International Journal for Multidisciplinary Research (IJFMR)
E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

A Review on Twin Strand Slab Casting and Impact of Speed Variation on Quality of Steel

Kumar Mangalam

Mechanical Engineer and Former Process Engineer, Jindal Steel

Abstract
Twin strand slab casting, in which a single tundish feeds two parallel strands, is a preferred configuration for high tonnage production of flat steel because it approximately doubles caster output at modest additional cost. Within this configuration the withdrawal speed is the dominant operating variable, since it fixes the time available for heat extraction and thereby governs shell growth, the depth of the liquid core, the metallurgical length and the population of defects. This review condenses recent modelling studies, industrial trials and analytical treatments on how variation of casting speed affects slab quality, with attention to the twin strand layout. Faster withdrawal thins the mould exit shell in inverse proportion to the square root of speed, lengthens the metallurgical length in direct proportion to speed and raises the ferrostatic load, intensifying centreline segregation, porosity and bulging, while abrupt speed transients cause localised shell thinning that traps solute rich liquid. Speeds that are too low impair mould flux melting and promote slag entrapment, so an optimum speed window exists for every caster. Reported data indicate that the centreline segregation index rises from about 1.05 to more than 1.40 as slab speed increases from about 1.2 to 2.0 metre per minute, that mould exit shell thickness can fall below 10 millimetre above about 1.4 metre per minute, and that longitudinal cracking can rise by up to 40 percent above about 1.6 metre per minute unless countermeasures are applied. Dynamic soft reduction, optimised mould taper, high frequency non sinusoidal oscillation, electromagnetic braking and stirring, engineered mould fluxes and data driven control are shown to widen the usable speed window. Twin strand specific issues are highlighted, notably symmetric flow distribution between strands from a shared tundish, the sensitivity of that symmetry to thermal disturbance, and the need to match strand speeds within the safe window of each strand.

Keywords: Twin Strand Slab Casting, Casting Speed, Shell Thickness, Centreline Segregation, Dynamic Soft Reduction, Mould Taper, Mould Oscillation, Bulging, Slab Quality

1. Introduction

Continuous casting solidifies the overwhelming majority of world steel output, having displaced ingot teeming because it couples high yield with a favourable steady state. In slab casting, liquid steel passes from ladle to tundish, through a submerged entry nozzle into a water cooled copper mould, and then through secondary cooling and support zones where it is fully solidified before cutting. Many phenomena interact simultaneously, including turbulent multiphase flow, heat transfer, solidification, thermal and mechanical distortion, segregation, inclusion transport and microstructure formation, and their interplay determines product quality, as set out in the comprehensive reviews of modelling and simulation by B.G. Thomas (2018) and (2002) [1, 28].

A twin strand slab caster is an embodiment of this process in which one tundish distributes steel to two parallel strands. The tundish is a reservoir between the intermittently replaced ladle and the continuous moulds and, in a multi strand machine, must divide the flow evenly while acting as a reactor for cleanliness, temperature and composition control. Twin strand machines roughly double throughput for a modest increase in cost and are widely used for low and ultra low carbon flat products. Reported industrial machines cast slabs near 230 millimetre thickness in widths from about 990 to 1550 millimetre at speeds up to about 2.1 metre per minute and process grades from interstitial free through peritectic, micro alloyed, high strength low alloy and silicon steels [2].

Representative modern conventional twin strand machines cast slabs of about 180 to 260 millimetre thickness in widths from roughly 800 to 1700 millimetre at maximum speeds up to about 2.5 metre per minute, and process a broad product mix dominated by low and ultra low carbon grades but also including medium and high carbon, high strength low alloy, peritectic, silicon, line pipe and dual phase steels. Producers face unrelenting pressure to raise throughput, lower unit cost and meet tighter quality specifications together. Raising twin strand speed from a conventional 1.0 to 1.2 metre per minute toward 1.8 to 2.2 metre per minute can raise throughput by roughly 25 to 30 percent depending on grade and section [3]. The difficulty is that casting speed is not a free variable: because it sets the time for heat extraction, an increase in speed thins the shell, deepens the liquid pool, lengthens the metallurgical length and raises the ferrostatic load, so a change intended purely to lift productivity propagates into every quality relevant subsystem. Casting speed variation is therefore treated here as a subject in its own right. Section 2 describes twin strand fundamentals, Section 3 treats solidification and shell growth against speed, Section 4 the heat transfer limit, Section 5 the speed dependence of defects, Section 6 the countermeasures, Section 7 the analytical framework, and Sections 8 to 11 the validation, discussion, future work and conclusions.

The literature was identified through ScienceDirect, Scopus, Web of Science, SpringerLink and Google Scholar, with preference for recent original research and validated models supplemented by established reviews. The emphasis is on slabs and on phenomena that respond directly to speed. It is noted that twin strand slab casting, with two parallel strands from a shared tundish, is distinct from twin roll strip casting, in which steel solidifies between two rolls; results from the latter are cited only for contrast.

2. Fundamentals of Twin Strand Slab Casting

A twin strand caster comprises a ladle turret, one tundish with two outlets, two submerged entry nozzles, two moulds, two oscillation systems and two independent secondary cooling and containment sections. The strands are arranged symmetrically about the tundish centreline so that the metallostatic conditions at the two outlets are nominally identical, and each strand behaves as a conventional bending slab caster with a primary cooling mould region and an extended secondary spray and support zone. An industrial twin strand machine has been described with a machine radius of nine metre, a metallurgical length of thirty six metre and an output near 2.5 million tonne per annum [2]. Because the strands share a tundish but not their moulds or cooling circuits, they can be run at slightly different speeds, which is both an operational advantage and a source of complexity.

2.1 Representative Machine Configuration

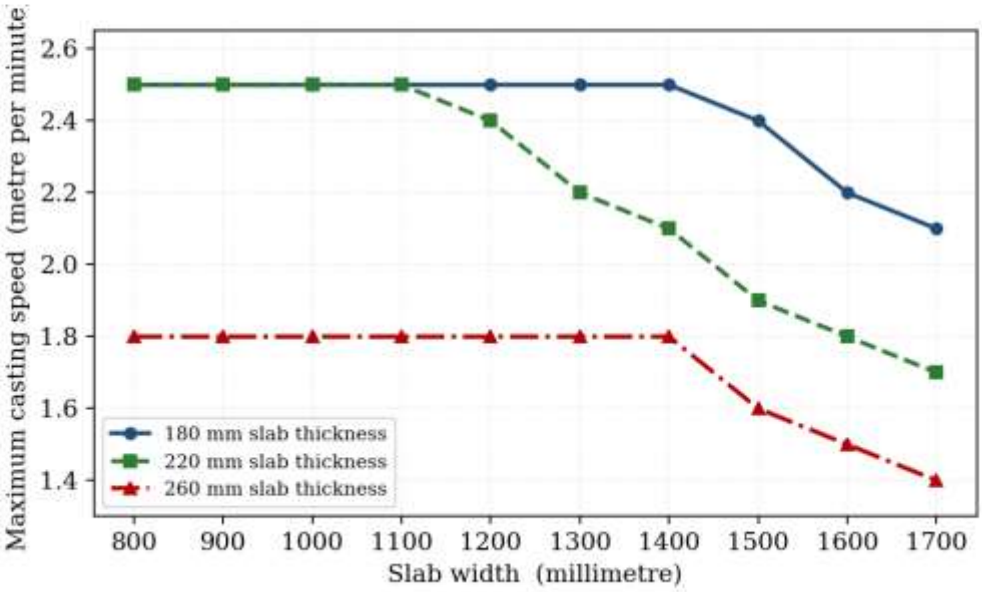
To make the discussion concrete, the principal data of a representative modern conventional twin strand slab caster are summarised in Table 1. The machine is of the vertical curved type with two strands per caster, a main radius of about nine metre and a total length of the order of forty two metre from the meniscus to the machine exit. Each mould is about 900 millimetre high with flat broad face plates and multi tapered narrow face plates whose width and taper are adjusted online, and the strand is contained and cooled through eighteen support segments with air mist secondary cooling. Slabs are produced in three nominal thicknesses of 180, 220 and 260 millimetre, in widths from 800 to 1700 millimetre and lengths from 5.5 to 12 metre, over a casting speed range from about 0.8 to 2.5 metre per minute. The mould is equipped with a multi mode electromagnetic system providing level stabilisation, flow acceleration and rotative stirring, the oscillation is hydraulic and capable of both sinusoidal and non sinusoidal waveforms over a wide frequency range, and dynamic soft reduction of the order of four to six millimetre is applied automatically over the final containment segments. These values, typical of current conventional twin strand practice, are used below to ground the more general relationships between casting speed and quality.

Table 1: Representative Configuration of a Modern Conventional Twin Strand Slab Caster

Feature	**Representative Value**
Configuration	Two strands per caster, vertical curved
Main machine radius	9.0 metre
Total machine length (meniscus to exit)	About 41.6 metre
Mould height	900 millimetre
Containment and cooling	18 segments, air mist secondary cooling
Nominal slab thickness	180 / 220 / 260 millimetre
Slab width	800 to 1700 millimetre
Slab length	5.5 to 12 metre
Casting speed range	0.8 to 2.5 metre per minute
Tundish capacity (working)	75 tonne
Mould electromagnetic system	Multi mode (level stabilisation, acceleration, rotative stirring)
Mould oscillation	Hydraulic, 25 millimetre stroke, sinusoidal and non sinusoidal
Dynamic soft reduction	4 to 6 millimetre over final segments

The strong dependence of the usable casting speed on the section is illustrated in Figure 1, which plots the maximum casting speed permitted for low carbon slabs against slab width for the three nominal thicknesses of this representative machine. For a thin 180 millimetre slab the maximum speed is held at about 2.5 metre per minute up to roughly 1400 millimetre width before falling toward about 2.1 metre per minute at the widest section, whereas for a 260 millimetre slab the ceiling is about 1.8 metre per minute across most widths, falling to about 1.4 metre per minute at 1700 millimetre. The pattern confirms that the appropriate speed cannot be chosen independently of width and thickness, since both enlarge the heat to be extracted and lengthen the solidification path, and it is a direct industrial expression of the shell thickness and metallurgical length relationships developed in Section 3.

Figure 1: Representative Maximum Casting Speed Versus Slab Width for Low Carbon Slabs at Three Nominal Thicknesses (Compiled by the Author from Data for a Representative Modern Twin Strand Caster)



The two strand tundish most clearly distinguishes the configuration, since it must divide one ladle stream into two nominally identical strand streams. Residence time, dead volume, inclusion flotation and temperature uniformity all depend on the internal geometry and on furniture such as weirs, dams, turbulence inhibitors and the ladle shroud, and particle image velocimetry has been used to characterise the flow field and to place flow modifiers so both strands receive comparable steel [4]. Symmetry is not guaranteed even for symmetric geometry: numerical and physical modelling of a two strand tundish under non isothermal conditions shows that small thermal disturbances trigger a self sustaining asymmetry, described by analogy with the butterfly effect, in which greater steel reheating strengthens the asymmetric buoyancy driven structures [5]. The two strands may therefore differ in delivered superheat and cleanliness, and since solidification structure and defect propensity depend on superheat as well as speed, an asymmetry originating in the tundish can express itself as a difference in quality between strands at the same nominal speed. Engineered ladle shroud designs that moderate the incoming momentum improve the evenness of delivery [6].

Casting speed and superheat must be considered per strand and in relation to each other. Because both strands draw from a common tundish, changing the total casting rate alters tundish residence time and delivered superheat, thermally coupling the mechanically independent strands. Matching the strand speeds, or deliberately biasing them to offset a known thermal asymmetry, is therefore part of twin strand operating strategy and has no single strand counterpart. The appropriate speed also depends on slab width, since the choice of speed must be made jointly with width so that the metallurgical length stays within the containment length and the shell at unbending resists cracking [7]. Grade matters greatly, because the solidification range and crack sensitivity differ: peritectic grades are especially prone to uneven shell growth and longitudinal cracking, as the delta to gamma contraction opens an air gap that reduces local heat transfer, a difficulty aggravated where the shell is already thin at high speed.

3. Solidification and Shell Growth Under Varying Casting Speed

Shell growth is governed by the rate at which the latent and sensible heat of the steel is conducted through the solid layer and removed by mould and sprays. To first order the shell thickness increases with the square root of local solidification time, from the one dimensional Stefan solution, equation (1), where s is shell thickness, k is a solidification constant embodying the steel properties and the efficiency of heat removal, and t is the time since the point entered the mould.

$$s = k \times \sqrt{t} \qquad (1)$$

The constant k for steel is typically about 20 to 28 millimetre per square root of minute, larger where cooling is intense. The local time relates to speed through equation (2), with z the distance below the meniscus and Vc the casting speed.

$$t = z \div Vc \qquad (2)$$

Combining these gives the shell at a distance z as a function of speed, equation (3), which expresses the central fact of high speed casting: at a fixed position such as the mould exit the shell thickness varies with the inverse square root of speed, so faster withdrawal necessarily thins the shell unless k is raised by more intense cooling.

$$s(z) = k \times \sqrt{(z \div Vc)} \qquad (3)$$

The mould exit shell thickness is a primary safety and quality variable, since a shell too thin to support the ferrostatic pressure may rupture in a breakout and, short of that, bulges more and cracks internally. Consistent with equation (3), representative figures place the mould exit shell near 15 millimetre at about 1.2 metre per minute, falling below 10 millimetre above roughly 1.4 metre per minute, with plant trials reporting about a 15 percent decrease when speed rises from 1.4 to 1.8 metre per minute [8]. A common practical threshold is that the shell should not fall below about 8 to 10 millimetre for wide sections, which with equation (3) sets an upper bound on speed for given cooling. Work on solid shell growth confirms that the growth rate is governed jointly by speed and heat extraction intensity, and that the finite heat extraction capacity of mould and sprays sets the ceiling on speed [9]; speed and cooling are thus a coupled pair felt through the shell thickness.

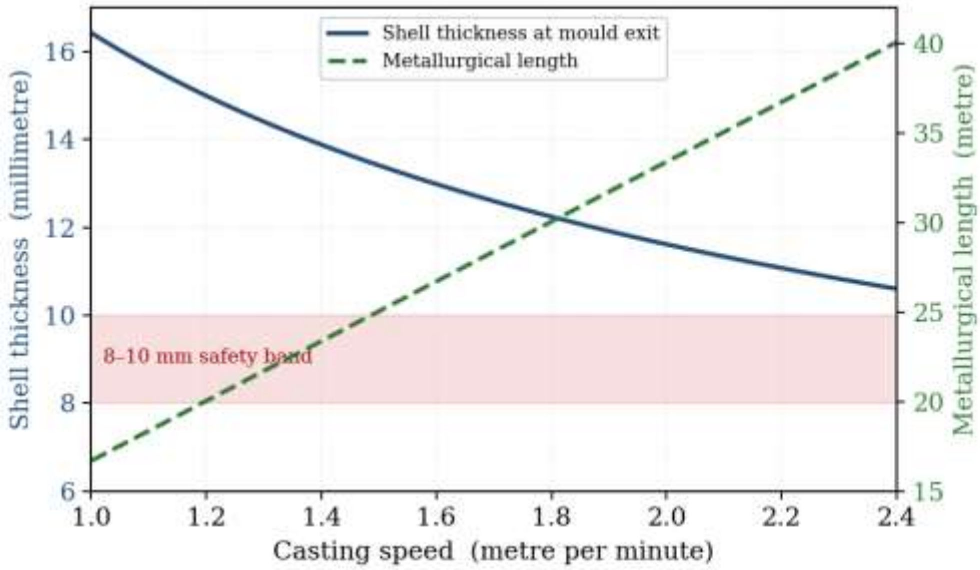
The metallurgical length is the distance from meniscus to full solidification, where the two shells meet. Setting the shell equal to half the slab thickness D gives the total solidification time, equation (4), and multiplying by speed gives the metallurgical length, equation (5).

$$t^f = (D \div 2k)^2 \qquad (4)$$

$$L_m = Vc \times t^f = Vc \times (D \div 2k)^2 \qquad (5)$$

Equation (5) shows the metallurgical length grows in direct proportion to speed. This has two consequences. First, the point of final solidification moves downstream with speed, and if it passes the last containment rolls the strand holds liquid where it is unsupported. Second, the location for soft reduction against segregation moves with the metallurgical length, so any technology acting on the final solidification region must track speed in real time. Figure 2 illustrates the opposing dependence of mould exit shell thickness and metallurgical length on casting speed.

Figure 2: Mould Exit Shell Thickness and Metallurgical Length Versus Casting Speed (Prepared by the Author from Equations 3 and 5 with Representative Constants; Shell Safety Threshold per [8])



Heat extraction divides between primary cooling in the mould, where heat crosses an interfacial gap of mould flux and, lower down, an air gap into the copper, and secondary cooling below the mould, where sprays impinge on the strand between rolls. In the mould the dominant resistance is the interfacial gap, and detailed one dimensional models such as that of Y. Meng and B.G. Thomas (2003) resolve the liquid and solid slag layers within it to predict the mould heat flux and shell profile [10]. Below the mould the surface temperature must be controlled so it neither reheats, allowing softening and bulging, nor cools so sharply that thermal stress cracks the surface; the sensitivity of the surface temperature profile to speed and superheat is confirmed by measurements of the billet surface temperature distribution [27]. Because the same length of strand passes any zone in less time at higher speed, the spray water flow must rise with speed, by roughly 0.035 to 0.04 kilogram per tonne for every 0.1 metre per minute increment if the surface profile is to be preserved [3], and the water cooling regime is central to shell integrity [30].

4. Heat Transfer Limits on Casting Speed

These relationships combine into a heat transfer limit on speed. As the mould exit shell thins with the inverse square root of speed while the ferrostatic and bulging loads rise, and the heat to be removed per unit time rises in proportion to throughput, there is a speed beyond which the available cooling cannot maintain a safe shell. Conduction through the shell follows Fourier law, equation (6), with q the interfacial heat flux, k_{th} the conductivity and ΔT the temperature difference across the shell of thickness s.

$$q = k_{th} \times \Delta T \div s \qquad (6)$$

A thinner shell conducts more readily for a given ΔT, partly compensating the shorter time, but incompletely, because the total heat rises faster than the conduction gain. The requirement that mould heat flux and spray cooling rise roughly in proportion to speed to preserve shell thickness is a statement of energy balance, confirmed by numerical models on real caster data showing that raising speed without matching cooling reduces the mould exit shell and raises breakout risk [9, 10]. The secondary cooling demand can be represented for engineering purposes by a rising function of speed, equation (7), with Q the specific spray water demand and a and b grade and machine dependent coefficients.

$$Q = a \times Vc^2 + b \times Vc \quad (7)$$

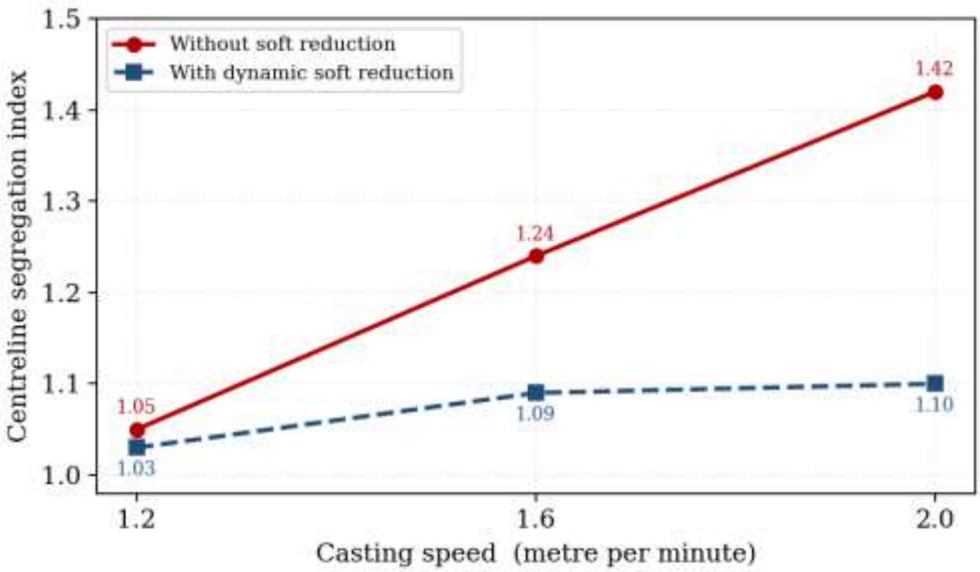
The limit is a property of the whole thermal system, not of speed alone: for conventional thick slab casters the practical ceiling is commonly near 2.0 to 2.2 metre per minute, whereas thin slab casters, whose small section solidifies quickly, operate up to about 6 to 8 metre per minute precisely because reduced thickness restores a favourable ratio of cooling capacity to heat load.

5. Defect Formation as a Function of Casting Speed

Slab defects group into internal defects, chiefly centreline segregation, internal cracks and porosity, and surface and sub surface defects, chiefly longitudinal and transverse cracks, oscillation marks and entrapped slag or inclusions, together with bulging and the catastrophic breakout. Speed influences all of these, and not in the same direction, which is why an optimum window exists.

Centreline segregation is the enrichment of solute along the central plane and is the internal defect most strongly linked to speed. As dendrites advance from both faces, solute is rejected into the remaining liquid, so the last liquid to solidify at the centre is the most enriched. Higher speed lengthens and widens the mushy zone, raising the permeability of the interdendritic network and allowing enriched liquid to be drawn to the centre by shrinkage and bulging, and it raises the ferrostatic pressure driving that flow. Billet experiments with mechanical reduction confirm that macrosegregation worsens with speed, the enrichment rising as withdrawal is raised, attributed to the enlarged mushy zone and increased interdendritic backflow [11]. The segregation index, the ratio of local to nominal solute concentration, has been reported to rise from about 1.05 at 1.2 metre per minute to about 1.42 at 2.0 metre per minute in twin strand casting of ultra low carbon steel [8]. Figure 3 shows this rise and the strong flattening achieved by dynamic soft reduction. Centreline segregation is often the binding constraint on speed for plate and heavy section grades, and the recent international standard for its evaluation reflects its industrial importance [12].

Figure 3: Centreline Segregation Index Versus Casting Speed With and Without Dynamic Soft Reduction (Prepared by the Author from Data Reported in [8], [11], [23] and [25])



Bulging is the outward bowing of the strand between rolls under the ferrostatic pressure of the liquid core. It is a shape defect, but its greater significance is that it pumps enriched liquid to the centre, aggravating segregation and opening internal cracks and cavities. The ferrostatic pressure is given by equation (8), with ρ the density, g the gravitational acceleration and h the metallurgical height above the point considered.

$$P = \rho \times g \times h \quad (8)$$

Because the liquid height rises with speed, the pressure at a given roll increases with speed, and the deflection follows a beam bending relationship, equation (9), increasing with the fourth power of roll pitch l and the pressure and decreasing with the cube of shell thickness s, with E the elastic modulus and C a constant absorbing hot shell creep.

$$\delta = C \times P \times l^4 \div (E \times s^3) \quad (9)$$

Since s falls and P rises with speed, both factors increase the bulge as speed rises, and empirical fits give a bulging strain power law, equation (10), with an exponent near 1.5 for low carbon steel, so a 20 percent speed rise gives roughly a 35 to 40 percent increase in bulging strain [13].

$$\varepsilon^b = C^b \times Vc^{1.5} \quad (10)$$

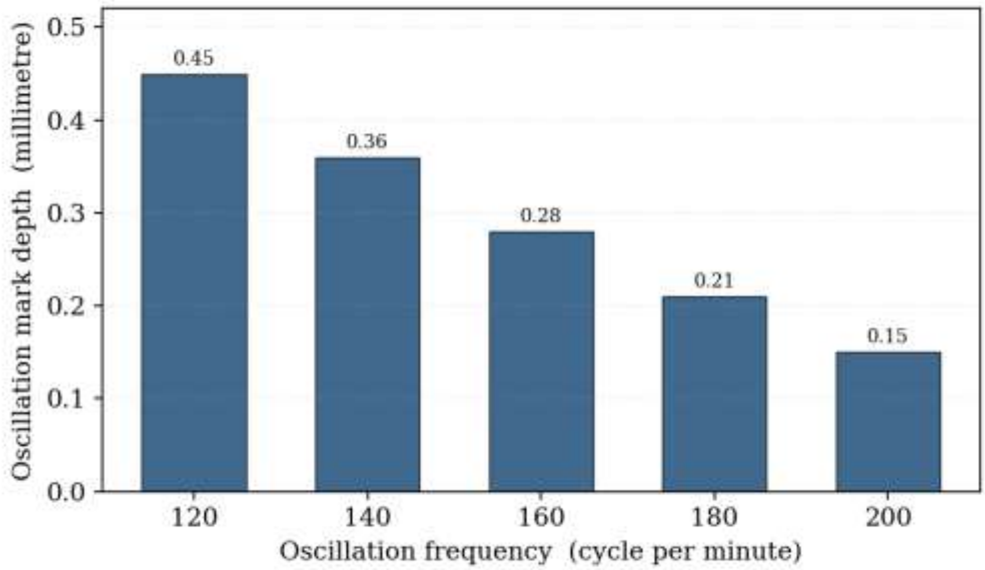
Bulging correlates with centreline porosity and cracking, so its online detection has been pursued using signal analysis such as the Hilbert Huang transform [14], and recent three dimensional models that account for molten steel deviation flow confirm the bulge grows with speed and liquid core depth [15]. The response, tightening roll pitch near the solidification end and applying soft reduction, is treated in Section 6.

Longitudinal cracks run along the casting direction on or below the surface and originate in the mould where non uniform heat transfer creates hot and cold bands in the thin shell. Distinct mechanisms include cracks from trapped casting powder, from an insufficient or uneven slag film, from thermal stress and from copper mould surface discontinuities [16]; all are aggravated by speed, which thins the shell, shortens the time for a uniform slag film and raises the surface velocity. Longitudinal crack frequency can rise by up to 40 percent above about 1.6 metre per minute if flux and oscillation are not re optimised [8]. Peritectic and hyper peritectic grades are especially susceptible, and optimising the mould flux to balance heat transfer control against lubrication is central to suppressing longitudinal cracks at high speed [16, 29].

Transverse cracks run perpendicular to casting, usually at the base of oscillation marks, and are associated with tensile strain at unbending and with embrittling grain boundary precipitation in the low ductility range. Speed acts through the surface temperature at unbending and through oscillation mark depth: if sprays are not increased in proportion the surface may enter the low ductility range at unbending, and deeper marks at unfavourable settings raise incidence by about 30 percent [8]. Data driven monitoring has advanced with deep learning models such as multivariate long short term memory networks that predict transverse cracks from process signals [17].

Slag entrapment and non metallic inclusions arise because the mould flux forms a liquid slag pool that lubricates, insulates and absorbs inclusions, and its entrapment is a major defect source. At high speed the nozzle jet raises the surface velocity and meniscus turbulence, shearing slag droplets into the shell as surface spots or internal inclusions, a mechanism analysed in multiphase flow modelling [18], and it drives argon bubbles and refractory debris into the strand. Once the surface fluctuation exceeds about plus or minus 5 millimetre the probability of entrapment rises sharply [19]. The relationship is not one sided: at speeds too low the pool is not renewed quickly enough, flux melts sluggishly and the slag layer destabilises, so surface quality also degrades, and studies of the liquid slag layer recommend an optimum speed window for stability [20]. This penalty at both extremes is a clear reason an optimum window exists and means the twin strand requirement to match strand speeds respects a lower as well as an upper bound. **Oscillation marks** are the periodic transverse depressions left by mould oscillation, which is needed to prevent sticking. Their depth matters because deep marks concentrate stress, initiate transverse cracks and trap slag and segregation. The mark spacing is set by the ratio of speed to frequency, and the depth is governed by the negative strip time, the interval per cycle in which the mould descends faster than the strand and heals the shell. Shallow marks follow from short negative strip time and high frequency: as shown in Figure 4, the mark depth falls from about 0.45 millimetre at 120 cycle per minute to about 0.15 millimetre at 200 cycle per minute, with a corresponding fall in transverse cracking [3, 21]. Because the spacing depends on speed, the frequency must rise with speed to hold spacing and depth in specification, which is why high speed casting uses high frequency and often non sinusoidal oscillation.

Figure 4: Oscillation Mark Depth Versus Oscillation Frequency (Prepared by the Author from Data Reported in [3] and [21])



Breakouts, the rupture of the shell below the mould with escape of liquid steel, are the most serious failure. Sticker breakouts occur when the shell adheres to the wall and tears, and thin shell breakouts when the mould exit shell is too thin for the ferrostatic load; both are promoted by high speed, the first through a fast turbulent meniscus and poor slag film, the second through the thinner shell of equation (3). Breakout prediction from mould thermocouple signatures is standard, and its reliability grows more important as speed rises. Although dissolved gases are controlled in steelmaking rather than the caster, hydrogen deserves mention because it is rejected at the solidification front, accumulates in porosity and promotes hydrogen induced cracking; higher speed enlarges the segregated and porous central region and thus the sites where hydrogen collects, so hydrogen control and speed control are complementary, with vacuum degassing the primary defence [22].

6. Mitigation Technologies for High Speed Casting

The defects are not an absolute barrier but penalties that can be paid down. Countermeasures act on internal quality by controlling final solidification, chiefly dynamic soft reduction; on the mould to protect surface and shape, through taper, oscillation and flux; on the flow electromagnetically; and on the whole through measurement and control [26].

Dynamic soft reduction is the controlled squeezing of the strand where the centre is still mushy, to compensate solidification shrinkage and prevent enriched liquid flowing to the centre; it is the principal countermeasure against centreline segregation and porosity. The total reduction is proportional to the solidification shrinkage over the reduction interval, equation (11), with Δ_{tot} the total reduction, β a shrinkage coefficient, f_s the solid fraction and the integral taken over the mushy zone, in practice from about 0.3 to 0.8 solid fraction.

$\Delta_{tot} = \int \beta \times (1 - f_s) \times Vc \times dt$ (11)

Dynamic denotes that the position and magnitude are adjusted in real time to track the moving solidification front, essential because the metallurgical length moves with speed by equation (5). Total reductions of about 1.6 to 7.0 millimetre applied over the correct solid fraction window reduce segregation substantially, lowering the carbon segregation ratio of a heavy rail grade from about 1.39 to about 1.09 and the sulphur segregation index from about 2.14 to about 1.29 at 2.0 metre per minute [11, 23], and a shrinkage compensation calculation validated on GCr15 bearing steel reduced the segregation index by about 22 percent [25]. Timing is critical: reduction too early wastes its effect on liquid that flows back, while reduction too late achieves little, so it must be centred on the correct solid fraction window and move with speed.

Mould taper follows the shrinkage of the shell so that contact with the copper is maintained; without it an air gap opens that reduces heat transfer and causes uneven growth, off corner cracks and longitudinal cracks. The residual air gap after taper is given by equation (12), with δ_m the gap, α the contraction coefficient, ΔT the shell temperature drop, L the distance down the mould and the taper a fractional narrowing per unit length.

$\delta_m = \alpha \times \Delta T \times L - taper \times L$ (12)

Because shrinkage depends on speed and grade, the optimum taper is speed and grade dependent. Inadequate taper below about 0.7 percent per metre above about 1.8 metre per minute leaves air gaps over 0.5 millimetre and causes off corner cracking and bulging, while optimised tapers near 0.8 to 1.2 percent per metre for low carbon grades minimise the air gap and longitudinal cracking, as summarised in Table 2 [24]. The optimum profile is generally non linear because shrinkage is greatest near the meniscus, so multi taper or parabolic moulds are increasingly used at high speed.

Table 2: Effect of Mould Taper on Longitudinal Cracking and Bulging

Mould Taper (percent per metre)	Longitudinal Cracks (per metre)	Bulging (millimetre)
0.5	4.2	3.1
0.9	1.8	1.7
1.3	0.6	0.9

Mould oscillation must be designed jointly with speed so that marks stay shallow and lubrication adequate. The negative strip time for sinusoidal oscillation is given by equation (13), with t_n the negative strip time, f the frequency, S the stroke and Vc the speed.

$t_n = (1 \div \pi f) \times \cos^{-1}(Vc \div (\pi \times f \times S))$ (13)

Shallow marks and low crack incidence follow from short negative strip time, about 0.10 to 0.12 second, and high frequency, about 160 to 180 cycle per minute, at high speed [3, 21]. Non sinusoidal oscillation, with a downstroke faster than the upstroke, tunes the negative and positive strip times independently to optimise healing and lubrication and is the preferred mode for high speed casters. **Electromagnetic braking** applies a static field across the mould that decelerates the nozzle jet, calming the meniscus and reducing the surface velocity that entrains slag, and it enables the highest speeds, while **electromagnetic stirring** applies a moving field that promotes a fine equiaxed centre, reducing segregation by breaking the columnar dendrites that channel enriched liquid; both act on mechanisms that worsen with speed [1]. **Mould flux** must lubricate, control heat transfer, insulate the meniscus and absorb inclusions, and at high speed these come into tension because faster casting needs more lubrication yet controlled rather than maximal heat transfer to avoid the thermal shock that cracks peritectic grades; the levers are viscosity, crystallisation temperature and basicity, whose role is long established [29] and whose optimisation reduces longitudinal cracking in hyper peritectic high speed casting [16]. Finally, the tight interdependence of speed, cooling, taper, oscillation and reduction means high speed casting is increasingly managed by measurement and computation: mould level control suppresses entrapment, big data characterisation predicts abnormal periodic level fluctuations [19], machine learning predicts defects in real time [17, 26], and dynamic secondary cooling and soft reduction models compute the solidification state from measured speed and temperatures and adjust the sprays and reduction so the countermeasures track speed [1].

7. Consolidated Analytical Framework

The equations form a connected framework. Shell growth follows the square root law of equation (1) with the local time of equation (2), giving the shell of equation (3); the metallurgical length follows from equations (4) and (5); the heat balance is the conduction of equation (6) and the cooling demand of equation (7); the loads are the ferrostatic pressure of equation (8), driving the bulging of equation (9) and the strain of equation (10); and the countermeasures are quantified by the reduction of equation (11), the taper air gap of equation (12) and the oscillation negative strip time of equation (13). Read together they explain why the defects respond to speed as they do and why the countermeasures must be applied in a coordinated, speed tracking manner. The safe speed window is the intersection of several constraints, the thin shell breakout limit from equation (3), the containment limit from equation (5), the bulging limit from equations (9) and (10) and the slag stability limits at both high and low speed, and the usable window is the range of speed in which all are simultaneously satisfied.

8. Industrial Validation

The predicted trends are borne out by plant and pilot data. Table 2 shows the strong reduction in longitudinal cracking and bulging as taper is increased toward the value that matches shell shrinkage, consistent with equation (12) and with the reported elimination of off corner cracks above about 1.0 percent per metre in high strength low alloy grades [24]. Figure 3 shows the segregation index rising steeply with speed without reduction but held near 1.1 with adequate dynamic soft reduction [8, 11, 23, 25], and Figure 4 shows the fall in oscillation mark depth, and hence transverse cracking, with frequency [3, 21]. Beyond these, the sources record about a 15 percent fall in mould exit shell thickness when speed rose from 1.4 to 1.8 metre per minute, speeds up to about 6 to 8 metre per minute in thin slab casting through electromagnetic braking and engineered high basicity powders, and a fall in centreline sulphur segregation from about 2.14 to 1.29 under dynamic soft reduction at 2.0 metre per minute [8, 11, 23].

Together these validate the central proposition, that high speed casting is feasible when, and only when, the cooling, taper, oscillation, flow control and reduction are re- optimised together for the higher speed.

9. Discussion

Casting speed is the master variable of slab quality, acting through the single intermediate quantity of solidification time. Every quality relevant consequence of a speed change traces to the reduced solidification time: the thinner shell of equation (3), the longer core of equation (5), the greater ferrostatic load of equation (8) and the deeper marks of a fixed frequency all follow from it. This unifies the correlations among defects, a bulged strand being also a segregated one, and explains why a countermeasure aimed at one defect, such as tighter roll pitch against bulging, also benefits another, segregation. It also explains the non monotonic behaviour: internal defects worsen steadily with speed, giving only an upper limit, whereas slag related surface defects worsen at both high and low speed, giving an optimum window. The usable speed is thus bounded above by internal defect and breakout limits and below by slag stability, and the mitigation technologies widen that window.

For the twin strand configuration additional considerations apply. Because one tundish feeds both strands, they are thermally coupled through the shared reservoir even though moulds and cooling are independent, and the demonstrated sensitivity of the two strand tundish to thermal disturbance means the strands may deliver steel of different superheat and cleanliness [5, 6]. Since defect propensity depends on superheat as well as speed, tundish asymmetry can cause the strands to produce different quality at the same nominal speed, so the strategy must bias strand speeds or enforce symmetry through tundish furniture [4]. Matching or deliberately mismatching strand speeds within each strand safe window is a genuinely twin strand problem, and it interacts with width dependent speed selection when the strands cast different widths [7]; moreover a slowdown on one strand changes total throughput, tundish residence time and delivered superheat to the other, so the strands are not fully independent even in transients.

A limitation of this synthesis is that much of the quantitative data derives from a mixture of slab, bloom and billet studies and from combined modelling and plant measurement, so the numerical thresholds, such as the shell falling below 10 millimetre above 1.4 metre per minute or the segregation index reaching 1.42 at 2.0 metre per minute, are representative magnitudes for the grades and machines studied rather than universal constants. The direction and approximate size of the effects are robust across sources, but exact values depend on section, grade, mould length, flux and cooling capability and must be established for each caster.

10. Future Directions

The field is moving toward tighter, faster and more predictive control of the coupled system. Machine learning models that predict the temperature field or specific defects within milliseconds allow the sprays, reduction and oscillation to be adjusted in a closed loop as speed varies, and surrogate models make such real time application feasible [17, 26]. Multi taper and adaptive moulds promise to widen the surface quality window at high speed, and improved electromagnetic braking and stirring continue to extend the achievable speed for a given section. Digital twins of the casting line, corrected continuously by measurement, offer a route to predictive maintenance and to anticipating quality excursions. For twin strand casting specifically, further work on tundish design and on active flow control to both strands is needed so that the thermal and compositional symmetry of the strands can be guaranteed across the full range of speeds and widths, since that symmetry, as much as the behaviour of any single strand, determines the uniformity of the product.

11. Conclusion

Casting speed is the dominant control variable for the quality of continuously cast slabs, its influence mediated by the solidification time it allows. Raising speed thins the mould exit shell in inverse proportion to the square root of speed, lengthens the metallurgical length in direct proportion to speed and raises the ferrostatic load, intensifying centreline segregation, porosity, bulging and associated cracking, while abrupt transients cause localised shell thinning that traps solute rich liquid. Slag related surface defects worsen at high speed through turbulence and entrapment but also at low speed through impaired flux melting, so an optimum speed window exists. High speed twin strand casting is nevertheless viable when the cooling intensity, mould taper, oscillation, electromagnetic flow control, mould flux and dynamic soft reduction are re- optimised together for the higher speed and made to track speed as it varies. The twin strand configuration adds the requirement that the two strands, fed from a shared and thermally sensitive tundish, deliver steel of matched superheat and cleanliness and run at speeds matched within each strand safe window, so that product uniformity depends on the symmetry of the whole machine and not on the control of a single strand alone.

13. Acknowledgement

The author acknowledges the process engineering experience gained during service at Jindal Steel, which informed the practical perspective of this review.

14. References

1. B.G. Thomas, "Review on Modeling and Simulation of Continuous Casting", Steel Research International, 2018, 89 (1), 1700312. https://onlinelibrary.wiley.com/doi/10.1002/srin.201700312
2. Primetals Technologies, "Modernization of a Twin Strand Continuous Slab Caster for Angang Iron and Steel", Primetals Technologies News and Technical Publications, 2020. https://www.primetals.com/press-media/news/primetals-technologies-to-modernize-continuous-slab-caster-for-angang-iron-steel
3. K. Mangalam, "A Review on Effect of Casting Speed Variation on Continuous Cast Slab Quality", 2025. (Unpublished)
4. J. Huang, Z. Yuan, S. Shi, B. Wang, C. Liu, "Flow Characteristics for Two Strand Tundish in Continuous Slab Casting Using Particle Image Velocimetry", Metals, 2019, 9 (2), 239. https://www.mdpi.com/2075-4701/9/2/239
5. A. Cwudziński, J. Pieprzyca, T. Merder, "Numerical and Physical Modeling of Liquid Steel Asymmetric Behavior during Non Isothermal Conditions in a Two Strand Slab Tundish, the Butterfly Effect", Materials, 2023, 16 (21), 6920. https://pmc.ncbi.nlm.nih.gov/articles/PMC10649647/
6. A. Cwudziński, L. Fogaraš, J. Demeter, P. Demeter, B. Buľko, "Influence of a Novel Umbrella Type Ladle Shroud on Liquid Steel Flow in a Two Strand Slab Tundish, Physical and Numerical Modelling", Materials, 2026, 19 (1), 96. https://doi.org/10.3390/ma19010096
7. H. Zhang, Y. Li, J. Wang, "Effect of Slab Width on Choice of Appropriate Casting Speed in Steel Production", Journal of Iron and Steel Research International, 2021, 28, 1367–1378. https://link.springer.com/article/10.1007/s42243-021-00729-5

8. K. Mangalam, "Effect of Casting Speed Variation on Continuous Cast Slab Quality, Dynamic Soft Reduction, Mould Taper and Oscillation Parameter Optimization", 2025. (Unpublished)
9. M. Velička, R. Pyszko, M. Machů, J. Burda, T. Kubín, H. Ovčačíková, D. Rigo, "Research on Solid Shell Growth during Continuous Steel Casting", Materials, 2023, 16 (15), 5302. https://www.mdpi.com/1996-1944/16/15/5302
10. Y. Meng, B.G. Thomas, "Heat Transfer and Solidification Model of Continuous Slab Casting, CON1D", Metallurgical and Materials Transactions B, 2003, 34 (5), 685–705. https://link.springer.com/article/10.1007/s11663-003-0040-y
11. Y. Gao, Y. Bao, M. Wang, M. Zhang, "On the Macrosegregation of Continuous Casting of High Carbon Steel Billet with Strand Reduction Process", Metals, 2024, 14 (2), 157. https://www.mdpi.com/2075-4701/14/2/157
12. International Organization for Standardization, "ISO 21224:2025, Evaluation of Centreline Segregation of Continuously Cast Slabs", 2025. https://www.iso.org/standard/86696.html
13. L.C. Hibbeler, B.G. Thomas, "Analysis of Bulging Behaviour during Continuous Casting", Associazione Italiana di Metallurgia Continuous Casting Proceedings, 2009.
14. H. Duan, X. Wang, M. Yao, Y. Liu, Y. Yu, "Prediction Approach of Bulging Position and Deformation Based on Hilbert Huang Transform in Slab Continuous Casting", Metallurgical and Materials Transactions B, 2020, 51, 1656–1667. https://link.springer.com/article/10.1007/s11663-020-01865-1
15. K. Li, S. Ai, J. Guo, "A Three Dimensional Bulging Deformation Prediction Model for Slab in High Speed Continuous Casting Considering the Effect of Molten Steel Deviation Flow", Metallurgical and Materials Transactions B, 2026, 57, 3895–3911. https://link.springer.com/article/10.1007/s11663-026-04086-0
16. Z.P. Yuan, L.G. Zhu, X.J. Wang, K.X. Zhang, "Analysis of Longitudinal Cracking and Mould Flux Optimization in High Speed Continuous Casting of Hyper Peritectic Steel Thin Slabs", Metals, 2024, 14 (8), 909. https://doi.org/10.3390/met14080909
17. M. Geng, H. Ma, J. Wang, S. Liu, J. Li, Y. Ai, W. Zhang, "A Deep Learning Framework for Predicting Slab Transverse Crack Using Multivariate Long Short Term Memory Fully Convolutional Network in Continuous Casting", Expert Systems with Applications, 2025, 260, 125413. https://www.sciencedirect.com/science/article/abs/pii/S0957417424022802
18. S.M. Cho, M. Liang, H. Olia, L. Das, B.G. Thomas, "Multiphase Flow Related Defects in Continuous Casting of Steel Slabs", Proceedings of the Minerals, Metals and Materials Society Annual Meeting, 2020, 1161–1172. https://ccc.illinois.edu/PDF%20Files/Publications/2020_Papers/20_TMS_CHO-SM%20Multiphase-Flow-Related%20Defects%20reprint%20post.pdf
19. X. Meng, S. Luo, X. Xi, "Characterizing and Controlling Abnormal Periodic Mould Level Fluctuations in a Commercial Slab Continuous Caster Using Big Data", Metallurgical and Materials Transactions B, 2024, 55, 4150–4162. https://link.springer.com/article/10.1007/s11663-024-03275-z
20. Z. Ding, C. Wang, X. Wang, P. Xiao, L. Zhu, S. Wang, "The Influence of Process and Slag Parameters on the Liquid Slag Layer in Continuous Casting Mould for Large Billets", Crystals, 2023, 13 (5), 964.
21. J. Elfsberg, "Oscillation Mark Formation in Continuous Casting", KTH Royal Institute of Technology, 2008. http://www.diva-portal.org/smash/get/diva2:7585/fulltext01.pdf
22. M. Zhang, B.G. Thomas, "Hydrogen Embrittlement in Continuously Cast Structural Steels", Metallurgical and Materials Transactions A, 2009, 40 (2), 364–375.

23. Y. Chen, G.J. Li, S.B. Yang, M.Y. Zhu, "Dynamic Soft Reduction for Continuously Cast Rail Bloom", Journal of Iron and Steel Research International, 2007, 14 (5), 13–17. https://link.springer.com/article/10.1016/S1006-706X(07)60066-1
24. C. Li, B.G. Thomas, "Thermomechanical Finite Element Model of Shell Behaviour in Continuous Casting of Steel", Metallurgical and Materials Transactions B, 2004, 35 (6), 1151–1172.
25. C. Ji, S. Luo, M.Y. Zhu, "Analysis and Application of Soft Reduction Amount for Bloom Continuous Casting Process", ISIJ International, 2014, 54 (3), 504–510. https://www.jstage.jst.go.jp/article/isijinternational/54/3/54_504/_article
26. D. Cemernek, S. Cemernek, H. Gursch, A. Pandeshwar, T. Leitner, M. Berger, G. Klösch, R. Kern, "Machine Learning in Continuous Casting of Steel, a State of the Art Survey", Journal of Intelligent Manufacturing, 2022, 33 (6), 1561–1579. https://link.springer.com/article/10.1007/s10845-021-01754-7
27. P. Drożdż, M. Rywotycki, K. Miłkowska Piszczek, "Effect of Casting Speed and Superheat Temperature on Temperature Distribution for the Billet Surface in the Continuous Casting Process", Proceedings of METAL 2019, 28th International Conference on Metallurgy and Materials, 2019.
28. B.G. Thomas, "Modeling of the Continuous Casting of Steel, Past, Present and Future", Metallurgical and Materials Transactions B, 2002, 33 (6), 795–812.
29. K.C. Mills, A.B. Fox, "The Role of Mould Fluxes in Continuous Casting, So Simple Yet So Complex", ISIJ International, 2003, 43 (10), 1479–1486.
30. J. Sengupta, B.G. Thomas, M.A. Wells, "The Use of Water Cooling during the Continuous Casting of Steel and Aluminum Alloys", Metallurgical and Materials Transactions A, 2005, 36 (1), 187–204.