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Tailor Blank Casting—Control of sheet width using an electromagnetic edge dam in aluminium twin roll casting

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ABSTRACT

A significant fraction of all sheet aluminium is scrapped during manufacture because the supply chain is configured to produce long coils of strip with constant width while end products are formed from irregularly shaped non-tessellating blanks. In this paper, an opportunity to reduce this rate of scrap is explored. Electro-magnetic edge-dams have been used previously to contain the melt in twin-roll strip casting of aluminium but here, equipment has been designed to allow rapid movement of such an edge dam during casting. This is named 'Tailor Blank Casting'. The equipment is described and the first experimental trials are presented, with one edge of the melt constrained by a moving electro-magnetic dam in order to achieve a controlled variation in sheet width. The trials demonstrated successful containment of the liquid prior to solidification, and a sheet with close to step changes in width was cast. From analysis of the results of these trials, the mechanisms of width change are proposed and the effect of the moving dam on product properties is studied. The paper concludes with a discussion about possible yield savings and the next steps for further development of the process.

1. Introduction

The aluminium supply chain is split into two distinct parts—the metals industry, which produces aluminium from ore and then casts and rolls the metal to make stock products such as coils of sheet, and the manufacturing industries which take these stock products and reshape them to make consumer products, for example car doors. This makes the supply chain subtractive—a large fraction of the metal cast is removed and does not reach the final consumer product. This loss may be quantified by the *yield* which is the ratio of metal in the final product to the original mass of metal cast. Cullen and Allwood (2013) calculate the average yield across all aluminium products as 60%, and in a case study of an aluminium car door Milford et al. (2011) found a yield of 40%, with half of the metal subtraction attributable to the rectangular sheet being cut to create a door and window outline in the blanking and stamping processes. Therefore, the ability to cast the outline of irregular sheet products directly would create an opportunity for a significant improvement in yield. In this paper, such a process is proposed—'Tailor Blank Casting'.

Tailor Blank Casting is envisioned as building on existing efforts to cast nearer to net thickness by adding extra controls to allow the width-profile of irregular sheet products to be cast directly. The most established direct sheet casting process, twin roll casting, is taken as the starting point. In twin roll casting (TRC), sheets are cast directly by feeding liquid metal through a ceramic feed tip between two counter-rotating cooled rolls. As soon as the liquid metal touches the rolls it starts to form a solid shell which grows as it moves towards the roll bite. The shells on the top and bottom roll meet at a solidification point just before the roll bite and from there the sheet is deformed as it is in the hot rolling process. A cross section of the solidification region is shown in Fig. 1.

An electromagnetic (EM) edge dam is used to manipulate the metal by applying a pressure along the sump during casting. This pressure controls the transverse edge position of the metal inside the feed tip, and the edge is moved to vary the width of the cast sheet. In an ideal embodiment, an EM edge dam would be used on each edge of the strip and additional EM actuators could be added to cast strip with holes (requiring additional modifications to the metal feed). As a first step, in this paper the process is demonstrated by controlling one edge of a cast strip on a laboratory scale twin roll caster.

2. Literature review

The methods of setting and changing width in conventional twin roll casting processes and the principles of electromagnetic

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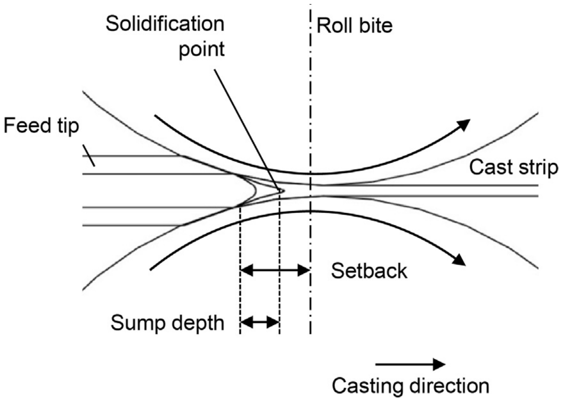

Fig. 1. Cross section of twin roll caster showing area of solidification.

containment are described below, and the opportunity of using an EM edge dam for width control identified.

2.1. Mechanical width control in twin roll casting

The twin roll casting process is described in detail in the text by Ferry (2006). Liquid aluminium is fed into the back of a TRC via a refractory feed tip, which fully contains the metal until it is solidified. The top and bottom pieces end at a fixed setback from the roll bite determined by the desired solidification length. Two edge pieces protrude further towards the roll bite to provide a physical barrier to the liquid metal, thereby acting as static mechanical edge dams. In order to vary the width of the strip, the casting process must be halted, and either a new feed tip with a different width inserted or refractory plugs used to reduce the width of the aperture in the existing feed tip.

Smith et al. (2004) propose and demonstrate on a pilot caster the Fata Hunter Optiflow system, which separates the edge dam from the feed tip so it may slide inside the tip, transversely along the width. A graphite seal prevents liquid aluminium from leaking through the gap and the edge dam is actuated to give a controlled width. Without stopping casting, they demonstrated a width increase of 200 mm incrementally over 2 h of casting, at a maximum rate of 1.5 mm/s. The Optiflow system is designed to cast sequential coils of sheet at different widths without interrupting casting, but problems could be encountered when trying to move the edge dam at much faster rates—can the graphite maintain a good seal in the feed tip, will its lifetime be compromised by rapid motions, and how does the moving edge dam interact with the partially solidified shell when decreasing the width? No follow up report has been made in the literature.

With all mechanical edge dams, there is a sliding contact between the solid shell which is moving forward and the static metal-facing surface of the edge dam. Friction and unwanted heat transfer out of the strip leads to defects at its edges. In particular edge cracks form via the mechanism described by Monaghan et al. (1993). The extra heat transfer through the edge dam causes solidification to occur earlier at the edges of the strip than at the centre, and therefore when the strip is rolled the edges are deformed more leading to cracking, particularly with hard alloys. This is a common problem in aluminium twin roll casting and as a result all industrial casters have edge trimming downstream to remove the cracked area, normally 20–30 mm from the total width of 2000 mm (Romano and Romanowski, 2009).

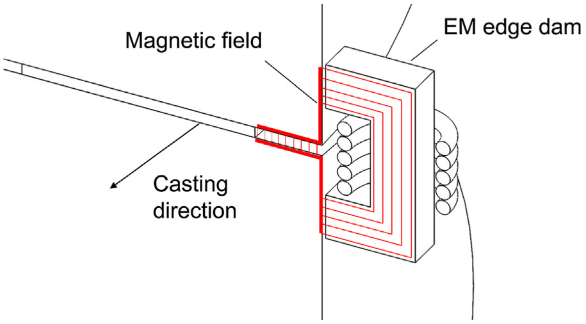

Fig. 2. EM edge dam by Whittington et al.

2.2. Electromagnetic containment

Given these defects, electromagnetic (EM) containment has already been proposed and demonstrated for use in aluminium twin roll casting. The principle, derived in more detail by Davidson (2001), involves applying an AC magnetic field of magnitude B_0 tangentially to the surface being contained. At a suitably high frequency (on the order of kHz), the alternating field may only diffuse a small distance into the metal (the ‘skin depth’). An electrical current is induced in the surface of the metal, and the interaction of the applied magnetic field with this current produces a magnetic pressure that acts to repel the metal from the field. The average magnetic pressure, P_m, is given in Eq. (1). μ_0 is the permeability of free space.

$$P_m = \frac{B_0^2}{4\mu_0} \tag{1}$$

The use of EM edge dams in twin roll casting has been demonstrated on a lab scale by Whittington et al. (1998) for horizontal aluminium TRCs, and in a theoretical design proposed by Gerber and Blazek (2000) for vertical steel casters. The geometry of the Whittington EM edge dam and its magnetic field are shown in Fig. 2. The Whittington design is a horseshoe-shape core bolted to the side of the caster, which uses the fact that the steel rolls are magnetic to direct flux into the roll bite. The distribution of the magnetic field is such that an increase in pressure in the aluminium would cause the

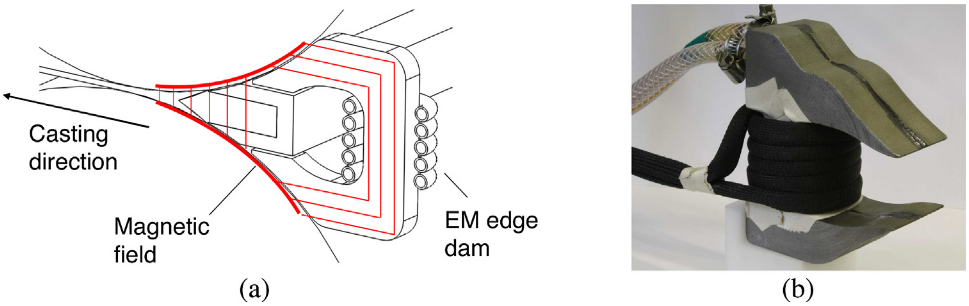

Fig. 3. EM edge dam design by McBrien and Allwood (2013)—(a) distribution of field and (b) manufactured EM edge dam.

field to bunch up and increase in strength, so that the arrangement is inherently stiff and stable.

The Whittington EM edge dam was operated at 16–30 kHz with up to 4000At applied, and successfully contained one edge of a cast strip. A small width variation of 3 mm was noted when changing the current applied to the EM edge dam during start-up, but because the field attenuates quickly away from the magnet large changes in width would be impossible by varying current alone. The operating frequency was chosen based on an optimisation for stiffness—at this frequency the change in width with pressure in the aluminium is minimised. The skin depth in the aluminium is 0.6 mm. With 4000At applied, the EM edge dam requires water cooling to extract heat by eddy currents and hysteresis in the core.

The Gerber design uses a wedge shaped conductor with no flux concentrator, with a magnetic field generated in concentric circles around it. The geometry of the conductor is designed so that the field becomes strongest at the roll bite, where the static pressure is greatest, so that the free liquid metal surface is approximately vertical.

Both EM edge dam designs are unsuitable for rapid and large variations in width because they cannot easily be moved transversely along the rolls without impacting liquid metal. A novel geometry was proposed by the authors in McBrien and Allwood (2013), and this design is shown in Fig. 3. Like the Whittington EM edge dam, a horseshoe-shaped electromagnet is used, but rotated by 90° and located behind the feed tip, pointing in the casting direction. The horseshoe is profiled to fit around the feed tip and to direct the magnetic field into the roll bite area via the surface of the rolls, allowing for it to move transversely to directly control width. This EM edge dam design was tested at frequencies of 5 kHz and 15 kHz with a low melting point alloy, and it was suggested that a lower frequency was required to increase flux density at the roll bite to improve strength and stiffness of containment.

Beyond containment, the interaction of EM fields and liquid metal can be used to produce a wider range of effects. In a review of industrial applications, Li (1998) identified uses in transporting metal (valves, brakes, and pumps), stirring to distribute solutes (in continuous casting of steel) or for melting metal. In industry, the use of EM for containment is primarily through EM fields replacing copper moulds in the DC casting process, where the alternate cooling conditions and stirring create a more uniform microstructure so that scalping of the cast billet to remove the surface is reduced. The CREM (‘Casting, Refining, ElectroMagnetic’) process described by Vives (1989) and the ‘Electromagnetic Roll Casting’ process by Mao (2003) both use the stirring effect of lower frequency magnetic fields (10–50 Hz) to refine the microstructure of the cast metal. Applied at the solidification point, stirring disrupts the solid–liquid interface and distributes nucleation sites widely. In both cases, the grain refinement observed was no better than that achieved by adding a dedicated grain refining additive.

2.3. Opportunity

There is currently no way of creating rapid and large variations in sheet width during twin roll casting. A novel EM edge dam design has been proposed by McBrien and Allwood for this purpose, and in this paper the first casting trials using this EM edge dam are reported. From these trials, we may begin to understand the possibilities and limiting factors for rapid width change and the effect on the properties of the cast sheet.

3. Experiment design

In this section, the equipment design is explained and a plan for casting trials with the novel EM edge dam is given.

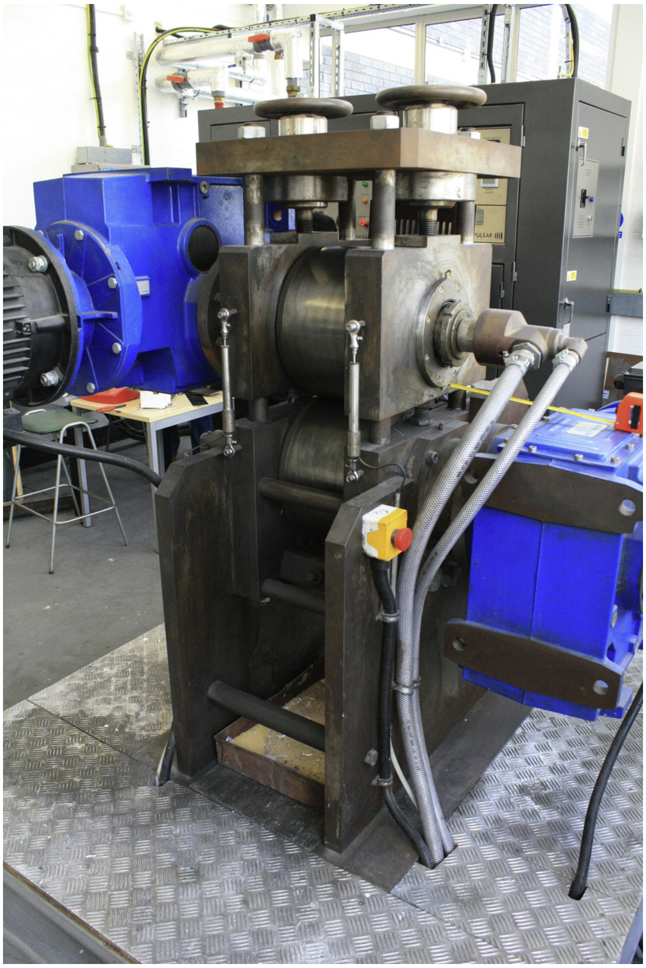

Fig. 4. Horizontal twin roll caster at BCAST, Brunel University.

3.1. Equipment

The experiments were carried out on the lab-scale horizontal TRC at BCAST, Brunel University, which is shown in Fig. 4. The caster is a smaller version of industrial scale units, with small diameter rolls (320 mm) and a narrow working section (120 mm sheet width compared to 2000 mm for the largest industrial casters). The rolls are made from H13 hot working tool steel, which has magnetic relative permeability around 680 (Smithells Metal Reference, 2004). The primary use of this caster is to conduct metallurgical experiments which require an undeformed microstructure, so it is designed with a low stiffness. The top roll can move upwards so as not to apply a large rolling force, meaning the strip microstructure is as close to the as-cast state as possible. The EM edge dam and other equipment were specifically to fit this caster.

The EM edge dam is a copper coil wrapped around a flux concentrator made from Fluxtrol 100. Fluxtrol 100 is an iron-doped plastic which has a relative permeability of 120 with reduced heat generation due to the minimisation of eddy currents. Despite this, the core must still be water cooled via an internal channel. As shown in Fig. 3, the concentrator geometry is profiled to direct flux into the roll surface where it is carried forward towards the roll bite, and fits around the feed tip. The transverse position of the EM edge dam is controlled via a linear actuator.

The feed system and the EM edge dam are shown in Fig. 5. The feed tip must be non-conductive and non-magnetic so as to be transparent to the magnetic fields generated by the EM edge dam. It is made from N17, a calcium silicate refractory material which is

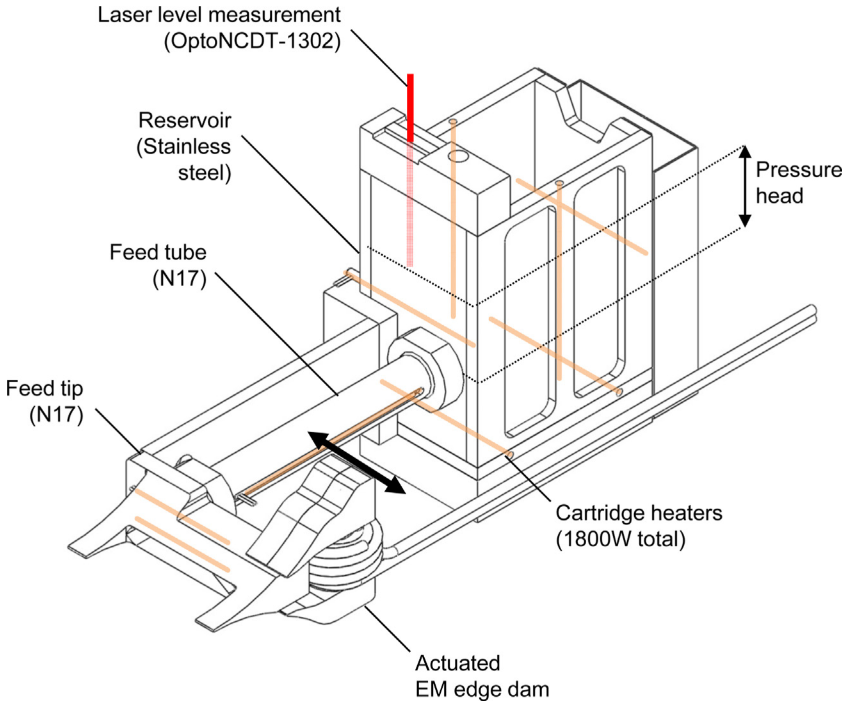

Fig. 5. Aluminium feed system for experiments.

commonly used in TRC feed tips. The feed tip was designed to be as thin as possible so that the EM edge dam could be placed closer to the roll bite, thereby increasing the strength of the magnetic field along the sump. Two mechanical edge dams are integrated in the feed tip—one to provide containment on the uncontrolled edge, and one beside the EM edge dam for use during start-up and to provide a failsafe situation if the EM edge dam switches off.

The target width variation is from 50% to 100% of the width of the feed tip opening (65–130 mm). To allow the required EM edge dam motion, the liquid metal feed into the tip is asymmetric. The inner profile of the feed tip is tapered to encourage even flow across the width. Once a blockage from already-solidified strip is established during casting, the liquid metal fills the entire tip. The liquid metal is fed via a tube (also made from N17) from a stainless steel reservoir which is far enough from the EM edge dam so as not to affect the distribution of the magnetic field. The entire feed system is preheated with cartridge heaters inserted in machined holes in each part. Low powers are used for the feed tip and feed tube (2 × 100 W heaters in each part, 400 W total) because the N17 is an effective insulator and has a low thermal mass, while the reservoir has more heaters and a higher power to compensate for more heat being conducted away (6 heaters, 1400 W total). The temperature of the liquid aluminium as it is delivered to the caster may be varied by changing the preheat temperature and/or time, or by varying the superheat of the liquid aluminium at pouring.

The metallostatic pressure of the liquid aluminium, which balances with the applied magnetic pressure from the EM edge dam, is set by the height of the liquid metal surface in the reservoir (with small flow rates and a low viscosity, pressure loss in the feed tube is ignored). An OptoNCDT-1302 laser distance sensor is used to measure the pressure head, and the head may be controlled manually by varying the pouring rate during casting.

A recommendation from previous testing with the EM edge dam concept was to operate at a lower frequency, in the range 1–3 kHz, in order to boost the strength of the field at the roll bite. With no off-the-shelf solutions of suitable specification available, a custom power supply was manufactured. This consisted of a signal generator and industrial amplifier which together produce a sinusoid output voltage. A parallel-resonant combination of inductor (the EM edge dam) and capacitors magnify the signal to give a high current into the EM edge dam. A circuit diagram is given in Fig. 6. The values for inductance and capacitance were chosen for resonance at approximately 1.2 kHz.

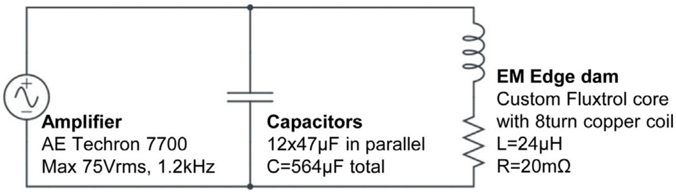

Fig. 6. Schematic circuit showing parallel resonant power supply for EM edge dam.

3.2. Design of experiment trials

The purpose of the experiments is to prove and quantify the operation of the EM edge dam in varying width, to identify which parameters or physical effects are important, and to check the quality of the cast strip.

Initially, commissioning trials were undertaken to determine the best setpoints for the new equipment for reliable casting. The EM edge dam was then tested as a static edge dam, aiming to maintain a constant width, and as a dynamic unit aiming to change width. The step response of the EM edge dam was obtained by keeping it stationary and switching it on and off, observing the change in width. Controlled width variations were attempted by moving the EM edge dam transversely, with and without variation of the pressure head in the reservoir.

To evaluate the quality of the cast strip, the surface and edge conditions were visually inspected to check for the occurrence of defects, for example edge cracks. The mechanical properties of the cast sheet were checked with tensile tests and hardness measurements, and metallographic analysis was carried out to

Table 1
Casting parameters.

Parameter	Value
Alloy	Al–2.5 wt% Mg
Liquidus temp.	650 °C
Solidus temp.	605 °C
Pouring superheat	40 °C
Preheat temp.—reservoir	660 °C
Preheat temp.—feed tube	800 °C
Preheat temp.—feed tip	800 °C
Preheat time	1.5 h
Feed tip setback	43 mm
Roll speed	1 rpm
Nominal roll gap	3 mm
Caster preparation	400 grit emery paper & graphite powder lubricant

identify any changes to the microstructure due to the magnetic field.

3.3. *Finite element model*

A finite element model was created in COMSOL AC/DC module to calculate the distribution of the magnetic field in the area between the rolls. The model calculates how the field interacts with the rolls and representative aluminium feed geometry, including the skin effect excluding the magnetic field from inside the conducting metals. The model assumes a shape for the free aluminium surface rather than solving the coupled problem of magnetic field distribution and fluid pressure/surface tension. It was previously verified through measurements taken on a mock-up section of the twin roll caster in experiments described in McBrien and Allwood (2013) and is used here to explain the observed effects on aluminium movement.

4. Results

The results from the casting trials are given below.

4.1. *Commissioning of equipment*

Starting from established successful casting trials with the Brunel University TRC, the casting parameters given in Table 1 were found to give reliable cast strips with no breakouts or premature solidification in the feed tip. To avoid sticking, the alloy chosen has a 2.5 wt% Mg content and the rolls were painted with a graphite lubricant before casting. The alloy was prepared from pure aluminium and magnesium beforehand, mixed and allowed to homogenise for 1 h before casting, and the oxides removed by skimming the surface just before pouring.

Temperature measurements taken in the feed tip indicated that heat loss was higher than expected, so a pouring superheat of 40 °C was used to compensate. The preheat temperatures were on the limit of the capabilities of the cartridge heaters but with sufficient preheat time a steady state could be reached.

The roll speed was set at 1 rpm, and with a nominal roll gap of 3 mm produced a strip of thickness 4–5 mm at a linear casting speed of 18 mm/s. This indicates that the solidification point is sufficiently offset from the roll bite to ensure the casting is not prone to liquid breakouts. Using the mechanical edge dams that are part of the feed tip, a strip of width 130 mm was produced and some edge cracks were typically observed.

The EM edge dam was tested independently of the feed system initially. Its operation was limited by the length of time the output signal could be maintained before the amplifier overheated and tripped. Operation at 170 A output (equivalent to 1400At applied to the 8-turn EM edge dam) and 1.2 kHz for 3 min was possible. Flux density measurements were taken at points on the centreline of the core projecting towards the roll bite. These measurements are compared with predictions from the finite element analysis model in Fig. 7, which shows the magnetic field strength using the custom power supply unit at 1 kHz and at the higher frequencies used previously. Because the frequency is lower, the magnetic field is carried further in between the rolls so is stronger in the area where final solidification occurs. The flux densities measured indicate a magnetic pressure from 6 mm_{Al} at the feed tip exit up to 15 mm_{Al} closer to the EM edge dam. These values will increase in the presence of aluminium, as the magnetic field lines tend to bunch around the aluminium edge.

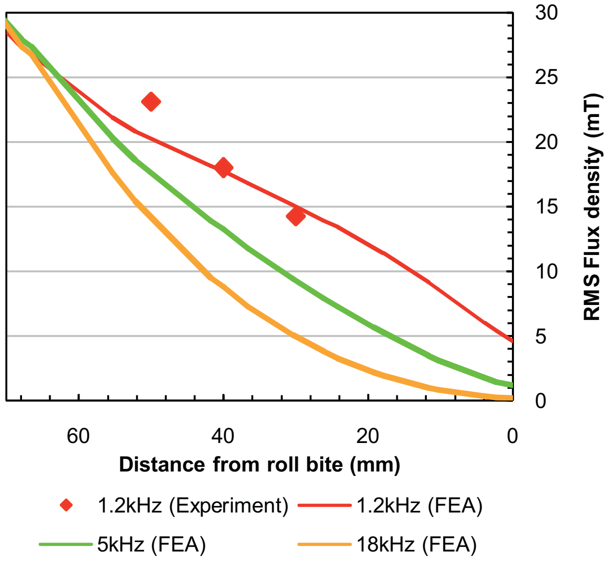

Fig. 7. Comparison of magnetic field measurements from earlier low frequency tests and new power supply (1700At applied to EM edge dam for all frequencies).

In the future, it would be possible to boost output by using a more powerful amplifier or two amplifiers in parallel, giving a stronger magnetic field. From previous experience with the higher frequency power supplies, the limit will be either the heat generation in the core or saturation of the core material. Taking these into account, with the increased amplifier power the magnetic field strength could be increased by a factor of two and therefore the pressure would be four times larger.

4.2. *Strip geometry*

The possibilities for varying width were studied through a series of casting trials with both a static and moving EM edge dam. The principle of varying width was demonstrated, with the most successful cast pictured in Fig. 8. Here, almost a step change in width was achieved, with the width varied from 130 mm to 75 mm and back almost immediately along the length. A step change is the most rapid variation in width possible, so is a very encouraging result for the potential of directly casting a wide range of challenging product outlines. Other trials were used to calculate the strength and stiffness of the EM edge dam and to evaluate in more detail the potential of both a static and moving EM edge dam for changing width.

The static EM edge dam was switched on and used to cast a sheet of approximately half the width of the mechanical edge dams (50–80 mm). In these trials, the metal was poured before switching the EM edge dam on, so pressure head decreased as the metal ran out. The pressure head at the first observed changes in width was 12 and 15 mm_{Al} in the two trials, giving a lower bound for the strength of the magnetic pressure applied by the EM edge dam (additional force must be exerted at the time of width change to overcome

Fig. 8. Fastest width change in cast strip, showing immediate change in width from 130 to 75 mm and back.

inertia). These pressures were higher than expected from the measurements of the magnetic field, which predicted only 6 mm_{Al} at the feed tip exit, indicating that some other effects must be aiding containment of the aluminium.

A tapering of the width was observed, as shown in Fig. 9(a), and is used to infer the stiffness of the EM edge dam by plotting width against pressure head in Fig. 9(b). The stiffness is approximately 2.1–2.7 mm of width change per mm of change in pressure head per both casts, giving an indication of the accuracy of pressure control required to use the EM edge dam for casting at constant width. The plots also show that for identical applied current, pressure head, and casting conditions, the strip width varies by 10 mm, indicating that the response of the EM edge dam is not perfectly repeatable.

The step response of the EM edge dam was measured by switching current on and off while holding the EM edge dam stationary, again with the centre aligned with the centre of the feed tip. The strip produced is pictured in Fig. 10. Switching the EM edge dam on causes an initial decrease in width from 130 mm to approximately 75 mm, and there is a slight rebound before settling. A 'tail' feature can be observed on all vertical trailing edges. When switching the EM edge dam off, the width returns to 130 mm, in some cases with a brief overspill beyond the feed tip. There was a delay of approximately 5 s between turning power on and the observed width reduction, but when switching the EM edge dam off the response was immediate. This suggests that the mechanisms of increasing and

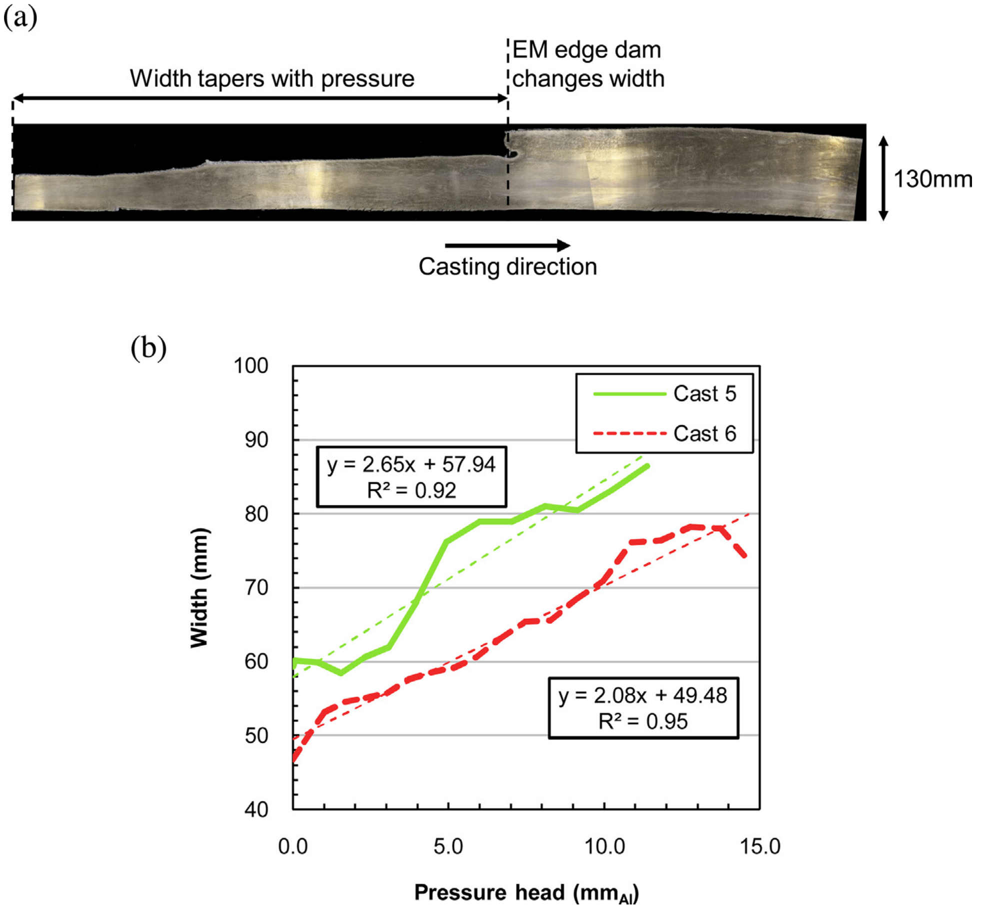

Fig. 9. (a) Casting trial showing change in width when magnet is switched on. (b) Stiffness plot of stationary EM edge dam.

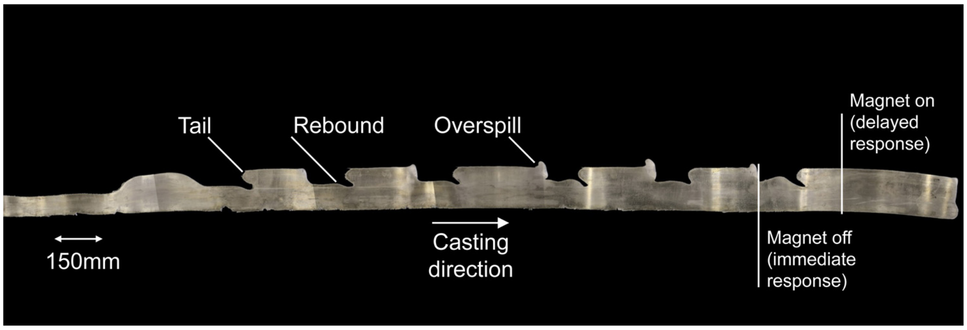

Fig. 10. Cast strip with EM edge dam turned on and off to observe step response in width.

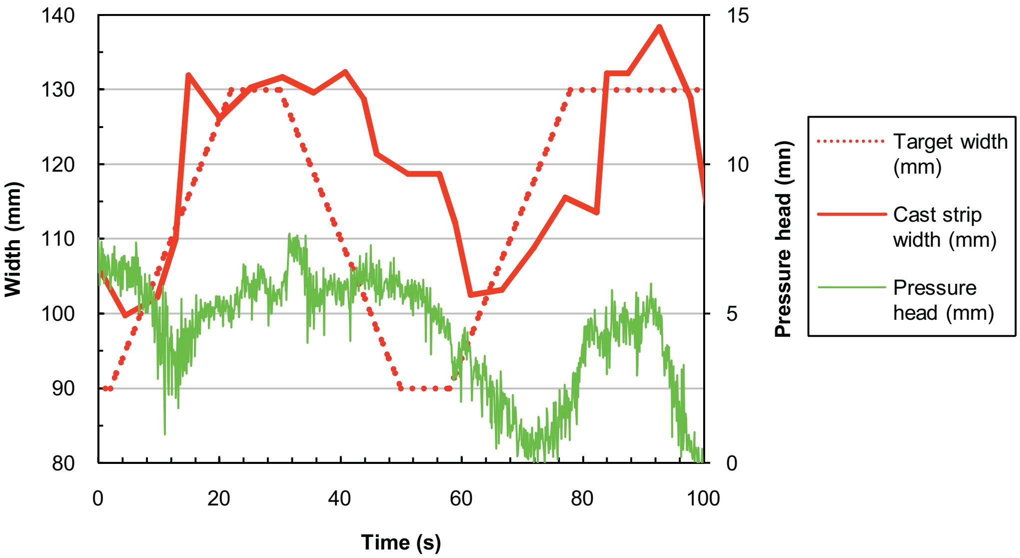

Fig. 11. Measurements of strip with moving EM edge dam and variable pressure head.

decreasing width are distinct, and is explored further in Section 5.3.

A final set of casting trials were carried out with a moving EM edge dam, aiming to change the width from 90 mm to 130 mm and back again through ramp motions at a speed of 2 mm/s. The most accurate result achieved is shown in Fig. 11. The target width is calculated from the motion of the EM edge dam, while the real width was taken via direct measurements on the sheet. Also given are the measurements of the pressure head taken with the laser. With some manual perturbation of pressure head by changing the pouring rate, the sheet width follows the same shape as the target. The change in width of the strip is approximately 30 mm for a 40 mm movement of the EM edge dam. Again, there is a delay observed between the action of the magnet and the decrease in sheet width, while increasing width is almost instantaneous.

4.3. Product quality

For Tailor Blank Casting to be useful, the quality of the cast strip would be expected to be the same or better as casting without varying width. Specifically, this means no increase in the occurrence of defects at the edge or on the surface, and comparable strength and ductility to the normal cast strip.

With the EM edge dam active, there was no discernible change in edge cracking or in the visible condition of the strip surface. Tensile test coupons were taken from strip with and without the EM edge dam active and tested according to ASTM B557-06, with the mechanical properties obtained plotted in Fig. 12. The results show that both the strength and ductility of the cast strip increase when a magnetic field is applied. However, the spread of the results is larger with the EM edge dam used, and for the worst case coupon there was a visible void in the failed surface, suggesting that the effect of the EM edge dam is unsteady. The results in Fig. 12 are from longitudinal specimens—transverse specimens were also tested and no difference in properties was found.

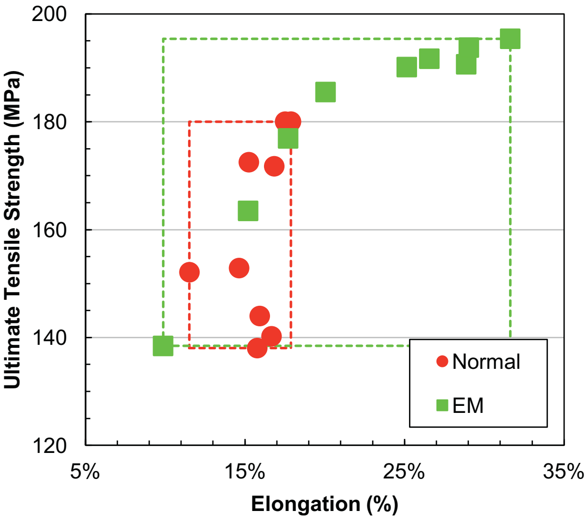

Fig. 12. Spread of ultimate tensile strength and elongation for tensile test specimens with and without EM edge dam (tested according to ASTM B557-06, 1 in. gauge length, 0.5 mm/min).

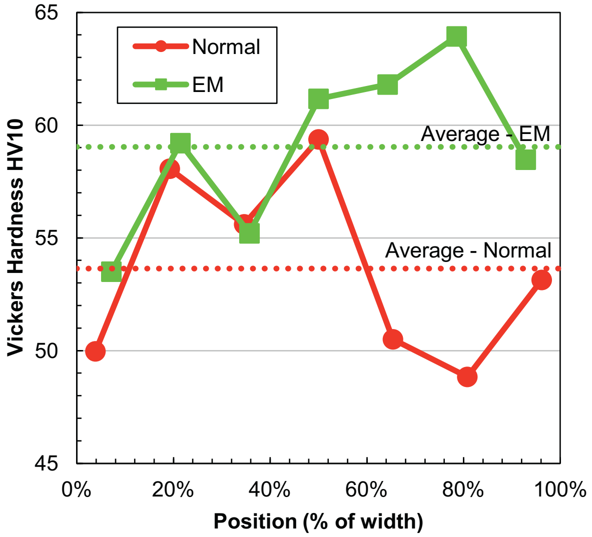

Fig. 13. Hardness variation across the width of normal and EM strip (tested according to ASTM E92-92 with a 10 kg load).

Hardness measurements were also taken across the width of the top surface of the strip at three points, with and without the EM edge dam switched on. Fig. 13 shows the averages across the width and the overall averages for the normal strip and EM edge dam. The average hardness of the aluminium increased from 53HV to 59HV, although from the plot in Fig. 13 we can see that like the tensile tests the values had a larger variation than the 'normal' strip. There was no significant difference in hardness across the width, indicating the EM edge dam has some affect at a distance of 60 mm from the edge.

In order to explain the apparent improvement in mechanical properties, micrographs were taken from samples comparing the normal microstructure of the strip to the microstructure with the magnetic field applied. Specimens were cut, mounted and polished and then etched electrolytically in Barker's solution, with the specimen as the anode and a stainless steel pot as the cathode, at 20 V for 30 s. Images were taken under polarised light with a tint plate.

Fig. 14(a) and (b) are longitudinal views examining the microstructure through the thickness for normal and EM casts respectively (note that there is a difference in thickness between samples; this is due to the reduced deflection of the caster when the strip is narrower). Both microstructures show a fine grain size at the surface where there is contact with the rolls and a very high local cooling rate, and centreline segregation at the final solidification point about 2/3 of the thickness up from the bottom surface. However, while the normal strip has large dendritic grains throughout, the EM strip shows significant grain refinement and a more rounded 'rosette' grain shape in the top portion of the strip. The bottom third section appears to be unaffected by the action of the field.

Also shown are transverse views comparing the edge of a normal strip (Fig. 14(c)) with EM strip at the nearest (d) and farthest (e) edges from the EM edge dam. Again, grain refinement can be seen, but to a lesser extent further away from the EM edge dam suggesting a non-uniform affect across the width of the strip.

5. Discussion

The casting trials have demonstrated control of the strip width and an interesting change in its properties. In this section, the implications of these results are discussed.

5.1. Equipment

Overall, the new feed system design and method of preheating worked as expected, with no problems with metal freezing prematurely and a solid strip with reasonable edge quality obtained. The asymmetry of the feed caused no issues with casting. However, there is reason to believe that the casting operation was inconsistent enough to interfere with the performance of the EM edge dam. Fig. 15 shows a plot of width against thickness for a range of points taken on different trials with the EM edge dam, with the points coloured based on whether the trial was successful (green, indicated change in width controlled by the action of the EM edge dam), unsuccessful (red, no change in width), or somewhere in between (amber, where the width changed but not correlated directly to the action of the EM edge dam).

There is a general trend where the thickness at a given width is greater for more successful trials. The ratio between width and thickness is determined by the stiffness of the caster, which is constant, and by the growth of the solidifying shells which force the rolls apart. Thicker cast sheet can be attributed to earlier solidification, closer to the EM edge dam—in this case the magnetic field is stronger so the trials becoming more successful is expected. The roll speed was varied to try to test this theory directly, and the results agreed. In casts 11 and 12, a slower roll speed was used to cause earlier solidification, resulting in a larger thickness as expected.

Therefore, the combination of caster and feed system used here is not repeatable enough to fully isolate and evaluate the performance of the EM edge dam, which is clearly sensitive to the location of the final solidification point. This could be due to variations in either the aluminium temperature as it exits the feed tip or in the roll speed and both would need to be checked independently before further trials. The observed thickness variation which occurs with this low stiffness experimental twin roll caster would not be expected to occur in a production caster.

5.2. Physical action of the EM edge dam

The maximum contained pressure was 15 mm_{Al} (from Fig. 9(b)) which is significantly larger than the magnetic pressure at the feed tip exit (Fig. 7), even when taking into account the boost in field strength from the presence of aluminium. The aluminium did not leak out, so there must be an additional factor aiding containment of the strip edge.

The physical effect of the magnetic field is to apply a magnetic pressure to the surface of the aluminium edge. This pressure must balance with the fluid pressure, surface tension and, in dynamic cases, inertia and viscosity. In three dimensions, the problem is complicated—the edge of the liquid aluminium forms a free surface that can change shape in profile in the feed tip, and in section along the edge. The distribution and strength of the magnetic field is coupled to this shape, and the contribution of surface tension changes depending on the contact angle with the fixed geometry of the feed tip and the moving solid shells.

A simple 2D approximation is proposed in Fig. 16(a), which shows a section transverse to the casting direction. It is assumed that there is no variation out of plane, and that the liquid metal is confined between two solid shells of separation, h, with a bulge to form some contact angle, α, between the liquid and solid surfaces on which a surface tension, γ, acts. The magnetic field is carried vertically between the rolls and is confined to the surface of the aluminium due to the skin effect. It exerts a magnetic pressure, P_m, which acts to repel the strip. Finally, there is an internal fluid pressure, P_f, from the pressure head in the reservoir acting to push the liquid aluminium outwards from the free edge and potentially a contribution from inertia and viscous drag, F_i and F_v respectively, both opposing the motion of the liquid aluminium.

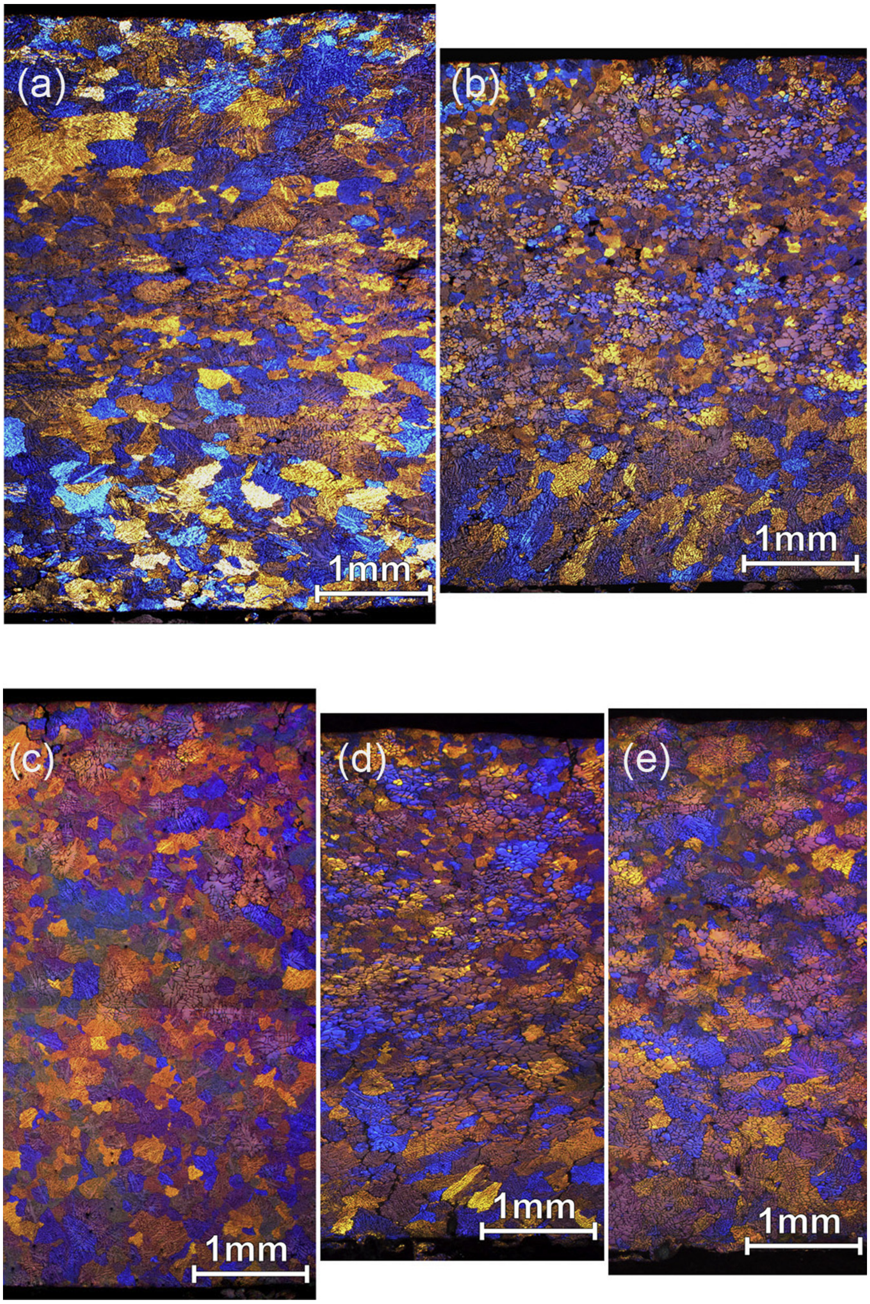

Fig. 14. Through-thickness micrographs of cast strip—(a) longitudinal view, centreline of strip, no EM edge dam (EMED); (b) longitudinal view, centreline of strip, EMED on; (c) transverse view, edge of strip, no EMED; (d) transverse view, EMED on, near edge; (e) transverse view, EMED on, far edge.

The balance of forces varies depending on the magnet motion, and there are three distinct regimes:

- *Constant width*, where the inertia and viscous forces are zero and surface tension works with the magnetic pressure to contain liquid aluminium
- *Increasing width*—fluid pressure head overcomes surface tension, inertia, and viscosity, and the role of the magnetic field is to control the final width
- *Decreasing width*—the most challenging case, where the magnetic field pushes the edge inwards and must overcome pressure head, inertia and viscosity as well as replacing the contribution of surface tension to containment.

Clearly, the biggest challenge is to decrease the width of the strip, as borne out by the delay in response in this case during the casting trials.

For the *constant width* case, where inertia and viscous forces are zero, a horizontal force balance is given in Eq. (2):

$$P_m h + 2\gamma \sin\alpha = P_f h \tag{2}$$

Using this equation, we may determine how surface tension plays an important role in helping the EM edge dam with liquid metal containment in the sump through the plot of Fig. 16(b). The separation of the solid shells, *h*, gets smaller closer to the roll bite as the solid shells grow, and therefore the effect of surface tension in the horizontal force balance increases. At the feed tip exit,

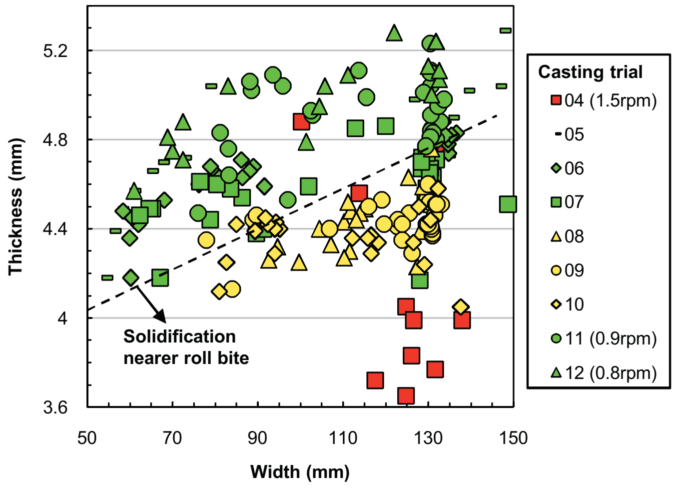

Fig. 15. Measured width and thickness for successful (green) and unsuccessful (red) uses of the EM edge dam. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

where there is separation of $h = 16$ mm between the just-forming solid shells, surface tension may hold up to 4 mm_{Al} pressure head. This increases up to the final solidification point, for example 5 mm before solidification a 20 mm_{Al} pressure head can be held by surface tension alone.

If surface tension is important for static containment, then any case where the width is varying requires overcoming surface tension as well as the pressure head, inertia, and viscosity. *Increasing width* is relatively simple, as the magnetic field may be reduced in strength by moving or reducing the power of the EM edge dam and the pressure head increased to overcome surface tension if necessary. This explains why no delay was observed when increasing sheet width.

To *decrease width*, the magnetic field must push the liquid meniscus back inside the feed tip and maintain containment between the solid shells. For a frequency that gives a small skin thickness, the solid shells will mostly act to block the field from the area that has already begun to solidify. Therefore, width change must begin inside the feed tip and there will inevitably be a delay that depends on the solidification length and speed of the rolls. A delay was observed in trials both with the moving EM edge dam (Fig. 11) and with the static, switched EM edge dam. The offset was 43 mm and roll surface speed 18 mm/s, giving a delay of 2.4 s. This is shorter than the observed delays (5–10 s), so other factors must be playing a part.

Inside the feed tip, two effects oppose motion of the liquid metal. Firstly, surface tension will act to try to maintain the minimum free surface area, which would be obtained with a straight edge from solid shell to back of the feed tip. Secondly, the inertia of the liquid aluminium and viscous drag on the walls of the feed tip must be overcome. None of the casting trials give clear evidence for the effect of surface tension, and calculating the inertial forces will depend on how the fluid flows inside the feed tip. As an approximation, we may say that if the mass flow out of the caster (which scales linearly with width if thickness and sheet velocity are fixed) is much greater than the transverse mass flow in changing width, then only a small volume of metal need be affected by the EM edge dam and inertia has only a small effect. If the transverse mass flow is large (corresponding to a rapid width change), then for conservation of mass the metal must be pushed back into the reservoir and the inertia forces are large.

With a moving EM edge dam, the response of the strip was inconsistent, the response of strip width lagged the motion of the magnet on decreasing width, and the overall change in width was not equal to the distance moved by the EM edge dam. Control of the pressure head can be used to mitigate some of the drag effects in changing width (acting within limits that maintain a consistent casting process). Specifically, decreasing pressure head as the EM edge dam acts to decrease width and increasing pressure head to push liquid aluminium outwards when increasing width would give a faster rate of change in both cases.

In order to verify these proposed mechanisms and to improve the accuracy of the strip width, the relative size of the magnetic pressure to surface tension and inertia should be increased. This could be achieved either by using a more powerful magnetic field or repeating the casting trials with magnesium, which has both a lower density and surface tension than aluminium. In both cases, a reduction in the delay of the change in width would be expected, and it should be possible to control the width more accurately through movement of the EM edge dam.

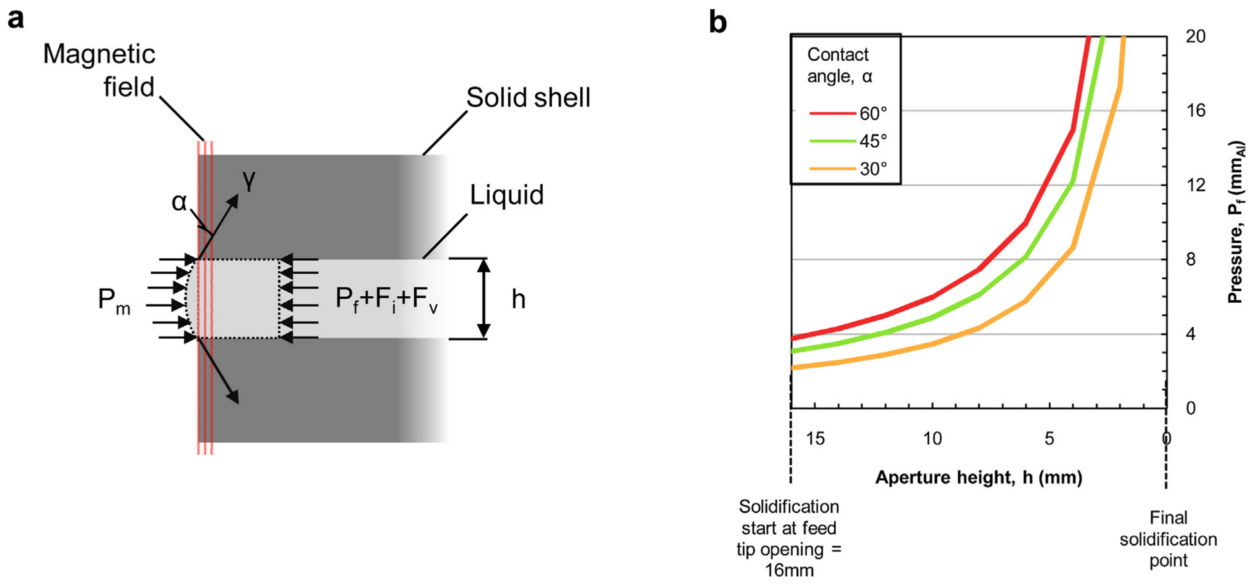

Fig. 16. (a) Simplified 2D slice for balance of forces. (b) Contribution of surface tension to containment.

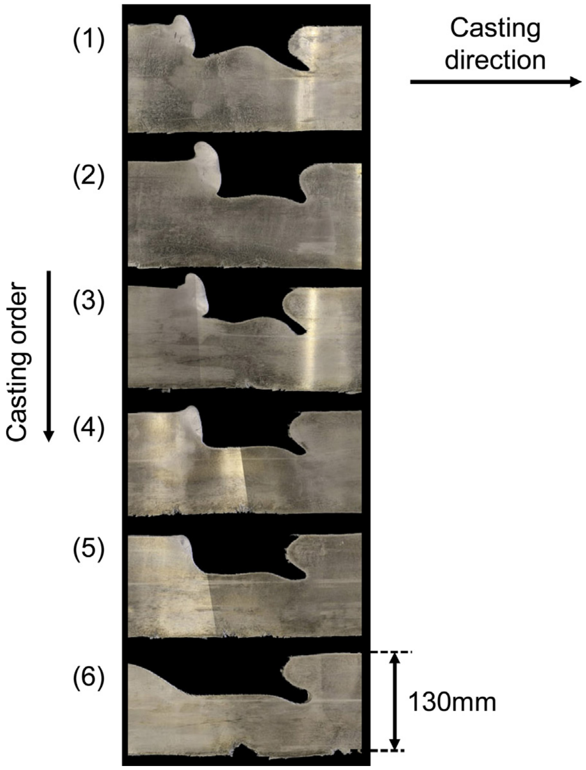

Fig. 17. Step response of width to stationary EM edge dam input.

5.3. Varying width by switching a static EM edge dam on and off

The step response of the strip, which showed a very rapid variation in both decreasing and increasing width, implies there is a further mechanism for controlling strip width. Rather than acting to move the edge of the strip, when the EM edge dam is switched on it divides the flow already in the feed tube. Fig. 17 shows the characteristic pattern produced in casting trials with the switched, stationary, EM edge dam, and how this pattern varies with the duration of the cast. Because the field is generated in the middle of the strip, it effectively splits the metal in the feed tip in two at the centreline. The fixed edge, on the bottom in Fig. 17, has a continuous feed of aluminium, while the feed to the top edge is blocked by the magnetic field. The remaining aluminium solidifies as a tail from this top edge, then quickly runs out leaving a strip of approximately half width.

When the EM edge dam is switched off, an overspill beyond the aperture set by the mechanical edge dams occurs briefly before the standard 130 mm strip is produced. Without the blockage provided by already-solidified strip, the liquid metal can initially flow beyond the width of the feed tip, but providing this liquid metal solidifies without leaking from the caster completely then a solid barrier is formed and the situation quickly resolves back to give a stable cast. The overspill effect becomes smaller and then disappears later in the cast, when the pressure head is smaller and the metal will have cooled, suggesting that it would be possible to prevent overspill with suitable control of these parameters.

In all cases, a single oscillation of the width occurred after turning on the EM edge dam. The overshoot and final settled width vary with casting time, and because the reservoir is at a lower temperature than the poured aluminium, then a change in feed temperature is the most likely cause of this variation, and there is a common trend observed. The highest feed temperature gives the largest overshoot and widest strip, and as the temperature decreases the overshoot and width decrease down to their minimum for the final step. The feed temperature affects the solidification profile, again showing the importance of the location of the solidification point in determining the performance of the EM edge dam.

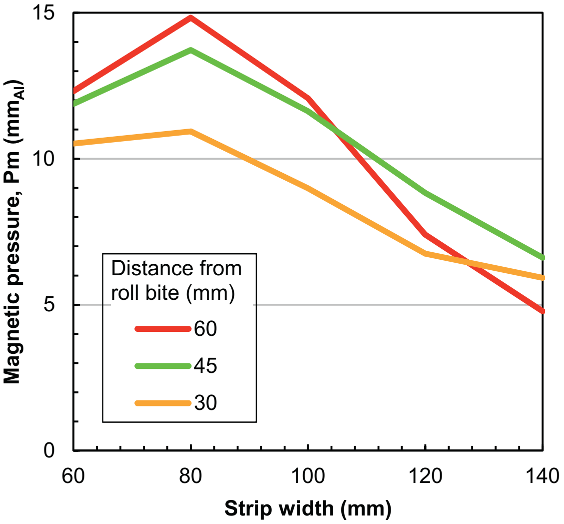

Fig. 18. FEA calculation of change in pressure on aluminium free surface as width changes.

The distribution of the field changes depending on the extent to which liquid aluminium fills the feed tip, with a plot of magnetic pressure at the surface of the metal against the strip width made in Fig. 18. These values have been calculated from the finite element model, with the assumption that the liquid aluminium takes a shape that completely fills the feed tip up to the width of the strip, and that the free edge is parallel to the casting direction—both of these are unlikely to be true in practice so only qualitative conclusions may be made from these results. The results show that the magnetic pressure on the free edge is weak for a wide strip, increases to a maximum where the free edge aligns with the EM edge dam location, and then decreases again. This may explain why a rebound and settling effect is observed in the step response—the metal responds slowly at first because the field is weak, accelerates towards a smaller width and overshoots, and then because the field is weaker it rebounds to the equilibrium position in line with the EM edge dam. If this mechanism is correct, then the accuracy of the step response may be improved with control of the EM edge dam current and pressure head to damp this oscillation.

Further work is required to determine whether these added controls would improve the accuracy of the strip profile in this case. If it does, the static EM edge dam switched on and off may be the preferred embodiment for twin roll casting.

5.4. Quality of cast sheet

The strip must meet or exceed the requirements on normal sheet, in order for it to be used to make products. In practice, this means that the EM edge dam can produce a poor quality edge, as trimming is expected, but the surface quality of the strip must be good and the mechanical properties of the sheet must exceed specifications and ideally be uniform throughout the sheet. There is no discernable change in edge cracks or surface quality, but mechanical properties are improved due to a change in the microstructure.

This change may be attributed to a stirring action of the EM edge dam. A mechanism for the creation of this stirring motion is proposed in Fig. 19. The magnetic field attenuates towards the roll bite, and this gradient sets up a fluid flow along the edge parallel to the casting direction. By mass conservation the liquid metal

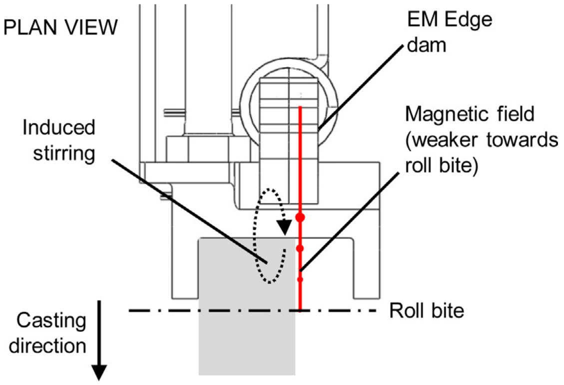

Fig. 19. Proposed stirring action of magnetic field.

must recirculate, giving a transverse flow of liquid aluminium at the liquid–solid interface. This transverse flow interrupts dendritic growth, distributing potential nucleation sites and produces the characteristic rosette structure observed instead. No comparison was made with the addition of grain refiner, but it appears that the EM edge dam would at least achieve parity with the mechanical properties of normally cast sheet.

The micrographs of Fig. 13 showed that the microstructure refinement occurred mostly in the top half of the strip, with the bottom third of the thickness showing little modification from the normal strip. This is likely due to differences in the heat transfer and therefore rate of solidification of the strip—because the centreline segregation is found nearer to the top surface of the strip, it is clear that the solid shell grows faster on the bottom roll than on the top, leaving less time for stirring to affect the microstructure. The difference in rate of solidification can be attributed to the details of the setup of the feed tip and the difference in contact pressure between the liquid metal and the rolls. The feed tip is fixed relative to the bottom roll of the caster, and contact between the liquid metal and this bottom roll would be immediate at the exit of the feed tip, while the top roll is deflected upwards by 1–2 mm causing a delay in initial contact. Contact pressure also varies because the pressure head is of the same order of magnitude as the thickness of the sheet, so that the top surface contact pressure is as low as half that of the bottom surface, leading to a reduced heat transfer coefficient and therefore slower solidification. Further investigation is required to determine which of these mechanisms is more important.

An additional problem with the mechanical properties was their inconsistency—not all of the samples taken from the EM-controlled strip had an improvement over the normal strip. This suggests that there is an unsteady element to the stirring flow generated. In practice, the certified properties of the entire sheet would have to be set at a level below the properties that could be repeatedly realised in the process, so if the inconsistency cannot be avoided then there is effectively no difference between strips produced with or without the EM edge dam. Regardless, the properties are at least as good as normal twin roll cast strip, and because the primary intention is to improve yield, this is still a successful result.

6. Conclusions and next steps

The proposed EM edge dam design has been successfully demonstrated to vary width in twin roll casting much more rapidly than any prior attempts, albeit without the degree of control required to make the process ready for use in practice. Casting trials with the EM edge dam have identified two ways of changing width—moving the EM edge dam transversely with a concurrent change in sheet width, or by switching a static EM edge dam on and off, which divides the flow and gives discrete step changes in width.

The switched, static EM edge dam produced a more rapid width variation, but both methods may be improved with additional control. In particular, the casting process must be stabilised further due to the sensitivity of the EM edge dam performance to the solidification profile, and direct control of the pressure head together with EM edge dam position and current is necessary to achieve an accurate geometry and faster width changes.

Scaling up the process for use in production would involve casting a wider range of real profiles. To do this, a second EM edge dam could be used to control the opposite edge in a similar way, giving full control of the width. Additionally, an electromagnet may also be positioned centrally around the feed tip and with some modifications to the way metal is fed in, used to cast holes which would give the flexibility to cast any profile in sheet achieving the maximum possible reduction in yield loss.

Because edge cracks are still present, some trimming would be needed and the yield would not be 100%, but in highly irregular products the improvement would still be substantial. The most suitable target application would be car body panels, although this would require some development of the twin roll casting process to improve the quality of the cast sheet in tandem with developing the abilities of Tailor Blank Casting.

The next step in developing the process is to focus on improving the repeatability and accuracy of the width variation. The casting procedure must be refined to control the solidification point more accurately, and ideally a wider twin roll caster would be used so as to demonstrate larger variations in width. The EM edge dam may be refined by increasing the output with a more powerful electrical supply (for example, using multiple amplifiers in parallel). These modifications would give a more stable base from which to build a control system that links EM edge dam current and position with control of the pressure head in the reservoir in order to cast exact width geometries. The need for this control has been shown for both constant and varying width cases.

In order to prove viability as a real process, the sensitivity of the casting process to width variation must be investigated—in particular how does the temperature profile vary across the rolls in different width change regimes, what effect does this have on the strip, and how is the microstructure and therefore properties of the cast strip affected across the width. The downstream processes, which may require heat treatment, hot rolling, and stamping, must all be developed to work in tandem with the output of the Tailor Blank Casting process.

Overall, a first step has been made in demonstrating a method of continuously casting nearer to net shape in dimensions not previously considered. The ability to cast profiles would significantly increase yield and therefore reduce energy consumption in the production of irregular sheet metal parts.

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