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# DEVELOPMENT OF A NEW STARTING BLOCK SHAPE FOR THE D.C. CASTING OF SHEET INGOTS

## PART I: EXPERIMENTAL RESULTS

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## Abstract

In D.C. casting of aluminium sheet ingots butt curl of the ingot, which occurs when the bottom of the ingot is immersed in the direct cooling, can lead to cracking, melt bleed-out and stability problems of the ingot. In addition, it makes necessary a considerable amount of sheet ingot butt sawing. To reduce butt curl, modifications of the water cooling such as by pulsed water and $CO_2$ in the cooling water can be used. The paper shows, that the geometry of the starting block can also have considerable influence on ingot butt curl. A newly developed starting block shape for the D.C. casting of aluminium sheet ingots is presented which substantially reduces butt curl of the ingot during the starting phase and, as a result, greatly adds to casting safety.

## Introduction

The successful D.C. casting of a sheet ingot is largely determined by the start-up process. Modern D.C. casting systems place particular demand on the start-up procedure. The problem of starting to cast sheet ingots lies in the fact that the butt of the sheet ingot curls on its narrow side and thus loses contact with the starting block, as is shown schematically in Figure 1 [1,2]. Butt curl is due to thermal stress and to the easy deformability of the solidified shell in the mould. The curling action begins immediately the sheet ingot butt is immersed in the mould direct cooling water. The butt curl time sequence is shown in exemplary fashion in Figure 2 [3]. From this, it can be seen clearly that the curling speed is greatest at the beginning, so that the total extent of butt curl is, in essence, determined in the first few seconds following the start of curling. Subsequently, the curling speed decreases very quickly, and within about 1-2 minutes of the start of curling, the process is concluded, independent of the ingot size. It is important in the start-up procedure that no negative speeds occur i.e. the actual casting speed is always greater than the curling speed. The total extent of butt curl is determined by the ingot size. The thickness-width ratio of the ingot plays an important role in this; significant curling of the ingot butt especially occurs when the thickness-width ratio is ≥ 1:3. Figure 3 shows the influence the width of the ingot has on butt curl given for a constant ingot thickness. As expected, it can be seen that butt curl worsens considerably as the width of the ingot increases.

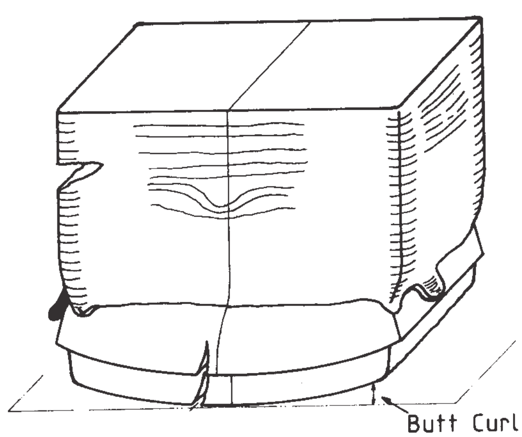



Figure 1: Schematical depiction of butt curl of D.C. cast sheet ingots

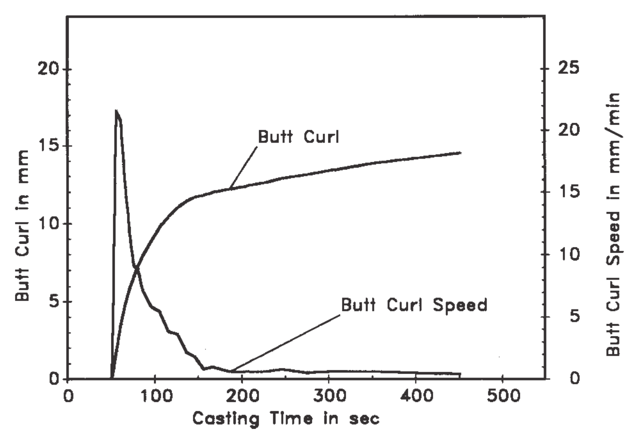



Figure 2: Time dependency of butt curl and butt curl speed

The occurrence of butt curl causes problems which can disrupt the casting process and influence ingot quality [4-6]. One casting problem is that curling greatly reduces the contact surface between the ingot butt and the starting block thereby reducing the stability of the ingot. Investigations have shown

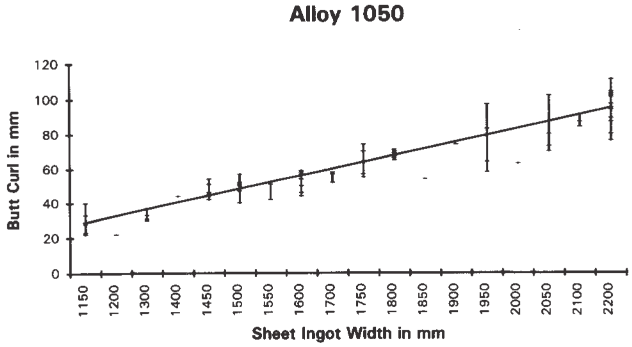



Figure 3: Butt curl in dependency on sheet ingot width
Ingot thickness: 600 mm

that, when employing the very widely-used, bowl-shaped starting block for an ingot size of e.g. 1700 x 500 mm, a contact zone of only 150 x 300 mm exists between the starting block and the ingot when curling comes to an end. The contact surface is elliptical in shape and is influenced not only by the ingot size and the related curling but also by the alloy being cast. A further problem of curling is that it can lead to the melting of the solidified shell of the curled ingot butt and, as a result, to melt run-out. Such an occurrence is very dangerous and has already led to several serious explosions. Melt break-out can also occur on the narrow side of the ingot if it loses contact with the mould wall because of curling and the formation of an air gap which subsequently leads to remelt of the surface shell. A further problem is that of strong evaporation of the cooling water which flows into the gap between the butt of the ingot and the starting block.This leads to the so-called "bumping effect". Frequent quality defects which occur in the ingot butt in connection with butt curl are cold and hot cracks. These are attributable to the build-up of internal stresses in the metal. In addition, the occurrence of cracks and cold shuts is to be seen in the corner of the ingot butt. These quality defects make a considerable amount of sawing necessary and thus lead to higher quantities of scrap.
To reduce or eliminate the aforementioned problems, a minimization of butt curl is essential. In addition, a reduction in direct water cooling in the start-up phase is necessary. Measures or processes which form the basis of these are the $CO_2$ Process, Pulse Water Cooling and the Turbo Curl Process [7-10]. Although these processes are very effective, distinct problems can arise when using them. The perfect functioning of the $CO_2$ Process depends very greatly on the quality of the cooling water; this process therefore cannot necessarily be used universally. This also holds true for the other two processes. The functioning of the Turbo Curl Process, in which air is injected into the cooling water system of the mould, depends on the design of the mould cooling system, whereas using Pulse Water Cooling for high-alloy qualities can lead to finely arranged surface cracks in the ingot butt. Furthermore, Pulse Water Cooling cannot be used with all types of moulds.
Due to the problems listed above, as well as others, to which belongs the availability of the aforementioned processes, there exists a need to look for a further alternative to reduce butt curl. Consequently, in view of the influence the starting block exerts on butt curl, the target was set to achieve a reduction in butt curl and to improve the stability of the ingot by taking further optimizing measures.

## Research Programme

The following programme of research concerning the influencing of butt curl was carried out:

A - Influence of the bowl depth of conventional starting blocks on butt curl and butt swell.

B - Influence of a newly developed starting block shape on butt curl and butt swell.

C - Investigation of the ingot liquid sump formation in the start-up phase.

D - Temperature measurements in the ingot butt and in conventional and newly developed starting blocks.

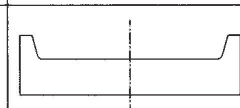
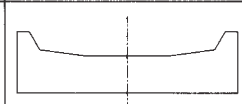
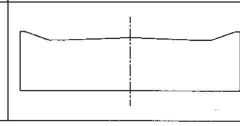
E - Modelling of the start-up phase.

In the first part of the paper, points A-C in the programme are described while the second part contains points D and E.

## Experimental procedure

Casting experiments using different types of ingot moulds and sizes were carried out on a laboratory and industrial scale to test new starting block shapes and their influence on butt curl. The types of ingot moulds and sizes used are listed in Table I as well as the relevant conventional starting block shapes with schematical depiction.

Table I: Used mould types and sizes and starting block shapes in schematical depiction

| Mould Type | Mould Size | Starting Block Shape |
|---|---|---|
| Hot Top Mould Type VAW | 600x200 mm<br>1100x400 mm<br>2200x600 mm |  |
| Hot Top Mould Type Elkem | 1950x600 mm |  |
| Wagstaff True Slot | 2100x600 mm |  |

The experiments with laboratory sizes 600 x 200 mm and 1100 x 400 mm were aimed at testing different starting block shapes and as a result finding the optimum shape which should then be tested for suitability in industrial-scale experiments.
The main test alloy used was alloy AA 1050. Tests were also carried out with alloys AA 3004 and AA 5182 but these will not reported on in-depth in this paper. The transfer of molten metal in the mould was effected either by means of a spout/stopper system or by level pour flow (Elkem mould). Distribution bags were used to distribute the metal in the moulds. In

all tests, the inlet temperature of the melt was between 700°C and 710°C.
In addition to the starting block shape, the mould filling time, the start-up speed and the amount of cooling water were used as test parameters. These were varied during the start-up phase within a defined cast length and within the framework of different start-up programmes which can also have an influence on butt curl [3]. In addition, starting aids such as $CO_2$ in the cooling water and Turbo Curl were used in combination with the newly developed starting block shape. For comparison, tests with the conventional bowl-shaped starting block were carried out with and without the aforementioned starting aids. Detailed information about the start-up conditions and the results are contained in the respective result report on the grounds of convenience and layout.

The measurement of butt curl was carried out using inductive displacement transducers [11]. These were linked to steel wires which projected into the hollow space of the moulds through vertical holes drilled in the starting block. The steel wires freeze into the butt of the ingot during casting start-up and transmit the movement of the ingot butt to the inductive displacement transducers. Two different measuring positions in the starting block were used in the experiments. These and the configuration of the measuring device are shown in Figure 4. For the laboratory tests, measuring position 1 was used exclusively while both measuring positions were used for the industrial-scale tests. By recording the displacement of the steel wire as a function of time, the maximum curl can be determined and the curl speed worked out.

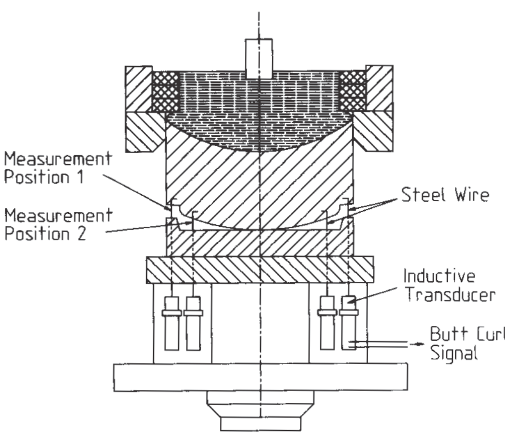



Figure 4: Schematical depiction of the device for butt curl measurement

As a supplement to the research on butt curl, investigations were also carried out on butt swell. For this, longitudinal slices were cut out of the middle of the ingot butt and the thickness of the ingot measured at various distances from the bottom of the ingot. Furthermore, research was done on the development of the liquid sump during the instationary start-up phase by charging liquid zinc into the ingot sump after defined cast lengths. The visualization of the liquid sump formation and the measurement of the sump depth were effected by means of macroetched longitudinal slices taken from the middle section of the ingot butt.

## Test results

As previously mentioned, tests were carried out on a laboratory scale and under normal production conditions. The test results which follow are broken down accordingly.

### Laboratory-scale tests

In preparatory fundamental investigations on a laboratory scale using hot-top moulds of a 600 x 200 mm size, the influence of the bowl depth of the conventional starting block shape on butt curl and butt swell was investigated. The results are shown in Figures 5 and 6. From Figure 5 it is clear that, from a determined bowl depth, butt curl decreases distinctly. In addition, butt swell also decreases with increasing bowl depths, as seen in Figure 6. Presumably, a connection exists here between the liquid sump formation during the instationary casting phase. The results of the relevant measurements are also displayed in Figure 6. Here, as expected, a crowning of the liquid sump depth is to be seen; the deeper the starting block, the bigger this becomes. The impression is that maximum sump depth coincides with ingot necking which becomes more marked as the crowning of the sump depth gets bigger. On the other hand, when the crowning of the sump depth is only slightly formed or missing completely, no necking but distinct butt swell can be observed in its place. Strong butt swell and significant necking can both increase the amount of scalping and scrap from sawing considerably.

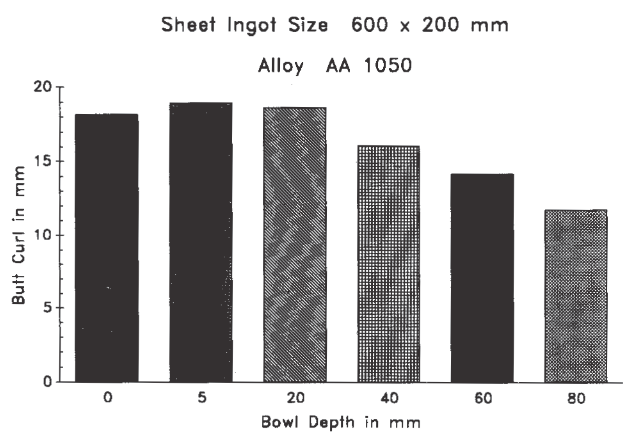



Figure 5: Influence of bowl depth of the starting block on butt curl.
Starting speed: 60 mm/min
Measurement position 1

The above-described results show that butt curl can be reduced appreciably by means of the bowl depth of the starting block alone. The problem with this measure, however, is that the metal content of the starting block rises and as a result the butt scrapping rate increases. A starting block shape which thus takes note of the positive aspects of the bowl depth and which is so designed as to make the smallest metal content possible must be used. These requirements are met by the newly developed starting block which is shown in Figure 7. The starting block takes the form of an axial trapezoidal cone with defined angles of the lateral faces. Figure 8 shows the results of laboratory tests using the block and a hot-top mould of 600 x 200 mm size. It can be seen that through the use of the cone, again in comparison

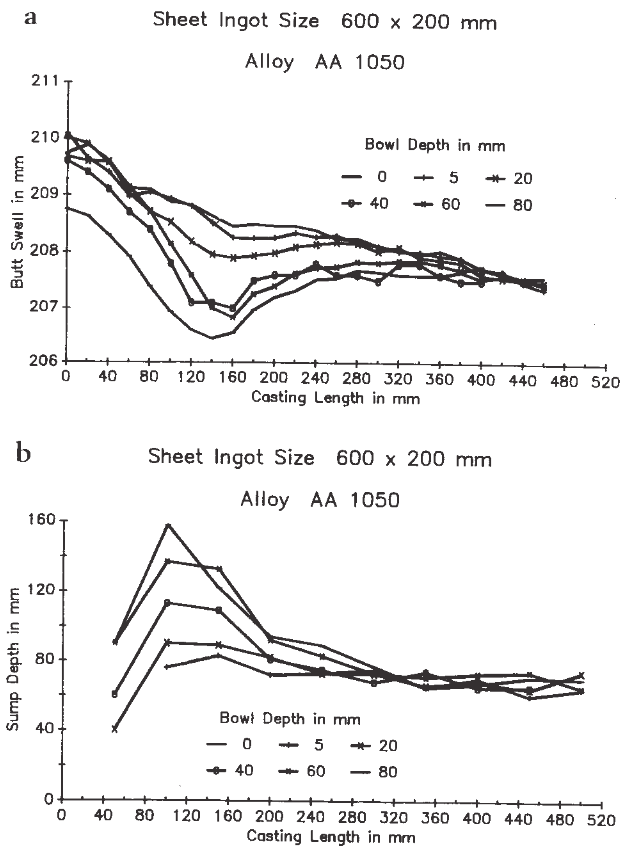



Figure 6: Influence of bowl depth of the starting block on butt swell (6a) and sump depth (6b)
Starting speed: 60 mm/min

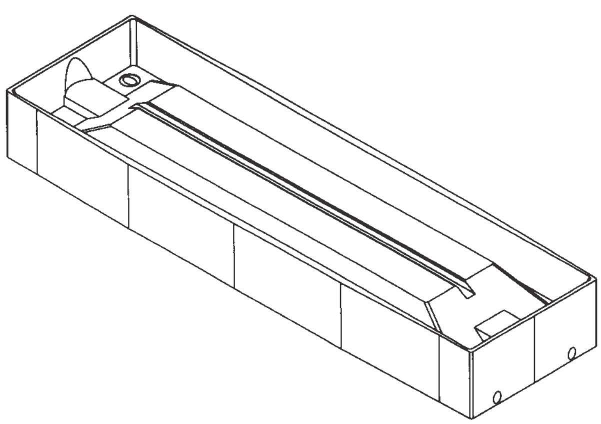


Figure 7: The newly developed starting block shape

to the tested maximum bowl depth (80mm), a further reduction in butt curl is achieved. The least butt curl occurs when the height of the cone is equal to the bowl depth. In addition, the results displayed in Figure 8 reveal that the bowl depth is also of great importance with this shape of block i.e. that despite the cone, butt curl again increases with decreasing bowl depth. The height of the cone cannot compensate for this unless the cone juts out above the starting block. This, however, as described later, cannot be done on casting practice grounds. The cone also has an influence on the geometry of the ingot butt. With increasing cone height, given a constant bowl depth, the thickness of the butt increases in comparison to conventional starting blocks with the same bowl depth. This is clearly seen in Figure 9.

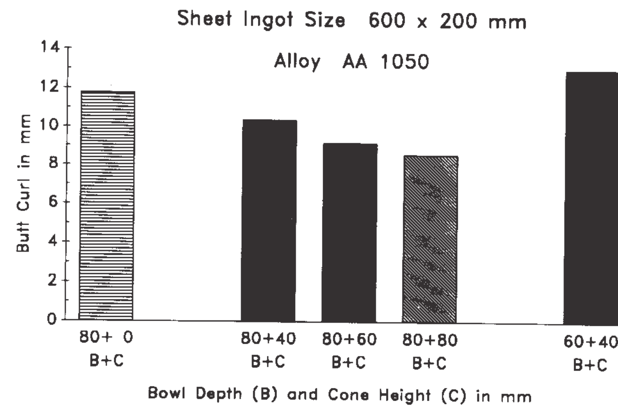



Figure 8: Influence of bowl depth and cone height of the newly developed starting block shape on butt curl

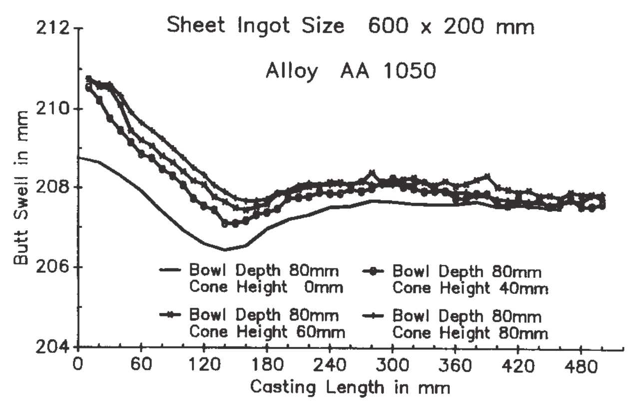



Figure 9: Influence of cone height of the newly developed starting block shape on butt swell
Starting speed: 60 mm/min

The decrease in butt curl also becomes logically apparent in curl diagrams, as shown in Figure 10. In comparison to conventional starting blocks, butt curl begins with much less speed when the conical starting block is used (10a). Butt curl can be reduced further by using suitable start-up programmes whereby the casting speed is deliberately increased within a determined start-up length up to a final value. A retardation of butt curl then occurs after immersion in the direct water cooling i.e. the maximum curl speed is reached later, as seen in Figure 10b.

## Industrial-scale tests

Industrial-scale tests with the newly developed conical starting block were carried out using three different types of mould and size. These have already been described above. Casting aids such as the use of

$CO_2$ in the cooling water and Turbo Curl were also used in the series of tests. In addition, comparative experiments were made using conventional starting blocks with and without casting aids. Figure 11 shows the test results for the Wagstaff True Slot Mould. For these tests, measuring position 2 was used for the measurement of butt curl. It can be seen that, when using a conventional starting block, butt curl was clearly reduced through the use of $CO_2$ and Turbo Curl under the used start-up conditions. The results of the tests using the conical starting block are also to be seen in Figure 11. These show that, through the use of the newly developed starting block shape, a distinct reduction in butt curl was achieved even without casting aids. When $CO_2$ and Turbo Curl were used, butt curl was once again reduced considerably. Figure 11 also shows these results for the used start-up conditions.

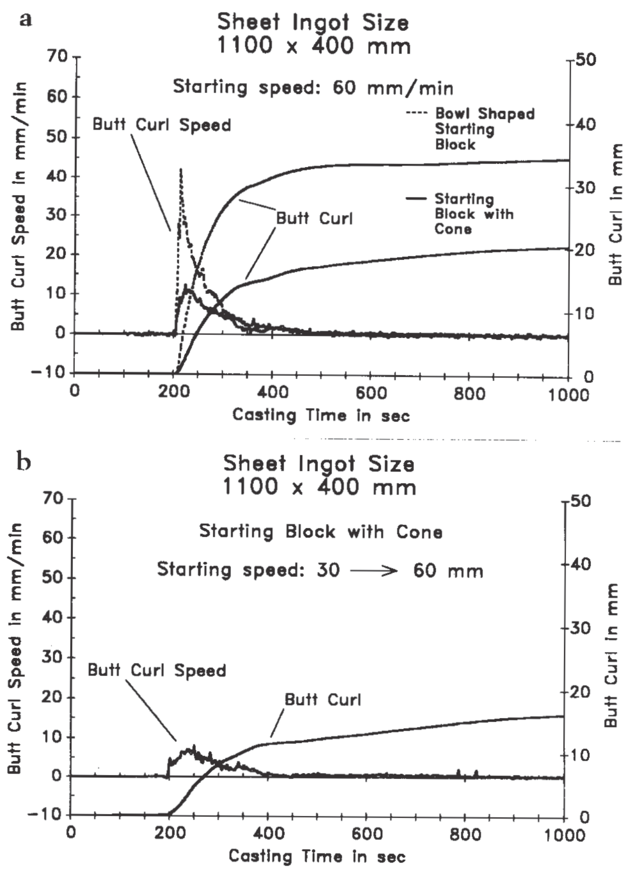



Figure 10: Influence of starting block shape on butt curl and butt curl speed

The results of the tests with the Elkem hot-top mould and the conical starting block are displayed in Figure 12 for measuring position 1. In these tests, additional $CO_2$ was used in the cooling water as a casting aid. It can be seen that, under the used start-up conditions, only a very small amount of butt curl, some 25-35 mm, occurred for this size due to the use of the conical starting block. By using $CO_2$ in the cooling water, a further reduction in butt curl to approx. 20 mm was achieved, as is shown in Figure 12. The results quoted here indicate a significant reduction in butt curl when compared to conventional starting blocks which show butt curl without $CO_2$ of between 100-150 mm and with $CO_2$ between 50-60 mm under the used start-up conditions.

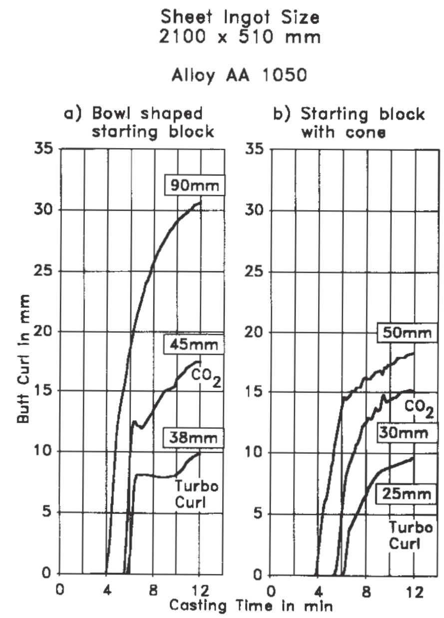



Figure 11: Butt curl of sheet ingots, cast with the bowl shaped starting block (11a), the starting block with cone (11b) and different modifications of the cooling water
Measurement position 2
□ -> Total butt curl
$CO_2$: 20 $m^3/h$ Turbo Curl: 8-12 SCFM

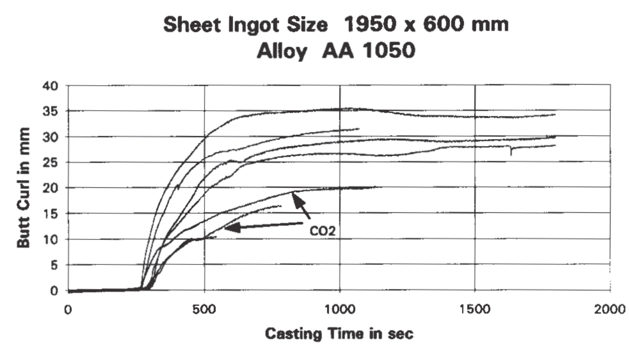



Figure 12: Butt curl of sheet ingots, cast with the newly developed starting block with a cone and $CO_2$ in the cooling water

The above-described test results for different types of mould and size have shown that, by using the conical starting block, a reduction in butt curl comparable with the $CO_2$ Process can be achieved. Furthermore, it is possible through the use of this starting block shape in combination with casting aids such as $CO_2$ in the cooling water and Turbo Curl to produce nearly straight sheet ingot butts.

As a supplement to the industrial-scale casting tests, casting experiments with a VAW hot-top mould and a size of 2200 x 600 mm were carried out under actual production conditions. A conical starting block in this size was placed in a 4-strand casting unit beside conventional starting blocks. The capability of the conical starting block was tested over a long production period and the butt curl which appeared on the narrow sides following the end of casting measured by hand. The results of these measurements are shown in Figure 13 in comparison to a conventional starting block in the same size. It can be seen that, also in these tests, a distinct reduction in butt curl through the use of a conical starting block could be determined. Furthermore, it is to be noted that the start-up conditions were adjusted to those of the conventional starting block which do not represent the optimum for the conical starting block. Given optimum start-up conditions, a further reduction in butt curl is to be assumed.

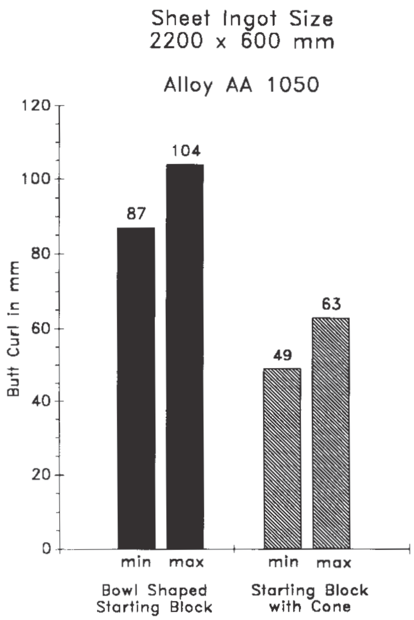



Figure 13: Butt curl of sheet ingots, cast with the bowl shaped starting block and the newly developed starting block with a cone Measurement position 1

Finally, it is also to be noted that the stability of ingot was found to be high in the industrial-scale tests. This can be put down to reduced butt curl and to the introduction of the cone shape of the newly developed starting block.

## Casting practice requirements for using the conical starting block

The use of the newly developed conical starting block places certain requirements on the casting practice. These have to be met for its successful application. Of great importance is the metal feed and distribution during the mould filling phase before lowering begins. An even metal distribution, preferably in the direction of the narrow sides of the mould, is necessary so that no weak points occur in the solidified ingot butt shell which can lead to crack formation. The metal distribution system must be fashioned accordingly, as well as the conical shape in support. Furthermore, a optimization of the mould filling time for each size is helpful in building up a stable ingot butt shell. The metal feed takes place by means of a spout and distribution bag or float; the height of the cone is limited, thus sufficient distance remains between the end of the spout and the top of the cone and any sticking of distribution bag to the cone is avoided. Here, possibly, a little less reduction in butt curl has to be accepted.

An important factor of the newly developed starting block shape is the angle of the cone sides. This angle must be set so that no solid shrinkage of the bottom butt takes place. On the other hand, the angle of the cone sides must be set so that a largely even upward shrinkage of the bottom butt takes place along the side surfaces of the cone. Figure 14 shows the upward shrinkage of the ingot butt during its cooling on the cone. The measurements were taken in accordance with the previously described principle of measuring butt curl, only here they were taken in the middle of the ingot long sides. From the measuring results in Figure 14, it is obvious that upward shrinkage begins after a determined cast length when butt curl has already ended. At the same time, it seems that the ingot butt alternately slips higher on one side or the other. Correspondingly, a displacement of the ingot butt from its zero or equilibrium position relative to the starting block occurs which can be displayed by the difference between the left and right measured value. Upward shrinkage begins presumably when the ingot has reached its maximum liquid sump depth in the start-up phase and cooling by means of direct water cooling is effective right into the centre of the ingot. After a defined cast length, a distinctly uneven upward shrinkage of the ingot causes a kink in the ingot which can be considerable under unfavourable conditions and make a deeper scalping of the ingot necessary before hot rolling. Correspondingly, an optimization of the cone angle as well as the start-up conditions are necessary in order to prevent the kink or keep it to a minimum. In addition, kink formation can be counteracted by taking further constructive measures on the starting block, as for example the use of a groove on the top side of the cone to guide the ingot butt during upward shrinkage.

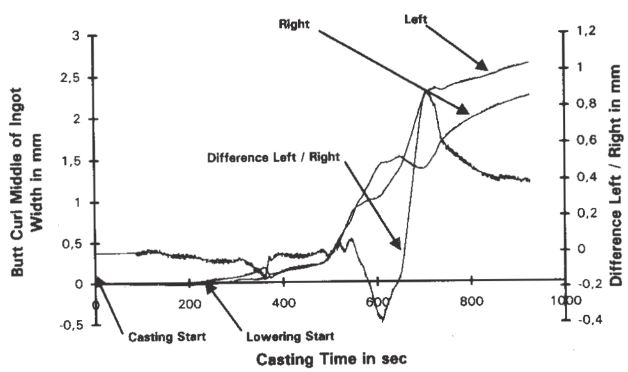



Figure 14: Butt curl in the middle of ingot width, for the example of an ingot size 1100 x 400 mm and the alloy AA 1050 Starting speed: 60 mm/min

## Conclusions

A newly developed starting block shape for the D.C. casting of sheet ingots was introduced which has a central cone. This starting block shape, without the use of casting aids, considerably reduces butt curl

in comparison to conventional starting block shapes. The extent of butt curl reduction depends on the depth of the bowl and the height of the cone of the new starting block. The effect of the newly developed starting block shape lies within the sphere of the $CO_2$ Process. The additional use of casting aids such as $CO_2$ in the cooling water and Turbo Curl reduces butt curl even further. For the new block shape to have its full effect, the geometric stipulations concerning the angle of the cone among other things have to be observed. In addition, an optimization of the start-up conditions is to be carried out. To this, in particular, belongs the metal feed and distribution when filling the mould before lowering begins.
The operating capability of the newly developed starting block shape was proven in numerous tests under production conditions and the distinct reduction in butt curl was confirmed.

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