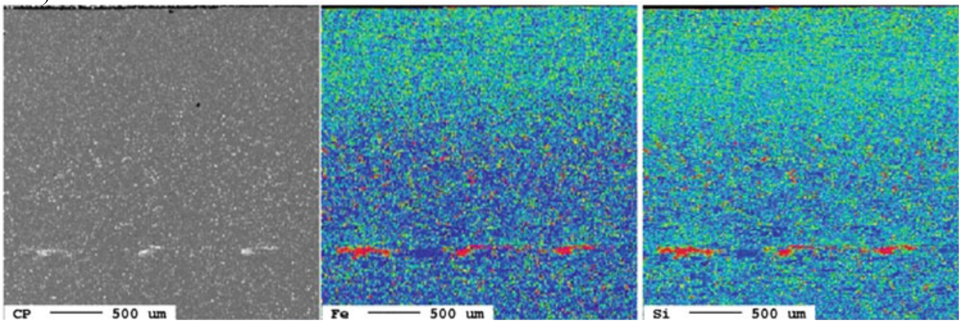
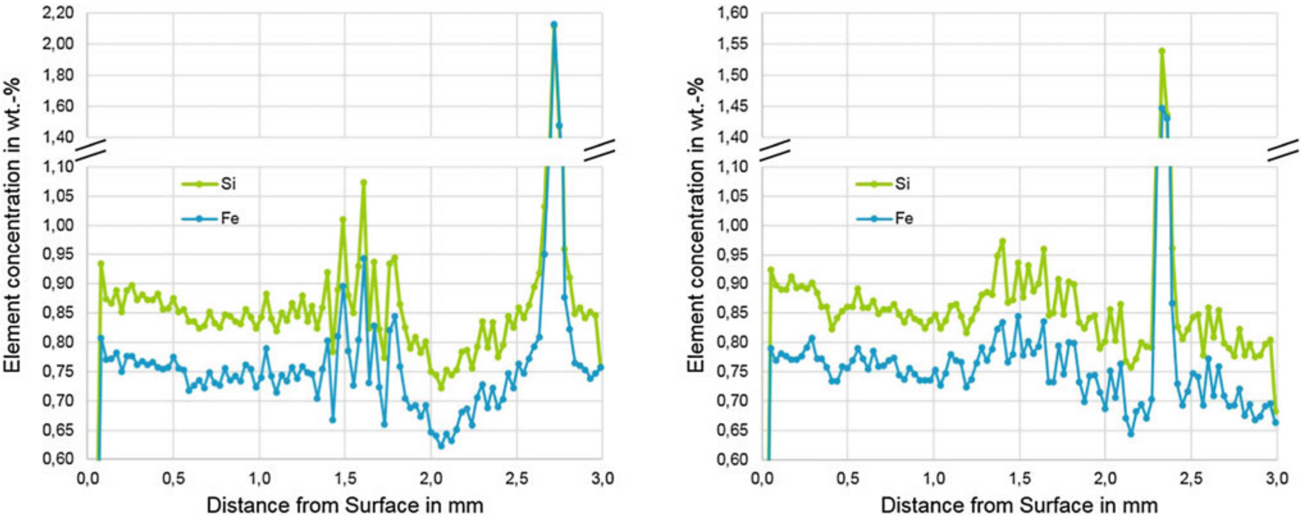


**Fig. 4** WDX maps of longitudinal sections of as-cast material with different casting speed



a) 1332 mm/min

b) 1596 mm/min

**Fig. 5** Depth profiles of iron and silicon derived from WDX maps

material enriched with silicon (caused by external deformation from the rolls) may cause positive segregation in the centre if this effect is strong enough to override shrinkage contribution. The forced fluid flow from the nozzle will penetrate directly into the centre and also sweep some of the enriched liquid away from the centre (but this flow does not penetrate all the way to the bottom of the mushy zone), this effect explains the maximum at some distance away from the centre. The balance of the forced fluid flow, permeability, shrinkage flow and deformation of the mush will decide where the segregations appear. Regarding the simulation results, these have to be assessed carefully. In such a

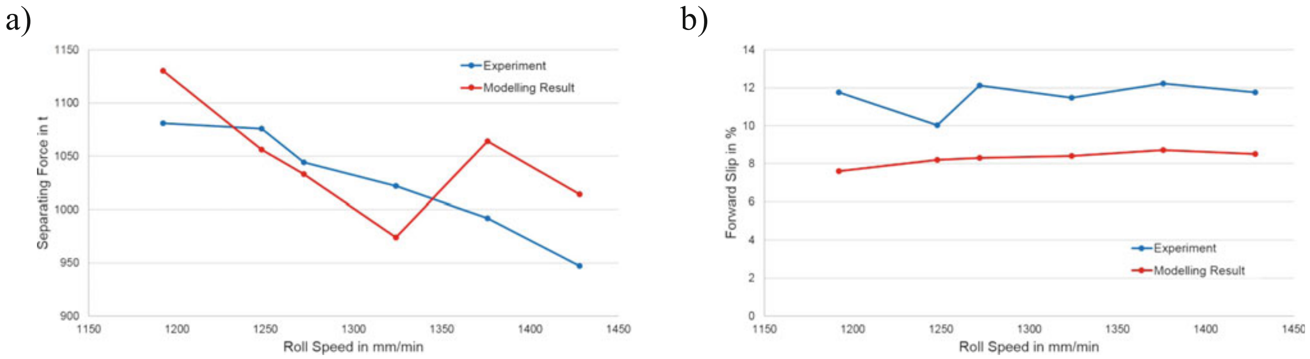


**Fig. 6** Comparison of: **a** measured separating force and **b** measured forward slip with simulation results as function of roll speed

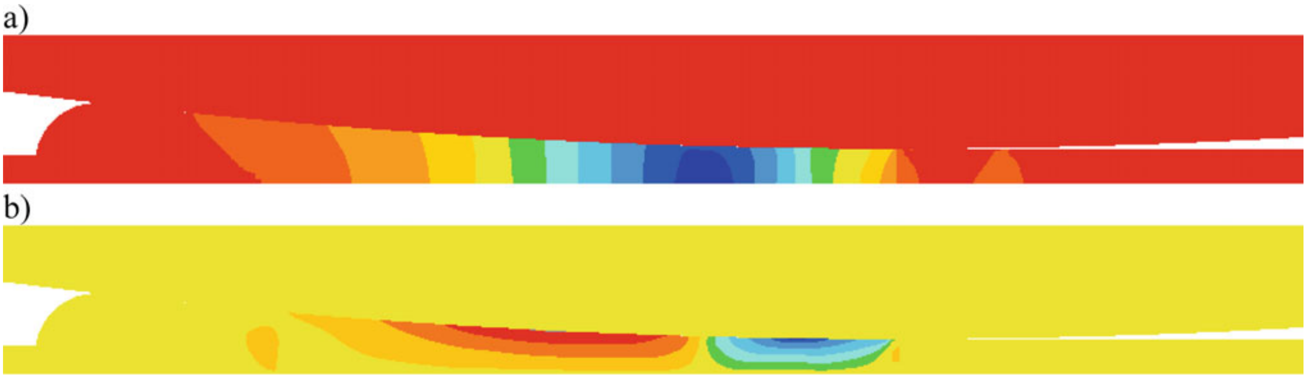


**Fig. 7** **a** Normal stress component from −400 to +40 MPa in step 40 MPa and **b** shear stress component from −100 to 50 MPa in step 15 MPa

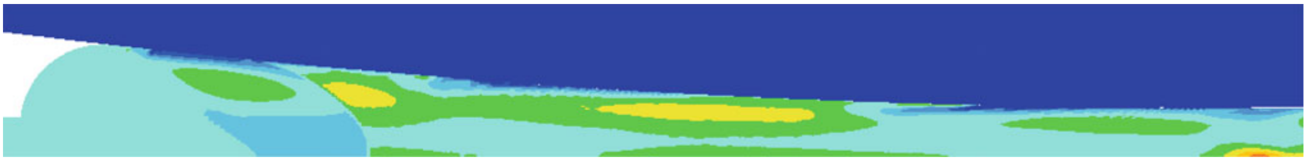


**Fig. 8** Concentration of silicon in wt% from 0.75 to 1.05 in step 0.03 wt%. Blue areas are depleted in Si. The mushy zone is visible to the left. The shrinkage flow causes the mixture concentration to appear depleted down to the fully solid

complex model also numerical effects may play a role and it is a time consuming process to validate each part of the model and the complex interaction of different physical mechanisms.

## Summary

Twin-roll casting trials with alteration of only the casting speed were performed with an AlFeSi alloy. Reactions of other process parameter were recorded and microstructure, segregations and distribution of the main alloying elements were measured. Supporting the experimental investigation, the Alsim model was used with a Scheil microsegregation model to visualize related effects and understand influencing factors on the final element distribution and segregation pattern in such an alloy out of the twin-roll casting process.

By increasing casting speed, the solidification front is shifted downstream leading to an increase in process temperatures and a reduction of separating force, strip thickness and profile height. While no surface bleeds are found, a certain extent of centerline segregation is always present. Its appearance changes from purely channel-like to a mixture of channel and deformation segregates with increasing casting speed. Generally, a mild form of a banded structure is observed, wherein the central band grows with increased speed. The local concentration of main alloying elements decreases steadily from strip surface presumably due to a decrease of cooling rate until the zone boundary, where a preferential segregation spot is observed. Within the central band the global minimum in concentration is found before a clear localization in centerline segregates.

The Alsim model is not yet perfectly calibrated for the present case and hence results have to be interpreted with care, but it confirms the trends in process parameters and provides insights into preferential sites and critical parameters for the localization of segregates. These are the balance of the forced fluid flow, permeability, shrinkage flow and deformation of the mush.

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