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THIN GAUGE TWIN-ROLL CASTING, PROCESS CAPABILITIES AND PRODUCT QUALITY

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Abstract

Traditionally industrial twin roll casters have been operated at gauges 6 - 10 mm, depending on the type of caster and the final product requirements. Over the past few years it has become apparent that a significant increase in productivity can be achieved when the casting gauge is reduced. Hydro Aluminium embarked on an extensive research and development, thin gauge casting programme, in the beginning of the 1990's and this paper presents some results from a five year lasting project (joint programme between Hydro Aluminium a.s. and Lauener Engineering). Based on more than 400 casting trials the major benefits and limitations of casting at reduced gauge and increased speed are outlined. Important aspects related to process development and product quality are discussed including: productivity and limitations, surface defects, microstructural characteristics, cooling rates and dendrite structure, segregation behaviour and mechanical properties after thermo-mechanical processing. Results for casting of several alloys are given. Additionally, numerical modelling results of the strip casting process are included.

Introduction

As twin roll casting combines solidification and hot rolling into a single operation, the process in general requires low capital investments and low operational costs compared with the traditional DC ingot and hot rolling route. Both mathematical model calculations and tests on laboratory installations have shown that twin roll casters operated at gauges 6 - 10 mm, are far away from the theoretical limitations and the productivity can be increased by casting at thinner gauges. The results presented in this paper are based on the outcome of an extensive five year lasting research and development programme focusing on all relevant aspects of thin strip casting. The programme has been driven by the following expectations:

- Increased output
- Reduced operational cost (incl. less subsequent rolling passes)
- Property improvements, with respect to:
  - surface quality/level lines
  - centre line segregation
  - geometrical tolerances
- Wider alloy range (increased solidification rate)
- New products

Some preliminary results of the research programme have been published in a previous paper /1/.

Pilot caster line

Most of the results reported in this paper have been obtained by casting trials on a pilot caster line, designed and built by Lauener Engineering, but located at Hydro Aluminium, Karmøy - Norway. The pilot line allows tests under real production conditions. During a five year period over 400 full scale casting trials have been performed. The main features of the casting line are:

- 13 ton melting/holding furnace
- Filter unit; gas flotation and particle filtration
- Strip caster;
  - 800 mm wide caster stand
  - Separating force capability: max. 4000 kN
  - Hydraulic thickness regulation
  - Automatic process-control unit
- Pinch roll unit
- Shear and Coiler

Productivity and process-limitations

Thin strip casting - present status

Within the five year timeframe of the research and development programme, thin gauge strip casting technology has been developed for casting down to 3 mm strip thickness. For alloy AA3003, a qualification test including 3 x 6 hours stable casting and full strip width is accomplished at a productivity of 1.65 kgs/hours/mm. Maximum productivity, 2.0 kgs/hour/mm, is documented for 3 mm strip thickness with reduced casting width due to separating force limitation of the pilot caster. The results are illustrated in Figure 1.

Calculations using a finite difference, 2D thermal model (assuming plane strain condition according to classical rolling theory) indicate scale effects in the range of 15 - 20 %, by increasing roll diameter from 540 mm up to 900 mm, see Figure 2. This implicates a productivity performance in the range of 2.3 - 2.4 kgs/h/mm.

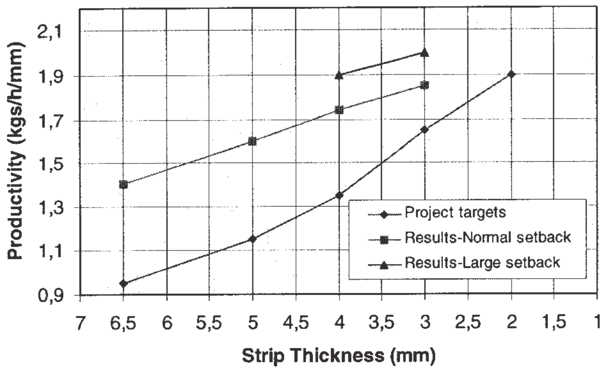


Figure 1: Productivity correlated to strip thickness for alloy AA3003.

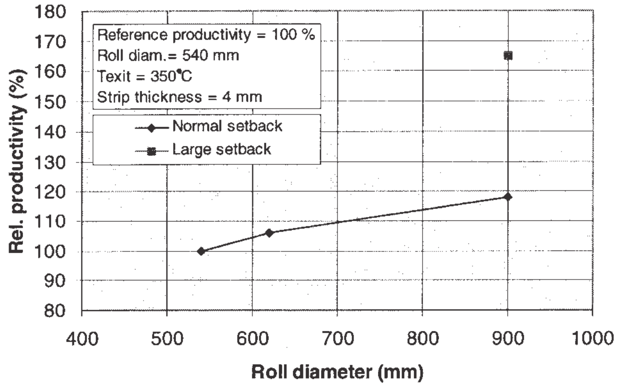


Figure 2: Productivity related to roll diameter.

The thin gauge technology established are including separating force requirements for new casters, thickness regulation system, automatic down-gauging and setback adjusting system, tip technologies, release agents and operational procedures for high productivity casting. Thickness regulation system has resulted in thickness variation within the thickness tolerances of the cold mill. This should justify the statement that the technology is acceptable for thin gauge strip casting down to 2 mm. Measurements and mathematical simulations have shown that temperature variations in roll shell surface is reduced by casting at thinner gauges and higher productivity and thereby reducing thermal fatigue tendency and improving roll shell life time. However, increased number of roll rotations per ton aluminium still make roll shell life-time performance unclear with reference to pilot caster experiences. Sufficient documentation on this issue can only be provided when thin gauge casting is fully implemented in production.

The extensive research effort has resulted in continuous improvements in the production plant owned by Hydro Aluminium. By implementation of new technology the Karmøy Rolling Mill, which is operating 6 Roll Casters, has increased the average productivity with 15 % in the period 1993 to 1995. This corresponds to an additional caster production based on the previous productivity performance. One caster which was revamped during the summer of 1995, is expected to cast strip down to 3.2 mm thickness at a productivity of 1.70 kgs/hour/mm. This would be equal to an increase of 70% of the caster performance established before the research programme was initiated.

The results from the thin strip casting programme have shown that the process still has a potential for improvements, beyond the successful achievements in the finalised programme. Process developments related to the release agent system in particular, should increase the possible exit temperature of the strip and thereby increase the productivity during casting. Thermal model calculations are given together with the experimentally obtained results in Figure 3. The present limitation of strip exit temperature is assumed to be close to 350°C. A temperature increase of 50°C is predicted to give approximately 20 % higher productivity at 3 mm strip thickness. This implicate casting with a deeper solidification front and less hot deformation of the strip material. The productivity increase must be counter balanced considering the specific product requirements. Improvements with respect to the release agent system should make it possible to utilise the remaining roll shell cooling potential in casting at gauges down to 2 mm. Comparing model calculations (T_{exit}=350°C) with the experimental results, the lower productivity performance indicates process lay-out limitations beyond the roll cooling capacity.

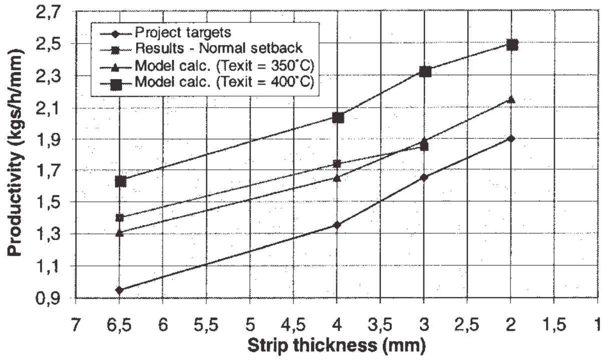


Figure 3: Productivity potentials for twin roll casting. Influence of T_{exit} on productivity.

Process stability and surface defects

Casting of thinner strips seems to give more possibilities in controlling different types of quality deviations in the process, compared with casting of thicker strips. However, the probability of unstable reactions in the roll gap increases. Several types of thin gauge defects have been observed and they need to be controlled in order to produce a high quality strip. The critical interaction between the cast rolls and liquid metal is assumed to be mainly linked to the behaviour of the meniscus. In case of unstable meniscus, a surface pattern would be generated which would imply a potential quality problem depending on alloy and application. Thinner gauges and higher productivity will significantly increase roll speed, which in turn will have a major influence on the stability of the meniscus. Therefore, based on the speed difference between roll and average aluminium bulk at actual setback position, a quality factor, Q(meniscus), is established in order to express the strong relationship between strip surface quality and casting conditions. Geometrical aspects will give the relevant correlation as indicated:

$$Q\,(meniscus) = f\,(roll\ speed,\ roll\ diameter,\ set\text{-}back,\ strip\text{-}thickness,\ forward\ slip,\ ......)$$

Important parameters that will influence on the predicted values of Q (meniscus) are:

- Metal feeding system; The quality of the metal feeding system including tip design and tip to roll distances is crucial in order to establish an optimised liquid metal flow up to the solidification front and a uniform temperature across the casting width.
- Release agent system; A release agent system should provide a uniform release agent layer on the roll surface.

The capability of the applied release agent system has been an issue of continuous focus due to surface quality problems that appeared at very consistent specific roll speed values. Productivity increase was very closely related to improvement of this system.

Combining the limitations related to roll shell cooling capacity as a function of strip thickness, we have information linked to productivity and a specified surface quality. This situation is illustrated in Figure 4. In this case the process lay-out will give highest productivity at specified quality for a strip thickness close to 3.5 mm.

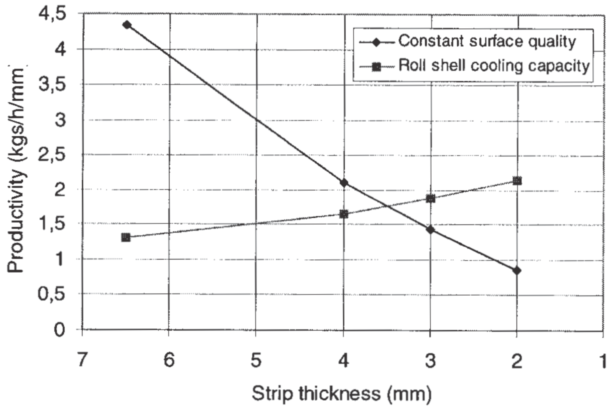
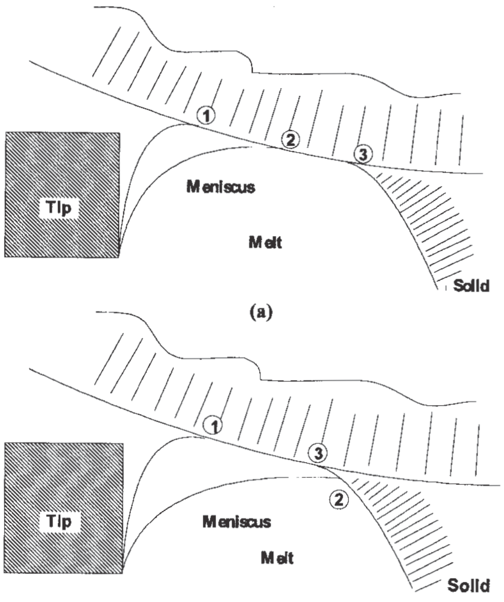


Figure 4: Effect of strip thickness on productivity with respect to a specified surface quality and roll shell cooling capacity. Productivity values are estimated on the basis of a thermal model with respect to roll shell cooling capacity, $T_{exit} = 350°C$, and a semi-empirical correlation is applied to reflect a constant surface quality factor, Q (meniscus), related to meniscus stability.

Major observations of surface phenomena/defects were related to the following:

Level lines: Transverse surface ripples or lines generated on as-cast strip surface at a frequency of 5 - 10 Hz due to unstable meniscus. The result is a micro disturbance in the as-cast structure in depth of <10μm which is characterised by coarser cell-structure and larger primary particles. The assumed critical process condition in order to generate level lines is illustrated in Figure 5, showing interaction between meniscus and solidified aluminium on the roll surface. No interaction between meniscus and solidified aluminium on the roll surface, i.e. a stable meniscus, implicate that level lines will not be generated. The stability will in addition to the roll speed influence depend on the metal feeding system and uniform roll surface properties. Speed increase and down-gauging will implicate a higher risk for unstable meniscus, however, by good process control level lines can be avoided. A level-line-free strip surface is more easy to produce in the low to medium casting speed range for strip thickness below 4.0 - 4.5 mm.



(a)

(b)

Figure 5: a) No level lines, b) Creation of level lines.
Position 1 - Static equilibrium of meniscus, Position 2 - Dynamic equilibrium of meniscus, Position 3 - Initial solidification.

Snake skin: Similar phenomenon as level lines but much coarser markings in the surface structure. The transverse lines are more visually apparent and show microstructure disturbances in depth down to approximately 20 μm. The frequency of the "snake skin" lines appearing on the as-cast strip surface could be very variable but were typically experienced in the range 1 - 5 Hz. The "snake skin" defect is especially experienced in 5000 series alloys. A schematic illustration of the phenomenon is given in Figure 6.

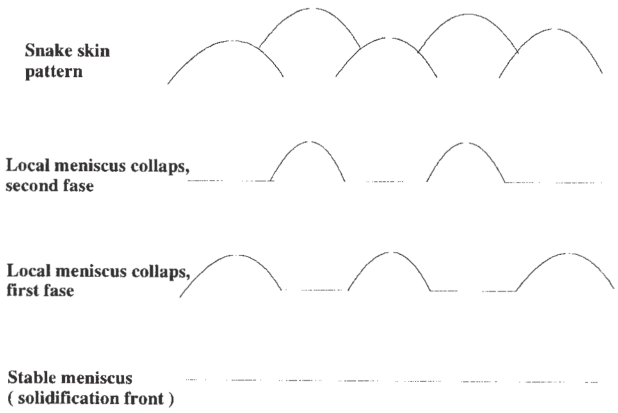


Figure 6: Creation of "snake skin" pattern on the strip surface, due to local interaction between the meniscus and the initial solidification.

Bleed outs: This phenomenon is assumed to be a result of a thin layer of aluminium which builds up on the roll in conditions where the solidification front creates a deep sump. Backward slip can result in a folding/buckling of the aluminium layer on the roll surface, in an early stage of solidification, which may result in reduced heat transfer and partly remelting. The result is interdendritic penetration of eutectic liquid metal from the centre to the surface of the strip, creating alternating bright and grey regions on the strip surface in a kind of wave surface formation. This will strongly reduce the application value of the strip. It is interesting to note that when this phenomenon starts to occur this is the beginning of large variations in the separating force, which shows that the process is unstable. The effect is normally observed only on the top surface of the strip. Similar observations have been reported by Monaghan and co-workers /2/. The phenomenon is strongly related to cooling capacity and casting parameters. Limitations due to this effect is especially experienced in 8000-series alloys but also in 1000-series alloys.

Cast product evaluation

Thin gauge casting has introduced a much larger process window related to productivity and product quality. This opens for a significantly higher production flexibility and options to tailor-make competitive processing routes to meet final product requirements.

As-cast microstructure and solidification mechanisms

Examples of as-cast microstructures for a conventional 6 mm roll cast strip and several thin strip cast variants are shown in Fig. 7. Large variations in the as-cast structure can be obtained when the gauge is reduced and the casting speed (or productivity) is increased. A gauge reduction in general results in the deformation getting more inhomogeneously distributed over the strip thickness, Fig. 7 b and d, due to a larger separating force giving enhanced hot deformation in the surface region. With increased casting speed (at constant strip thickness) a less deformed microstructure is developed, Fig. 7c and e.

The popular opinion of thin strip casting is that casting at thinner gauges results in a higher solidification rate thereby giving a refined metallurgical structure with smaller eutectic particles. Investigations of a large amount of samples cast at different "thin gauge conditions" have shown that this is not necessarily the case. In general, the grains in strip cast materials are characterised by a equiaxed dendritic head and a cellular tail region, see Fig. 8a /3/. The equiaxed dendrites nucleate and grow in the liquid, and when contact is made with the solid front the growth becomes directional. Experimentally determined DAS/cell spacings for alloy AA8111 are given in Fig. 8b. Measurements have been performed in a metallographic section approximately normal to the solidification front. It should be noted that all strips were cast using approximately equal grain refinement conditions. The 6 mm strip shows the typical dual grain structure described above with a cell spacing of 4.2 μm measured in the cellular part and a DAS value of 7.4 μm measured in the equiaxed part of the grain (strip centre). The DAS/cell spacings are seen to decrease slightly from the centre to the surface as a result of the lower cooling rate experienced by the central region. It is well established that both DAS and cell spacing correlates with the cooling rate in the form: $d=\beta Q^{-\alpha}$, where β and α are constants. Using this relationship

Casting direction →

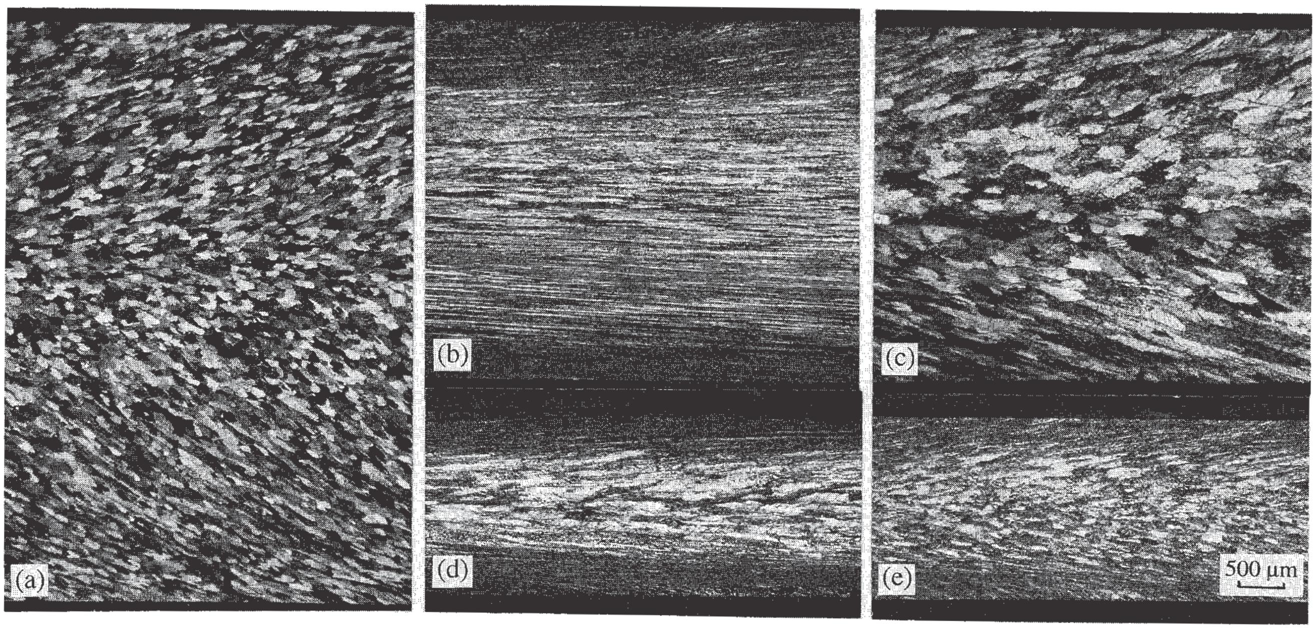
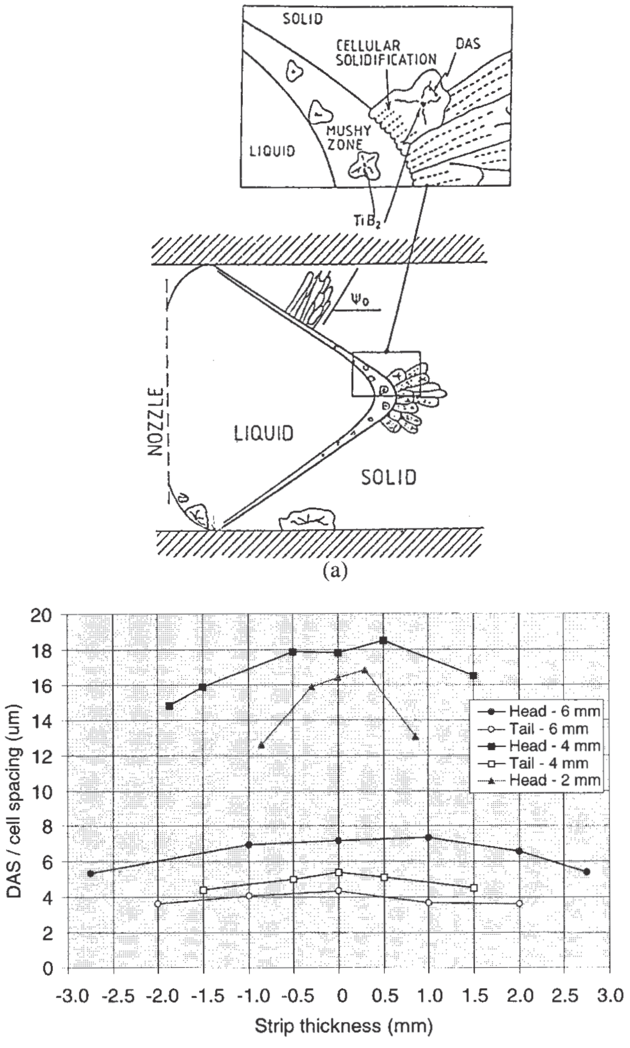


Figure 7: As-cast microstructure, alloy AA8111. a) 6 mm, conventional cast - 1.0 m/min, b) 4 mm - 1.9 m/min., c) 4 mm - 2.5 m/min, d) 2 mm - 4.0 m/min, e) 2 mm - 7.3 m/min.

cooling rates in the range 10^2-10^3 °C/sec. are obtained in the 6 mm strip. For the thinner strips larger DAS/cell spacings are found, which means that the microstructure solidifies with reduced cooling rate. This is somewhat unexpected but, similar observations have been reported previously for thin strip cast variants of alloy AA5052 /4/. The cooling rate in the 2 mm strip appear to be one to two orders of magnitude lower compared with the 6 mm strip, showing a DAS values in the range 12.5 - 16.8 µm. Note that in the 2 mm strip the cellular part of the grains are completely missing. Purely equiaxed grains are found, and this suggests that solidification in this case is completed by equiaxed growth in the mushy zone. This indicates more active nuclei, possibly because the melt spends a longer time in a state of substitutional supercooling. The overall conclusion must be that the new technology (thin-strip, high-speed casting) does not seem to give any significant higher cooling rate during casting. On the contrary, slower cooling approaching DC-casting conditions seems to be the case. This contradicts what was initially expected.



(a)

(b)

Figure 8: a) Schematic drawing illustrating the solidification front reaction (from Strid /3/). b) Experimentally determined DAS/cell spacings in alloy AA8111, 6 mm-1.0 m/min, 4 mm-2.5 m/min and 2 mm-7.3m/min

Segregation behaviour

Casting of thin strips at high speed has introduced different and new forms of segregation patterns which changes the particle picture, and results in an overall coarser particle distribution compared with conventionally 6 mm cast material. Examples of typical segregation patterns obtained for alloy AA8111 are shown in Fig. 9. Investigation of a large amount of conditions have shown that a correlation exists between the casting gauge, separating force and segregation behaviour. This has also been illustrated by

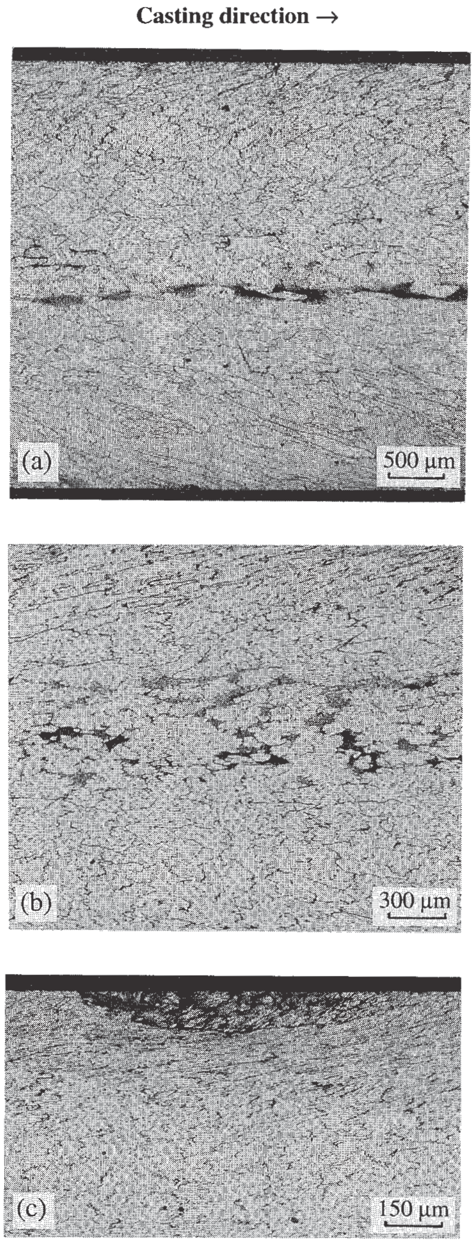


Figure 9: Micrographs showing typical segregation patterns, alloy AA8111. a) centre segregation (4 mm), b) “spread out” segregation (3 mm), c) surface segregation (2 mm)

Thomas and Grocock (see ref. /5/) who have introduced the concept of segregation limiting diagrams. Centre line segregation, which is a typical feature in conventional 6 mm material, can be found also at thinner gauges when casting at low specific load, Fig. 9a. Casting at high load seem to be the only way to obtain a segregation-free structure with a more or less homogeneous particle distribution. A transition exits between the above mentioned segregation patterns in which a more "spread-out" or distributed segregation type is found (Fig. 9b), caused by interdendritic liquid motion in a central band of the strip. At thinner gauges (2 mm and below) the segregation pattern changes towards a strong and disordered pattern and usually with a dominance of surface segregates (Fig. 9c). The type and amount of segregates will be strongly alloy dependent, controlled mainly by the solidification interval. In alloy AA8111 the surface segregation is manifested visually in the form of strong "bleed outs" on the strip surface. By optimisation of the process parameters the segregation can be minimised.

Numerical modelling of the strip casting process

To study the influence of the casting process on the solidification and deformation in the roll gap a mathematical model concept has been established. Details about this so-called Alstrip model are given in ref. /6/. This is a more sophisticated model than the thermal model used for prediction of productivities (see Fig. 2, 3 and 4). The concept is based on a two dimensional plane strain assumption in which the liquid, mushy and solid part of the strip are treated as a non-Newtonian fluid. Temperature, melt flow, deformation and stress are determined by solving the general field equations for mass, momentum and energy balance with the finite element program FIDAP. The model has proven its usefulness in several aspects, among other things in understanding micro-structure development and segregation behaviour for different casting conditions. Examples of temperature fields obtained using the model is given in Fig. 10. The conventional situation is characterised by columnar grains growing perpendicular to a V-shaped solidification front, Fig. 10a, sometimes causing extensive centre line segregation. Increasing the casting speed gives a deeper sump and mushy zone, and in combination with a gauge reduction the solidification front seem to get more vertical (or U-shaped), see Fig. 10b. The heat flux into the rolls is in this case directed more towards the exit side of the contact zone, and a more "spread out" segregation type are created. At even lower gauges and higher speeds the sump depth increases further, favouring equiaxed growth in the mushy zone. Additionally, the shape of the solidification front changes rather dramatically as indicated in Fig. 10c, the result being extensive surface segregation.

Suitability for down-stream processing

It has been shown in the previous sections that casting at thinner gauges creates different structures and segregation patterns. The obvious question then is: Are all of these different cast structures compatible with further down-stream processing and final end-product requirements ? Within the extensive research programme a considerable effort has been expended in investigating several alloys and their suitability for down-stream processing. As an example, the response to laboratory cold rolling and annealing will be presented for the foilstock alloy AA8111. When producing foil products, the most important material requirements are related to mechanical properties (strength and ductility) and surface appearance of the final foil. In terms of microstructure this means that we need a segregation pattern after casting which is compatible with rolling to thin gauges giving suitable mechanical properties, and additionally, a fine surface grain size after inter-annealing is necessary. If coarse surface grains are developed during the inter-annealing step an unattractive matt-side appearance in the foil will be created, due to a kind of orange-peel effect during the last double-foil rolling pass. Examples of grain structures obtained after the inter-annealing step (0.6 mm gauge), for initially different casting conditions, are given in Fig. 11.

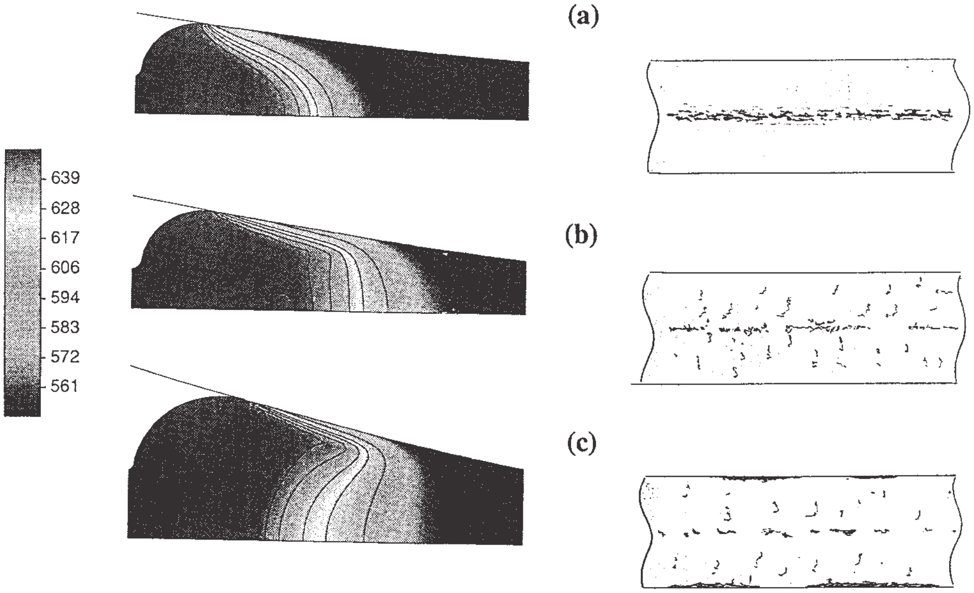


Figure 10: Temperature distribution in the strip during casting, and the resulting segregation pattern indicated schematically. a) 4 mm - low speed, b) 3 mm - high speed, c) 2 mm - high speed.

The structure shown in Fig. 11a will definitely not be suitable for foil applications, while Fig. 11b shows a satisfactory grain structure. Development of coarse surface grains (Fig. 11a) is related to the amount of surface shear deformation created during casting, and precipitation effects occurring during the inter-annealing step (for more details about metallurgical mechanisms, see ref. /7/).

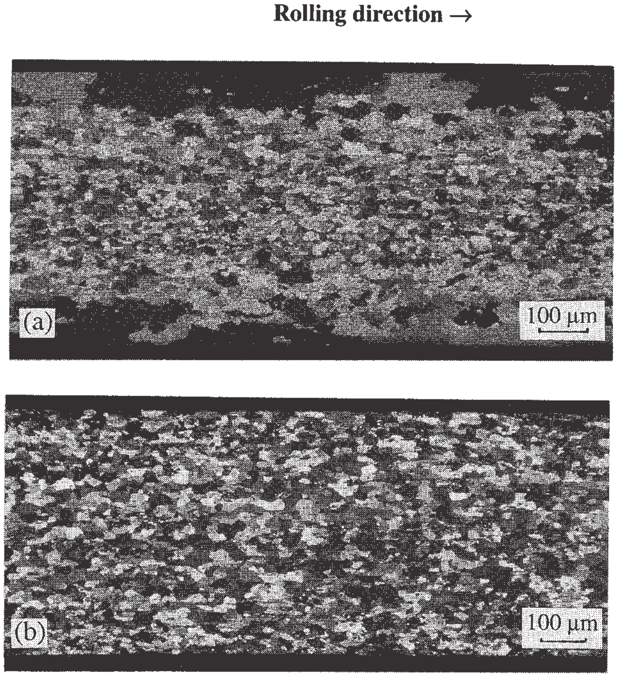


Figure 11: Recrystallized grain structure obtained after cold rolling and annealing, alloy AA8111. Initial casting condititon, a) 4 mm - 1.9 m/min, b) 2 mm - 7.3 m/min.

Looking at some properties obtained after cold rolling, shown in Table I, it is appearant that a reduction in the initial cast thickness results in lower strength values. This is expected because of the smaller amount of deformation applied when rolling to the same final gauge. Of more interest is the properties obtained after inter-annealing of the cold rolled strip. Note that all variants presented in Table I contained a fine grained structure after the annealing step. The yield and tensile strength are seen to be slightly reduced with a reduction in the casting gauge. Additionally, the elongation decreases significantly, especially when casting at gauges below 4 mm. This is obviously connected to the heavier particle clustering/segregation frequently observed when casting at thinner gauges. Heavy rolling are not able to remove the segregation pattern produced during casting. During tensile testing earlier and increased void formation are expected in the segregation regions. In the worst case transverse cracking in the vicinity of the segregates may even occur during the cold rolling operation. From the above it should be rather obvious that casting gauge and conditions must be carefully selected depending on the down-stream process and the final product requirement.

Summary and conclusions

- Thin gauge strip casting technology has been developed and proven for casting down to 3 mm strip thickness, with an almost 100% productivity increase compared with traditional 6 mm casting. Still lacking is the roll shell life time performance data related to thin gauge strip casting, which will be important for a complete cost/benefit evaluation of the new technology.
- The thin gauge casting technology includes a thickness regulation system for the roll caster that implicate cold mill thickness tolerances.
- In addition to increased productivity and output during casting, the new technology has the advantage of eliminating several cold rolling passes in the down-stream process.
- Casting of thinner strips, at significant higher casting speeds, have introduced several new types of surface defects which limits productivity. The defects are strongly related to casting parameters and the roll shell cooling capacity.
- Thin gauge casting technology can be applied for the full product range including all standard products as 1xxx-, 3xxx- and 8xxx-alloys down to 3 mm as-cast strip thickness. Focus on product quality is becoming increasingly important below 4 mm as-cast strip thickness, and casting parameters have to be carefully selected according to final product requirements.
- Thin strip casting are capable of producing a range of micro-structures, some of which are quite different from those produced by traditional casting of thicker strips.

Table I: Mechanical properties of AA8111 variants after cold rolling to gauge 0.6 mm. Tensile testing performed perpedicular to the rolling direction.

Cast condition		Properties after cold rolling			Properties after cold rolling and soft annealing		
Gauge	Strip speed (m/min)	$R_{p0.2}$ (MPa)	Rm (MPa)	A50 (%)	$R_{p0.2}$ (MPa)	Rm (MPa)	A50 (%)
6 mm	1.0	232	259	4	38	101	40
4 mm	2.2	210	236	3	37	100	38
	2.6	197	221	3	35	95	30
3 mm	2.7	204	230	3	32	97	32
2 mm	4.0	190	219	3	35	96	27
	4.9	186	212	3	34	93	26
	7.3	180	200	2	34	93	26

- One significant observation is that, contrary to popular opinion, casting of thinner strips does not give any higher cooling rates during solidification. Significantly slower cooling rates are in fact observed.

- Further improvements of the thin strip casting process are possible mainly by:
  - improving the release agent system and the metal feeding system in order to stabilise the liquid metal flow to the solidification front.
  - introducing new technologies that significantly increases the cooling capacity of aluminium in the roll gap.

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