Chapter 1

Historical Aspects and Key Technologies

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Continuous casting (CC) of steel, as an industrialized method of solidification processing, has a relatively short history of only about 50 years[1]—not much longer than oxygen steelmaking. In fact, the CC ratio for the world steel industry, now approaching 90% of crude steel output, attained a mere 4% in 1970 (Fig. 1.1).[2] During the rather lengthy incubation in the precursory periods, i.e., before the 1950s, important development stimuli came from the nonferrous industry, which had applied CC processes already—in particular, by the traveling mold principle—using casting wheels and/or belts to overcome mold friction. Later, genuine ideas emanating from steelmakers added various milestones to the driving of CC application to steel, albeit primarily by a process based on a stationary, oscillating mold.

With CC application rapidly growing in more recent times, the need to grasp solidification phenomena through scientific rationale—supporting the know-how with the know-why—found response in several fundamental textbooks,[3–5] apart from the ever-growing number of pertinent conference proceedings and technical reports. Another essential precondition for CC industrialization has been the concurrent progress in steelmaking technologies.[6,7] Cost-effective electric arc

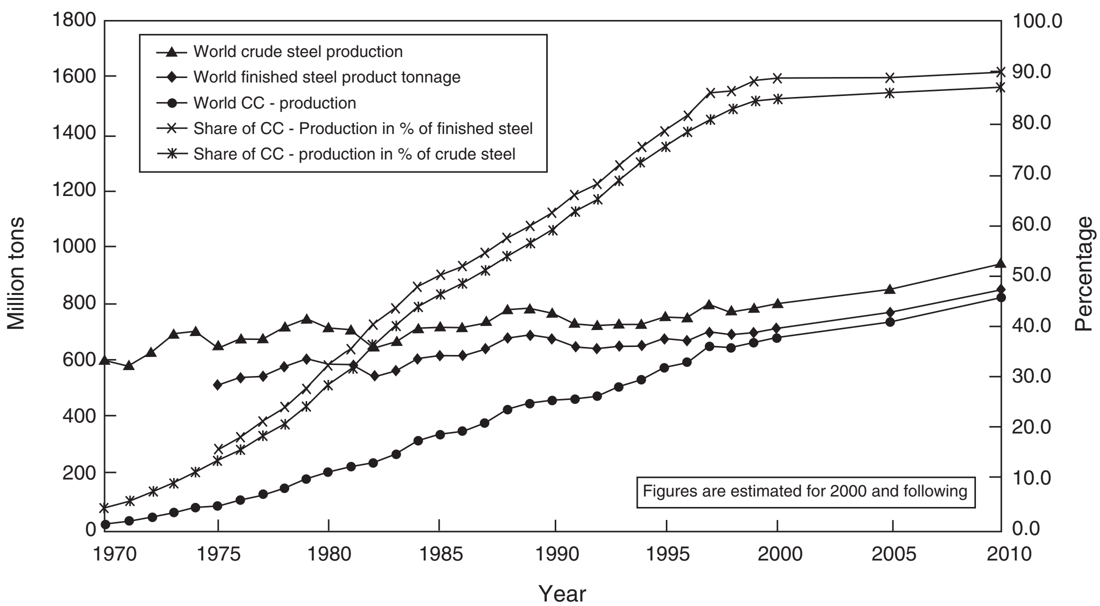


Fig. 1.1 Evolution of world steel production and share of continuous casting. *From Ref. 2.*

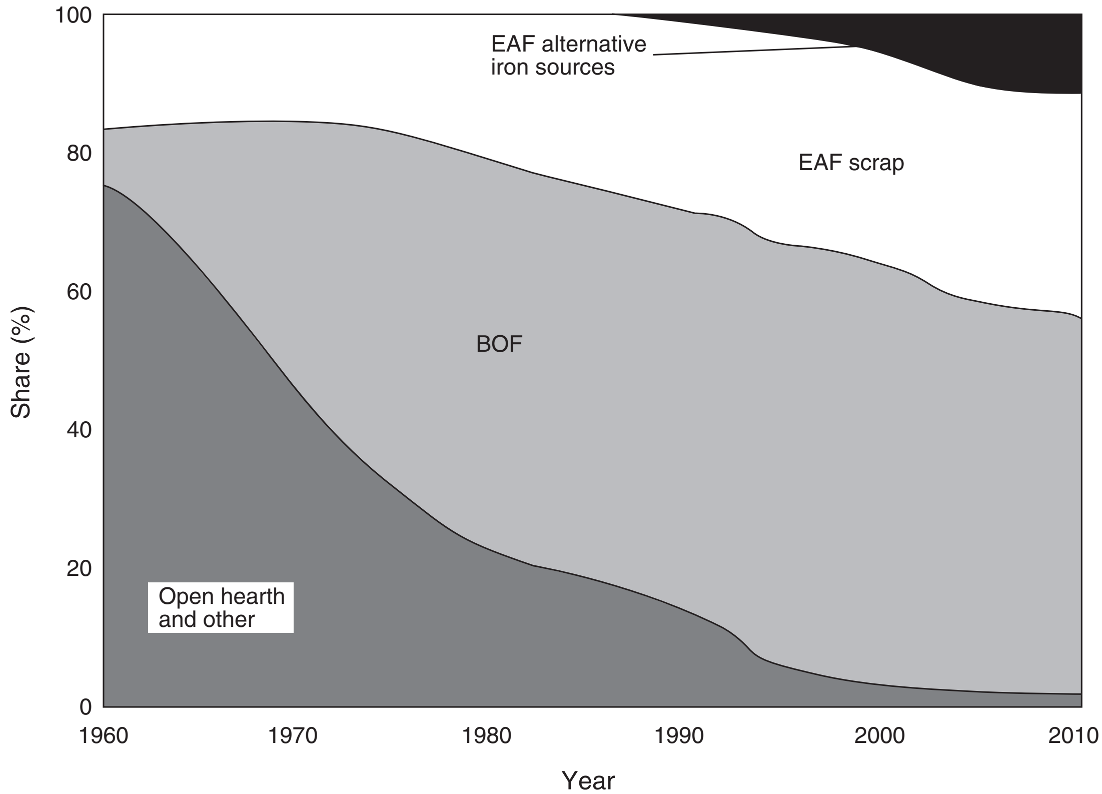


Fig. 1.2 Evolution of share in world steel production by steelmaking process. *From Ref. 9.*

furnace (EAF) operations, apart from specialty steelmaking, for commercial quality (CQ) products, were developed for emerging mini-mills,[8] in competition with the simultaneous development of the basic oxygen furnace (BOF) used by integrated steelmakers; both melting processes assure a much more stable steel supply to the caster than the once-dominant open hearth furnace (OHF) process (Fig. 1.2).[9]

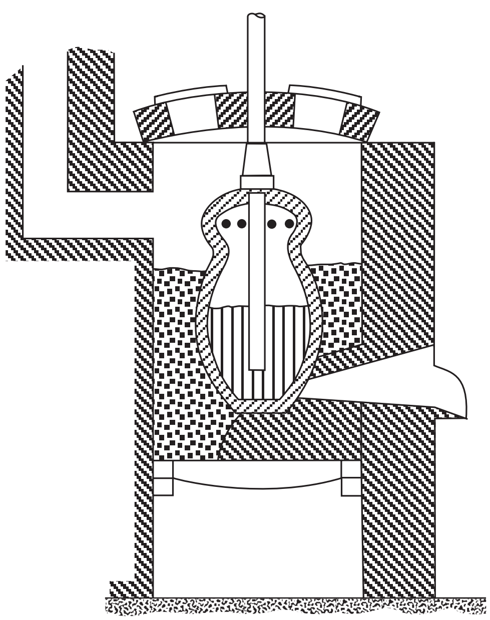
In the following section, significant precursor ideas and innovations will be highlighted first. Then, key technologies established by more recent development efforts are reviewed along the process route from steel supply to the caster, via solidification in the mold and below, until cutting and further processing of the strand cast products, always with the focus on the historical perspective.

1.1 Precursor Developments and Milestones

Among the various milestones listed in Table 1.1, the most spectacular of early CC attempts has been the direct strip casting effort by Sir Henry Bessemer in 1856 (Fig. 1.3). After successful blowing experiments in a melting crucible to produce liquid steel, he then disposed of it in his double-roller apparatus, which he used to cast thin strip for brass powder ("artist's gold") manufacture.[10] However, he did not pursue this technology, presumably giving higher priority to developing the steelmaking process first. In such further developments, Bessemer then implemented a tundish with stopper for slag retention (Fig. 1.4).[11] As shown, the 10-by-10-inch mold below the tundish incorporated a hydraulic ram to push the ingot upward for an intended direct rolling of the ingot without reheating—obviously a precursor for closing the lower end of the mold with a dummy bar. In the ensuing industrialization of the bessemer steelmaking process, the Swedish entrepreneur Goeran Fredrik Goeransson introduced a stoppered ladle for the transfer of liquid steel from the blowing vessel to the pouring pit via a hoist in 1858; the latter was replaced by Henry Bessemer

Table 1.1 100 Years of Precursor Milestones in CC Development

Year	Inventor	Milestone
1856	Bessemer	Twin-wheel strip casting (trials)
1856	Bessemer	Stoppered tundish; open-ended mold closed with ram
1858	Goeransson	Stoppered ladle
1859	Bessemer	Ladle turret
1885	Lewis	Ladle slidegate (concept)
1886	Atha	Vertical type billet casting with dummy bar
1889	Daelen	Vertical type billet casting with cut-off (concept)
1915	Rowley	Bending/unbending type billet casting
1921	Van Ranst	Mold oscillation (concept)
1933	Junghans	Mold oscillation and submerged pouring tube
1936	Junghans	Strand inline sizing (trials)
1938	Junghans/Rossi	Tundish heating and inertization, slag retention, spray water secondary cooling
1939	Williams	Roller apron strand support for slab section
1944	Bardin et al.	Plate mold for large bloom and slab section
1947	Harter et al.	Remote mold operation with TV-supervision and automatic mold level control
1947	Rossi	Funnel-shaped mold for thin slab casting (concept)
1949	Junghans	Electromagnetic stirring in the mold
1950	Tarquinee et al.	High-productivity caster with inline sizing (concept)



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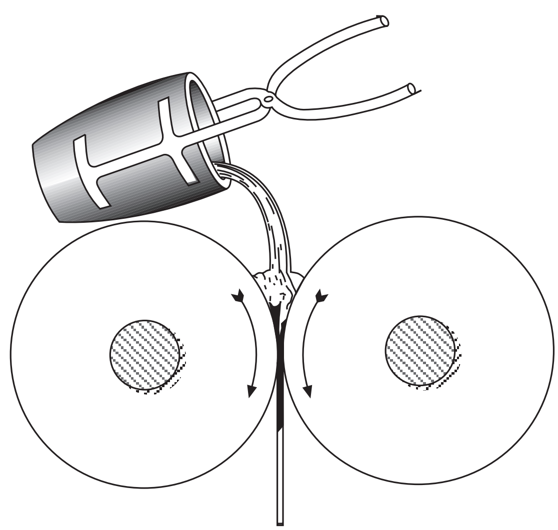


(b)

Fig. 1.3 (a) Early steelmaking in a crucible, and (b) direct strip casting trials by Henry Bessemer in 1856. *From Ref. 6.*

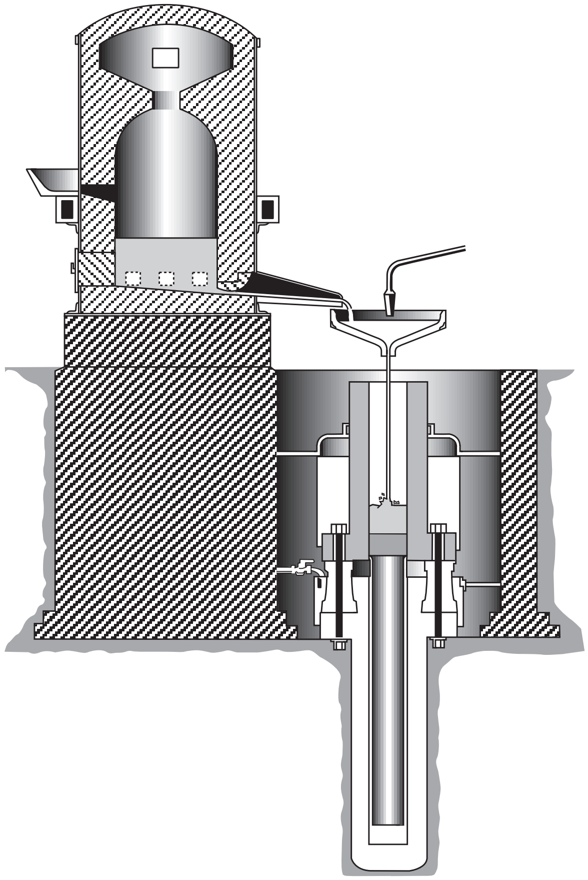


Fig. 1.4 Stationary steelmaking blowing converter, stoppered tundish and ingot mold with hydraulic ram applied by H. Bessemer. *From Ref. 11.*

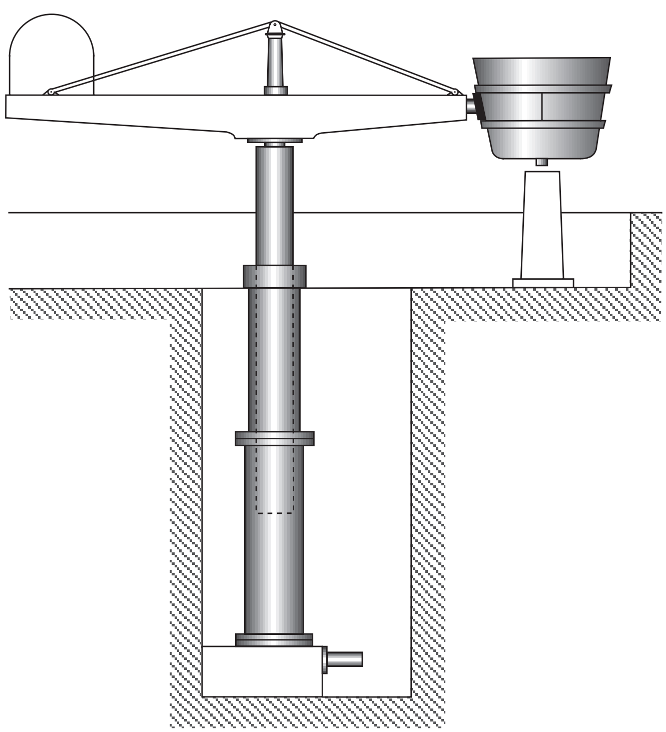


Fig. 1.5 Ladle turret for ingot pouring conceived by H. Bessemer. *From Ref. 11.*

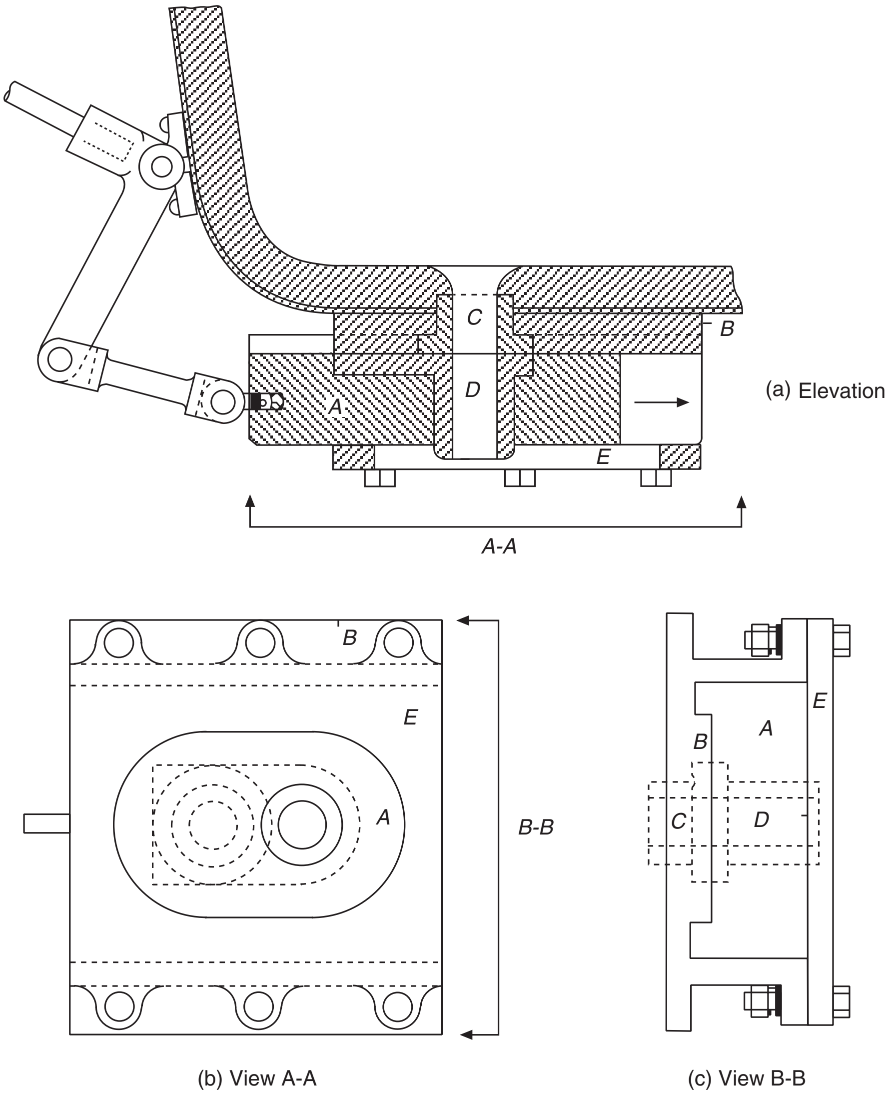


Fig. 1.6 First ladle slidegate invented in 1885 by D. D. Lewis. *From Ref. 12.*

in 1859 with a swing-type device, i.e., the first ladle turret (Fig. 1.5).[11] A first ladle slidegate had been conceived by David D. Lewis in 1885 (Fig. 1.6).[12]

The very first apparatus resembling a conventional CC machine is due to Benjamin Atha of the Atha & Illingworth Co. in Harrison, N.J., a tool steelmaker that merged into the Crucible Steel Co. of America in 1901 (together with 12 other leading special steel firms).[13] As shown in Fig. 1.7 from his 1886 patent application,[14] the water-cooled mold is directly connected with the tundish, while the dummy bar features a claw-shaped head and is withdrawn intermittently by a pair of driven rolls. Reportedly, several thousand tons in 100-by-100 mm of high-carbon file steel had been cast till 1910.[15] Independently, the German inventor and steel industry consultant R. M. Daelen patented in 1889 a similar (not actually used) apparatus with shear cutting on the fly;[16] this was indicative of the often-encountered phenomenon that identical solutions to a given task may surface simultaneously at different locations when circumstances have matured.

The first caster seemingly built by a genuine machine builder, i.e., Arthur McKee Co. of Cleveland, Ohio (who merged with Davy, Sheffield in 1978), had been designed by John T. Rowley of the United States Horse Shoe Co. in Erie, Pa., already with bending and unbending (Fig. 1.8).[17]

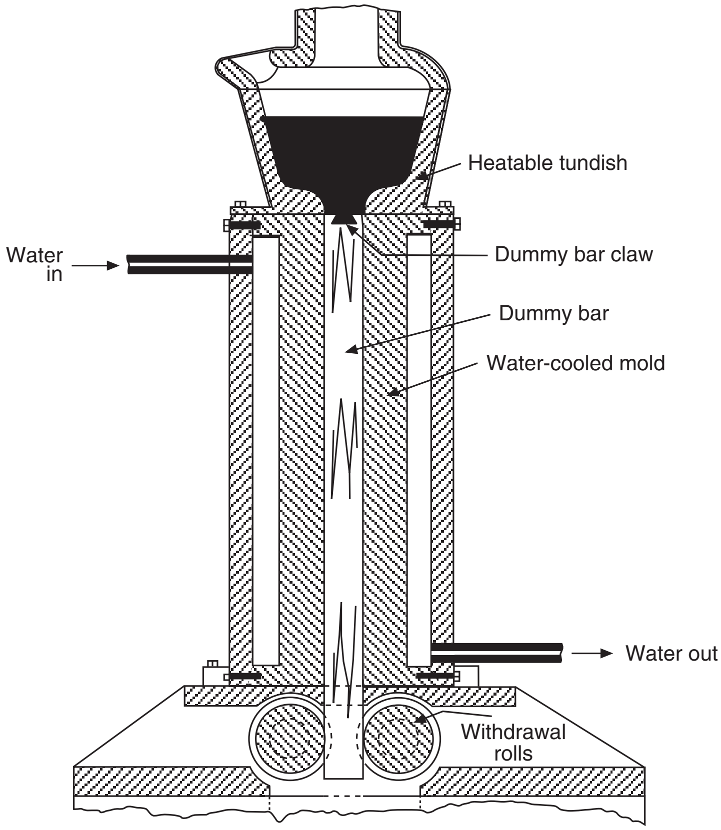


Fig. 1.7 First billet casting apparatus by B. Atha in 1886. *From Ref. 14.*

Reportedly, billet sizes were 45-by-45 and 75-by-75 mm in lengths ranging from 10–50 m (without cut-off on the fly), the somewhat erratic length control a consequence of excessive mold friction that caused shell sticking and tearing at random.[18]

Hence, it was a great relief when mold oscillation became implemented by Siegfried Junghans, the very secretive inventor and shop manager of the renowned Black Forest clockmaking enterprise, in 1933.[19] (The concept to reciprocate a short mold up and down to reduce mold friction had been patented by Cornelius W. van Ranst of New Rochelle, N.Y., in 1921 [20] (Fig. 1.9), but no application surfaced at that time.) When the engineer and businessman Irving Rossi of New York City met Junghans in 1936,[21] he obtained his sales

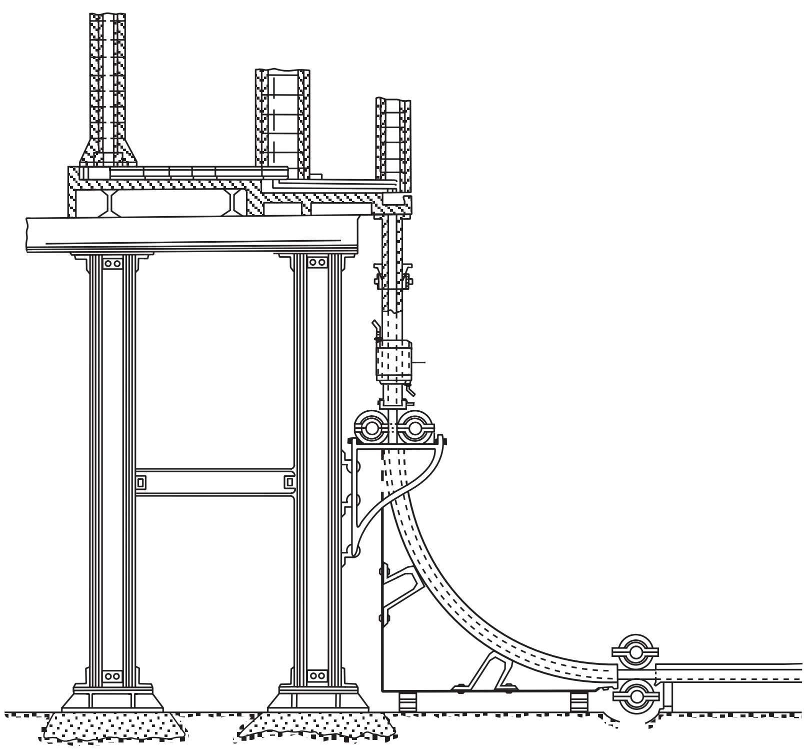


Fig. 1.8 First bending and unbending billet caster by J.T. Rowley in 1915. *From Ref. 17.*

rights for all territories outside Germany; this cooperation ultimately led to the industrialization of CC for steel.

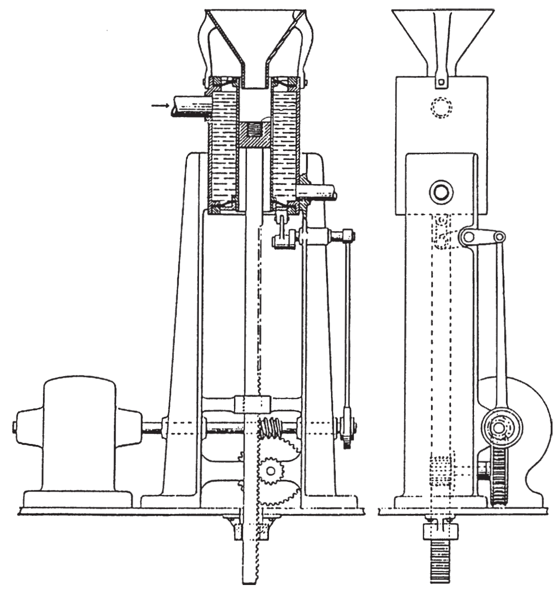


Fig. 1.9 First proposal for mold oscillation by C.W. van Ranst in 1919. *From Ref. 20.*

A first caster for nonferrous metals was sold by Rossi in 1937 to Scovill Manufacturing Co. at Waterbury in the famous Connecticut "brass-valley," an innovative enterprise having already applied several CC processes with traveling mold, including the Hazelett process, at that time. While the caster, with the oscillating mold plus direct cooling by water sprays below, looks rather simple (Fig. 1.10),[22] an elaborate melt supply and feeding system had been implemented:

- fully shrouded metal transfer from the ladle through a funnel into two induction-heated and inertized holding vessels, arranged in parallel;
- from there, shrouded metal transfer into a small and inertized intermediate feeding trough by inert gas pressure (assuring complete slag retention) via resistance-heated ducts, and equipped with a metal height indicator;
- then, gravity feeding through another resistance-heated duct into the gas-shrouded mold.

Rossi had guaranteed an uninterrupted caster operation of seven days,[21] which, indeed, was achieved from the very start.[22] Based on this success, industrial application of the "Junghans-Rossi" vertical caster with mold oscillation (short Cu-mold of 0.45–0.70 m long, block-type with drilled water passages, Cr-plated, rapeseed oil lubrication and inert gas shrouding, oscillation stroke 12–50 mm) found rapid acceptance in the nonferrous industry, with a total of 12 casters built and operating by 1951, five each in Germany and the U.S. and another two in Great Britain.[1]

Stimulated by this successful example of the nonferrous metals industry, efforts gradually intensified to apply CC technology to steel, too; albeit most of such developments were heavily curtailed in the years during and shortly after WWII. By the same token, very few design and operational details surfaced due to a general secrecy prevailing around such activities. An outstanding promoter has been Edward R. Williams, the president of Vulcan Mold and Iron Co. in Latrobe, Pa., who founded an engineering firm in 1933 devoted to CC developments. He went for a long and stationary mold and attempted to reduce mold friction by intermittent strand withdrawal (as horizontal casters still use today). Especially noteworthy is his patent application for a roller apron strand support required in the casting of slab sections (Fig. 1.11).[23] Williams then teamed up with Republic Steel to start a larger pilot caster in 1942 at the Corrigan-McKinney Works in Cleveland, Ohio, for billets 100-by-100 mm as well as mini-slabs 75-by-215 mm. Additionally, in 1948 a further pilot unit was jointly built by these partners in cooperation with Babcock & Wilcox at their Beaver Falls Works, Pa. (Fig. 1.12), already equipped with such advanced features as automatic mold level control and remote TV supervision.[24]

Based on a stationary fixed (nonoscillating) mold, many similar contemporary efforts were initiated then: in the U.S., Bethlehem Steel at Lebanon, Pa. (1941); in Great Britain, Low Moor Alloy Steelworks in Bradford (1946), and Bisra Battersea Labs in London (1948); in Russia, the Tsnichermet Labs in Moscow (1944); in Japan, Sumitomo Metal at Amagasaki (1947); in Austria,

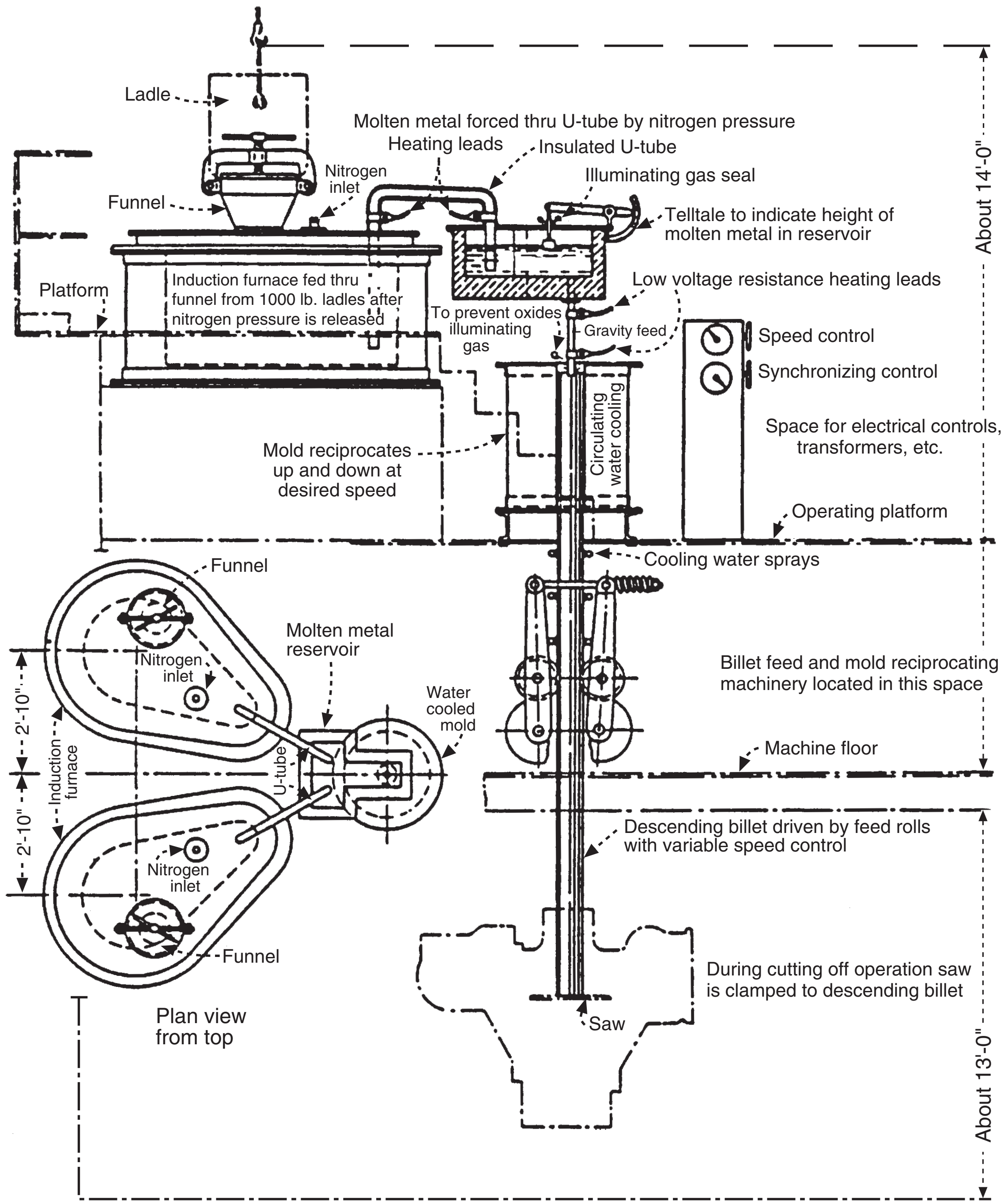


Fig. 1.10 First industrial Junghans-Rossi caster with oscillating mold at Scovill Mfg. Co., Waterbury, Conn., in 1938. *From Ref. 22.*

Schoeller-Bleckmann in Ternitz (1946), Edelstahl Breitenfeld in Mitterdorf (1948) and Boehler in Kapfenberg (1949); and in France, Holtzer at Unieux (1950).[1]

Obviously, these casting efforts were impaired by mold friction and, hence, were less successful than early pilot casting for steel with the oscillating Junghans-Rossi mold. Thereby, again, little is known about the Junghans trials at Mitteldeutsche Stahl und Walzwerke in Brandenburg (1943) and at Ruhrstahlwerke in Witten (1944), owing to wartime circumstances.[1] However, after he had started his own pilot caster, fed by a one-tonne Bessemer converter at Schorndorf (1949), Junghans entered a cooperation agreement with Mannesmann, who started their pilot caster at Huckingen soon afterward (1950). In 1952, the German and Austrian CC developers joined forces, later nominating Demag as their machine builder in 1956, which led to the group's acronym DMB, i.e., Demag-Mannesmann-Boehler.[25]

This left Rossi on his own. He sold his first steel caster to Allegheny Ludlum in Watervliet, N.Y., built by Koppers Co. and started in 1949, mainly for billet sections 140 mm round and mini-slabs 75-by-380 mm. Since he gave guarantees for caster productivity (minimum 20 tonnes per hour) as well as product quality, this unit may be considered the very first attempt at a commercial caster for steel.[21] Apart from the features seen in Fig. 1.13, inert gas shrouding of tundish and mold as well as resistance preheating of the (nonsubmerged) pouring tube are noteworthy.[26,27] For the eventual application of a submerged entry nozzle (SEN) to the thin-slab section, Rossi proposed and patented a funnel-shaped upper mold half (Fig. 1.14)[28] but did not use it. In 1950, Rossi formed the engineering company Continuous Metalcast Inc., registered in Wilmington, Del., with Allegheny Ludlum and Koppers among the shareholders. Shortly thereafter, he obtained

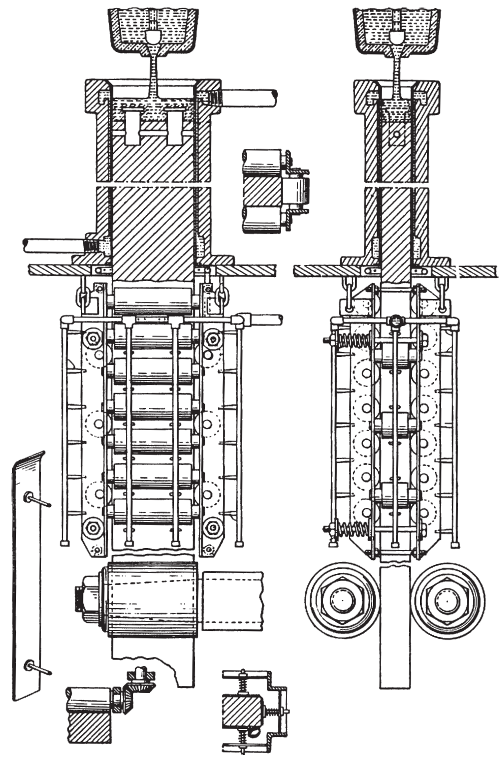
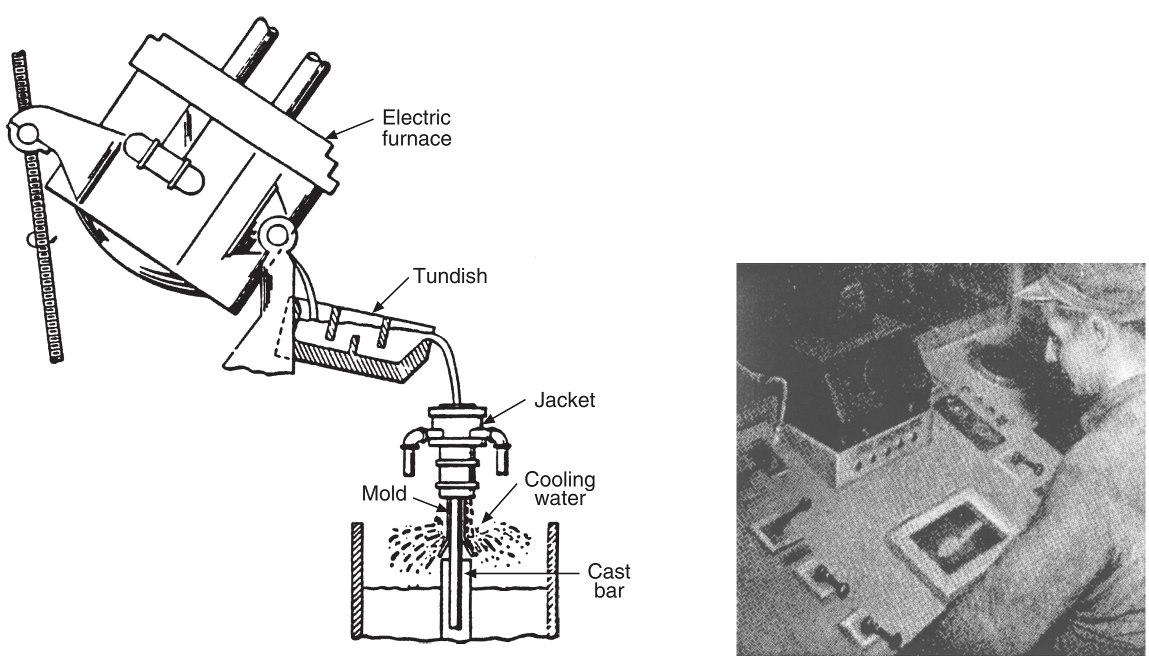
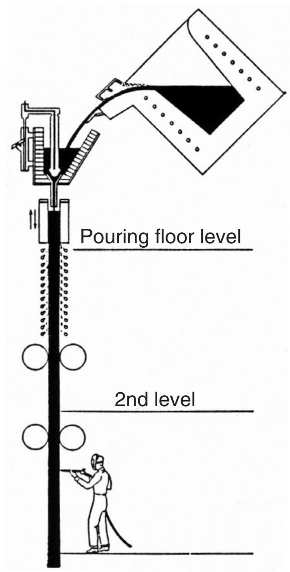


Fig. 1.11 Patent for roller apron strand support of slab sections by E.R. Williams. *From Ref. 23.*



(a) (b)

Fig. 1.12 (a) Sketch of Babcock & Wilcox pilot caster at Beaver Falls, Pa., with direct tapping from EAF through tiltable tundish with weir/dam system for slag retention and (b) caster equipped with remote mold supervision via TV monitoring system. *From Ref. 24.*



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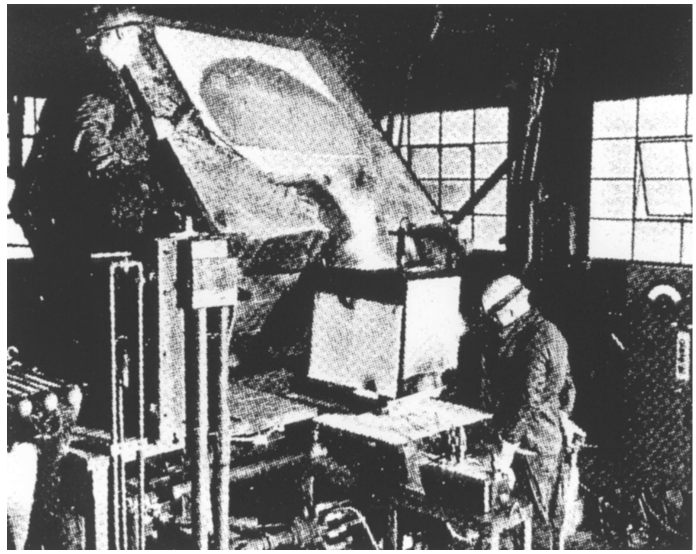
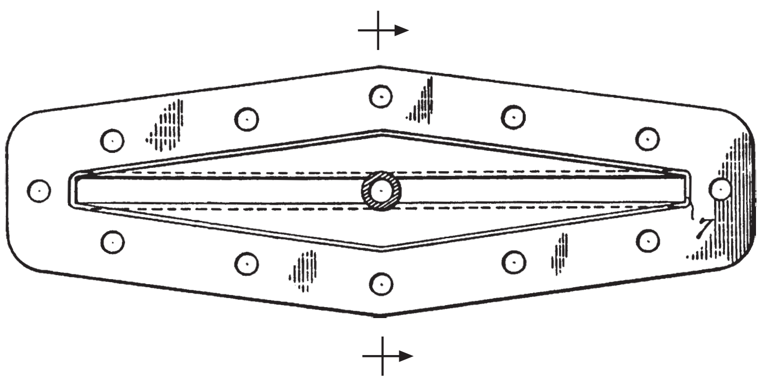


(b)

Fig. 1.13 First caster for steel with a production guarantee at Allegheny Ludlum with lip pouring from an induction furnace into a stoppered tundish: (a) schematic and (b) pouring floor view. *From Ref. 26.*

orders (mainly from specialty steelmakers) for four more casters, i.e., Atlas Steels in Welland, Ontario; Barrow Steel Works in England; Nyby Bruks in Eskilstuna, Sweden; and Forges d'Allevard in France. For handling the overseas business, Concast AG in Zurich, Switzerland, was founded by Rossi in 1954.[21]

Thus emerged the two main rival groups in caster design and supply at the onset of CC industrialization, apart from many other machine building efforts of smaller capacity.[1] An opportunity for a certain understanding between both groups arrived after implementation of the curved mold concept when both, the DMB consortium and the Concast group, formed a joint venture company in



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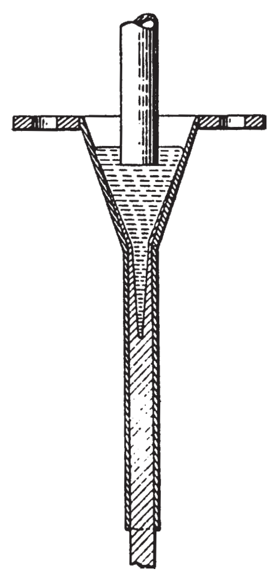


(b)

Fig. 1.14 Patent for funnel shaped thin slab mold by I. Rossi: (a) top view, (b) side view. *From Ref. 28.*

1963 called MBC (Mannesmann-Boehler-Concast) in Zurich for mutually exploiting their patents. In 1969, Boehler left this alliance in order to support the emerging caster business of Voest-Alpine Industrieanlagenbau (VAI), while Mannesmann and Concast maintained their joint patent interests until 1981, when the Concast group was dismantled into solitary marketing and machine building activities of the former group members.[21]

1.2 Continuous Casting Industrialization and Key Technologies

As is obvious from the above, initial CC development focused on the manufacture of specialty steels where potential yield savings entailed the largest cost advantage. Also, the smaller ladle capacity was more compatible with low caster throughput rate. Apart from the latter aspect, a further obstacle for adopting CC by "big" steel was brought about by the largely unsuccessful attempts in producing rimming steel of acceptable surface quality.[29] Thus, early efforts in slab casting were restricted to the manufacture of Mn/Si-killed plate grades, for instance.[30] Only the conversion to Al-killed steels and concurrent improvements in strand surface quality opened the way to a wider CC application for both flat and long products. In this context, developments in steel refining and ladle metallurgy[31] also became a vital prerequisite, equally important to both caster productivity and product quality.

In the course of CC development, several caster types have been realized, with significant differences in design height (Fig. 1.15),[32–38] including the vertical variant with the option to rotate around its axis. Some of these types, though, were constrained in caster productivity either due to limited support length (i.e., vertical type) or due to casting speed being limited by high mold friction (i.e., horizontal type). Besides, there are characteristic differences with respect to product quality as well. In order to briefly highlight the emergence of CC key technologies in the historical perspective, the process will be followed from the liquid to the solid phase (Table 1.2). This also allows a simple distinction by the three major quality criteria, i.e., steel cleanliness, surface quality and inner soundness (Fig. 1.16).[39] (Note: since the emphasis is on process technology, details of caster design are not highlighted in this review.)

1.2.1 Steel Supply and Tundish Operation

The supply and distribution system for liquid steel from the melting furnace to the caster via ladle and tundish depends heavily on the quality of refractory materials (Fig. 1.17).[40] Based on the intimate cooperation between steelmaking and refractory industries, the overall refractory consumption has been continuously reduced from about 50 kg per tonne of steel in 1960 down to now typically 10 kg per tonne of steel.[41,42] At the same time, refractory performance has been tremendously improved, with ladle lining life in excess of 300 heats and attaining better steel cleanliness (Fig. 1.18).[43]

From the onset of CC development, a main concern was liquid steel temperature control, which became a major obstacle for small ladle capacities (large surface-to-volume ratio) and/or long casting times. While early pilot casters were directly fed from the melting (or holding) furnace (Figs. 1.12 and 1.13), this has not been a practical solution for an industrial operation of larger scale. Thus, one rigorous approach was pursued by Halliday at Barrow Steelworks in England with a completely enclosed lip-pour (teapot) ladle that could be heated during casting by a can-jet burner through the ladle lid (Fig. 1.19), allowing casting times up to two hours from a seven-tonne ladle.[44] Halliday also insisted on high-temperature ladle preheating, i.e., close to the liquidus temperature of a given steel type.

For larger ladle capacities, the lip-pour ladle was not practical and had to yield to stopper flow control. Also, steel temperature control greatly benefited from the introduction of the ladle furnace

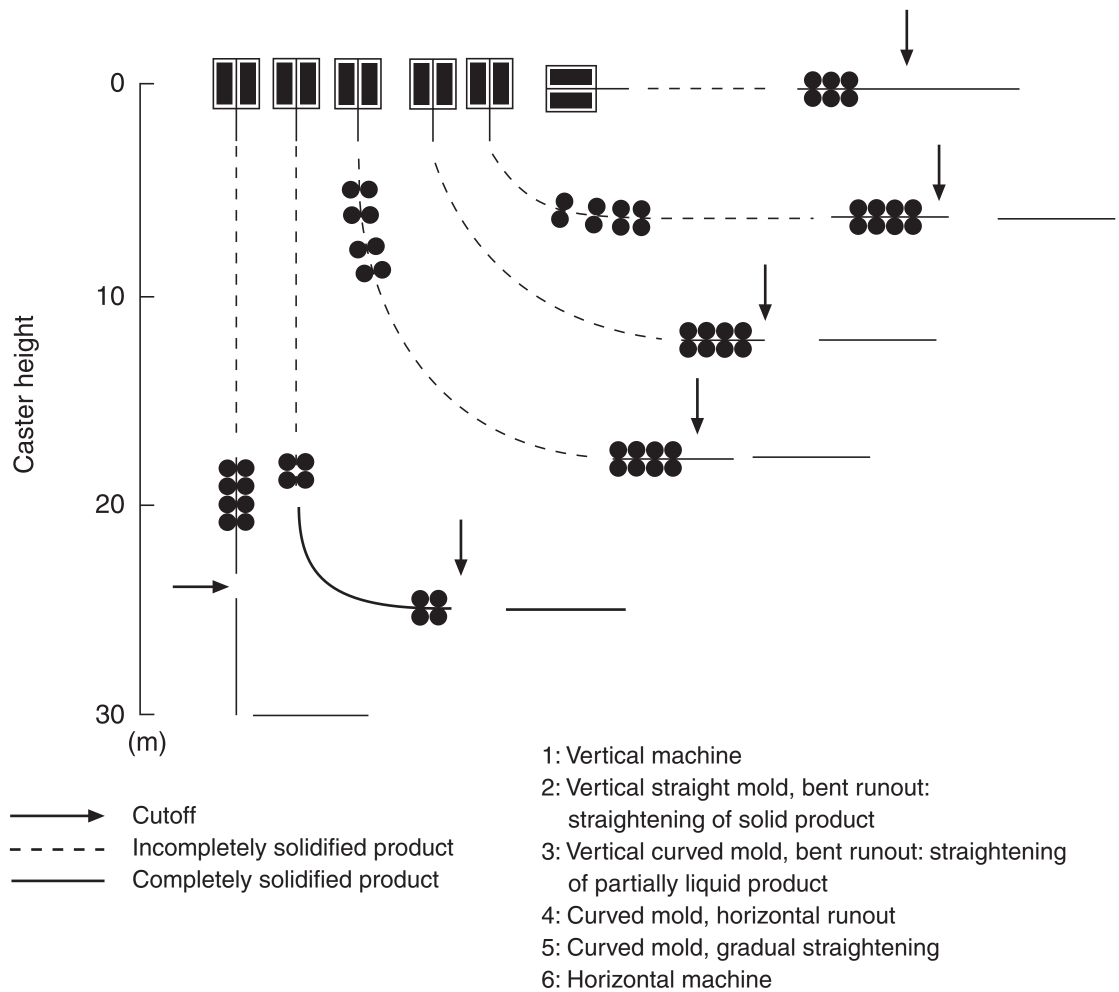


Fig. 1.15 Characteristic caster types and design height. *From Ref. 38.*

(LF), i.e., heated by electrodes, simultaneously promoted by ASEA and SKF in Sweden (Fig. 1.20)[45] and by C.W. Finkl at his Chicago plant.[12] In both cases, vacuum degassing was also incorporated, which widened the possibilities for ladle metallurgy, with steel refining and inclusion flotation enhanced by electromagnetic stirring in the former and inert gas purging through a porous plug in the latter case.[31] Of course, the use of stopper control was not well suited to the increasing metal residence times; a great advance in operational reliability and, hence, caster productivity was achieved by the implementation of the ladle slidegate (Fig. 1.21).[46,47]

With such a gradual shift of the refining process from the melting vessel into the ladle, the awareness of slag/metal reactions during ladle treatment has also increased in recent years.[31] Thus, ladle slag deoxidation to low FeO + MnO contents has become by now standard practice, depending on the cleanliness requirements of the final product (Fig. 1.22).[48,49] To circumvent nozzle clogging during casting in the case of Al-fine-grain steels, calcium treatment of the liquid steel in the ladle to modify solid alumina into liquid calcia-aluminate particles is also a widely adopted measure of modern steel refining since the early 1980s.[31,50] However, in the case of higher sulfur content in steel, care must be taken to restrict the calcium content to about 10 ppm or less.[49,51]

Upon delivering the ladle from the LF to the caster "just in time," one key requirement is reliable "free opening" of the ladle slidegate, which depends on multiple operating conditions.[31] It is also good practice to divert the slidegate filler sand from entering the tundish. Despite advanced precursor teeming practices (Fig. 1.10), the requirement of ladle stream shrouding has been recognized

Table 1.2 Key Technologies in CC Industrialization History

Key Technology	Main Inventor/Promoter (Year)
(A) Steel Supply and Tundish Operation:	
Ladle slidegate	Benteler (1960); U. S.Steel–Gary (1961)
Ladle furnace	Bofors (1967); Finkl (1968)
Ca-treatment of Al-fine grain steel	Von Roll Gerlafingen (1980)
Ladle stream shroud: hood type	Sumitomo Metal Industries Wakayama (1969)
long nozzle	SAFE Hagondange (1965)
Ladle slag detector	MPC (1980); Amepa (1984)
Tundish inertization	Timken (1969); Decazeville (1974)
Backflying tundish change/link casting	Thyssen Ruhrort (1980)
Tundish hot cycle	Maxhuette (1972); ALZ (1976); Kobe Kakogawa (1989); Sumitomo Metal Industries Wakayama (1996)
Tundish heating: – radiation	Timken (1969)
– induction	Decazeville (1974); KSC Chiba (1982)
– plasma	Nippon Steel Hirohata (1987); Kobe Kakogawa (1989)
Argon bubbling through tundish bottom	(over the years various trials only)
Tundish slidegate	U. S. Steel–Gary (1967); Sumitomo Metal Industries Wakayama (1971)
Argon through tundish stopper	Rheinstahl Hattingen (1970)
Pouring tube changer	U. S. Steel–Gary (1967); British Steel Lackenby (1986)
(B) Mold Technology:	
Multi-tapered mold geometry	Benteler (1963); UBC (1986)
Mold powder lubrication	Low Moor Alloy Steelworks (1960)
Exothermic starter powder	Mannesmann (1975)
Mold powder automatic feeder	Sumitomo Metal Industries Wakayama (1972)
Hydraulic mold oscillation	Koppers (1962); Mitsubishi Heavy Industries (1965); NKK (1977)
Bifurcated pouring tube	Mannesmann (1965); Dillingen (1965)
Multihole pouring tube	Inland Steel & Bethlehem Steel (1968)
Mold level control: – radioactive	B&W (1948); Barrow (1958)
eddy current: – mold integrated sensor	MPC (1974)
– suspended sensor	NKK (1979)
Mold electromagnetic stirring (MEMS)	Arbed/Irsid (1976)
Mold electromagnetic brake (EMBR)	Kawasaki Steel/ASEA (1982)
Mold instrumentation with thermocouples:	
– for sticker detection	Kawasaki Steel Mizushima (1982)
– for surface quality prediction	Nippon Steel Sakai (1985)
Straight-mold/bending caster:	
– with solid core	Barrow (1958); Dillingen (1964)
– with liquid core	Olsson (1962); VAI (1968)
Curved mold caster concept	Schaaber (1952); Schneckenburger (1956); Xu Baosheng (1960)
Twin-mold casting	Atlas Steels Welland (1954)
Beam blank mold and caster	Bisra (1964); Algoma (1968)
Slab mold width change during casting	Nippon Steel Nagoya (1974)

Table 1.2 Key Technologies in CC Industrialization History (cont'd)

Key Technology	Main Inventor/Promoter (Year)
(C) Strand Guiding, Discharge and Further Processing:	
Air-mist cooling	Mannesmann (1975)
Dynamic cooling control	Rheinstahl Hattingen (1970)
Split roller strand support	VAI (1968)
Progressive strand bending	Olsson (1960)
Progressive strand straightening	Mannesmann (1964)
Roller cavity checker	U. S. Steel–Gary (1976); Mannesmann/Wiegard (1980)
Strand electromagnetic stirring (SEMS)	
– bloom/billet	SAFE Hagondange (1975)
– slab	Nippon Steel /Yasukawa (1973)
Final electromagnetic stirring (FEMS)	Kobe Steel Nadahama (1981)
Strand soft reduction	NKK (1974)
Jumbo-slab slitting	National Steel Great Lakes (1977)
Strand inline sizing	Boehler/Demag (1967)
Inline quenching of Al-treated steel	Sumitomo Electric (1982)
Real-time quality prediction	Voest Alpine Stahl Linz (1986)
Hot surface inspection (eddy current)	Sollac Fos (1988)
Slab sizing mill/press	Nippon Steel Oita (1980); Kawasaki Steel Mizushima (1986)
Hot direct rolling	Benteler (1962); Nippon Steel Sakai (1981)

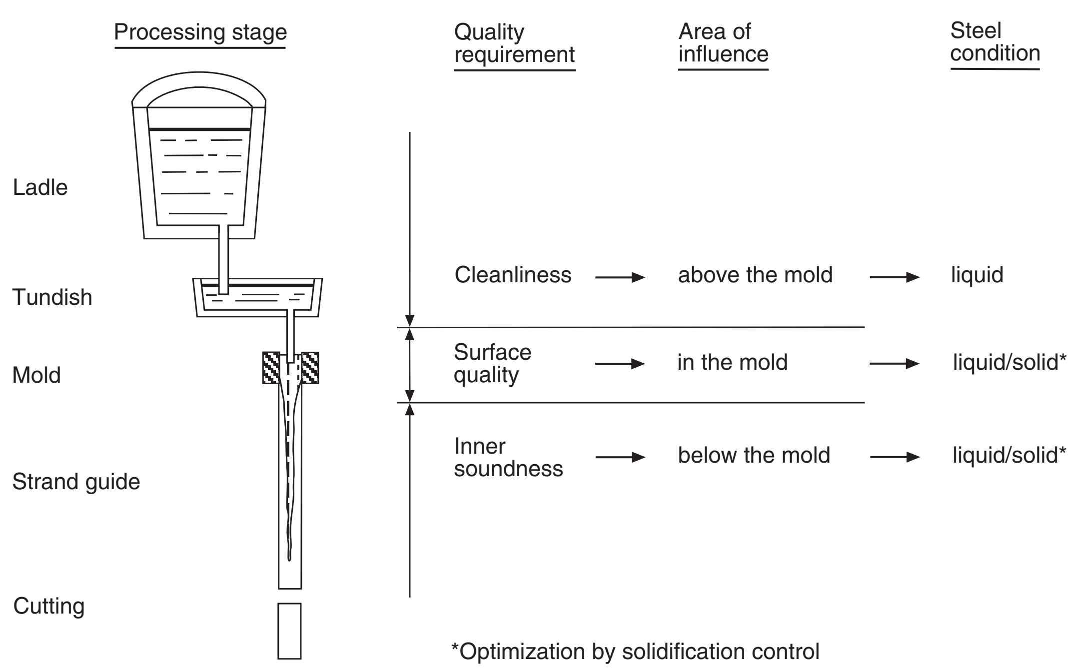
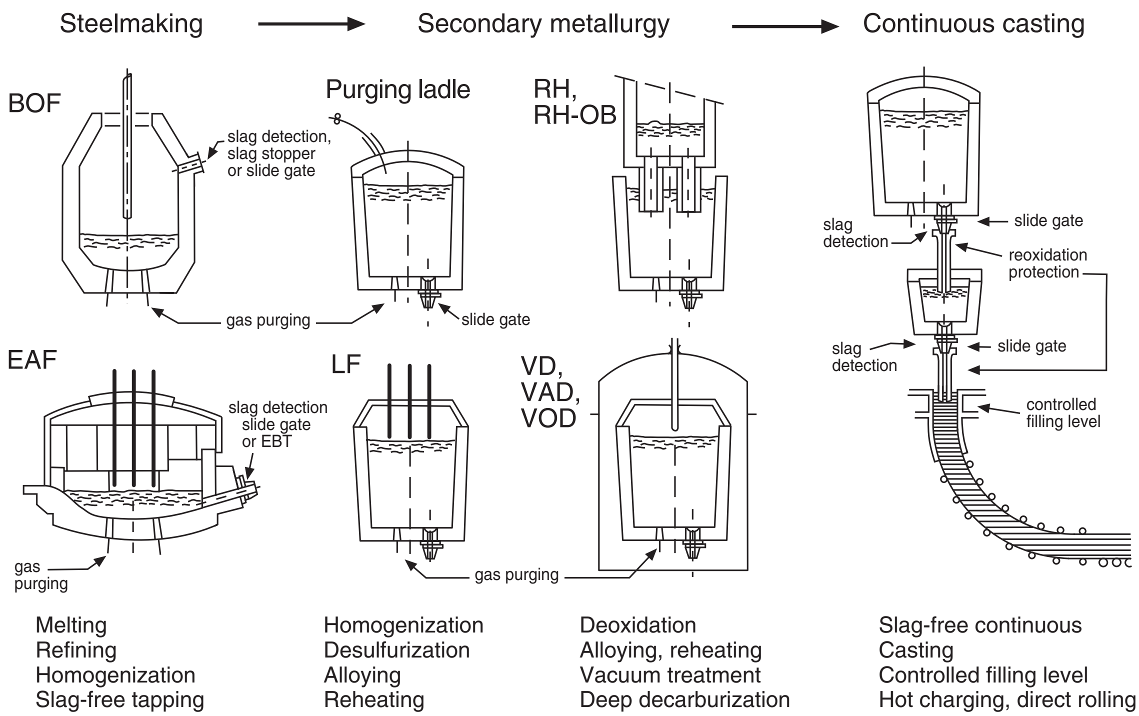
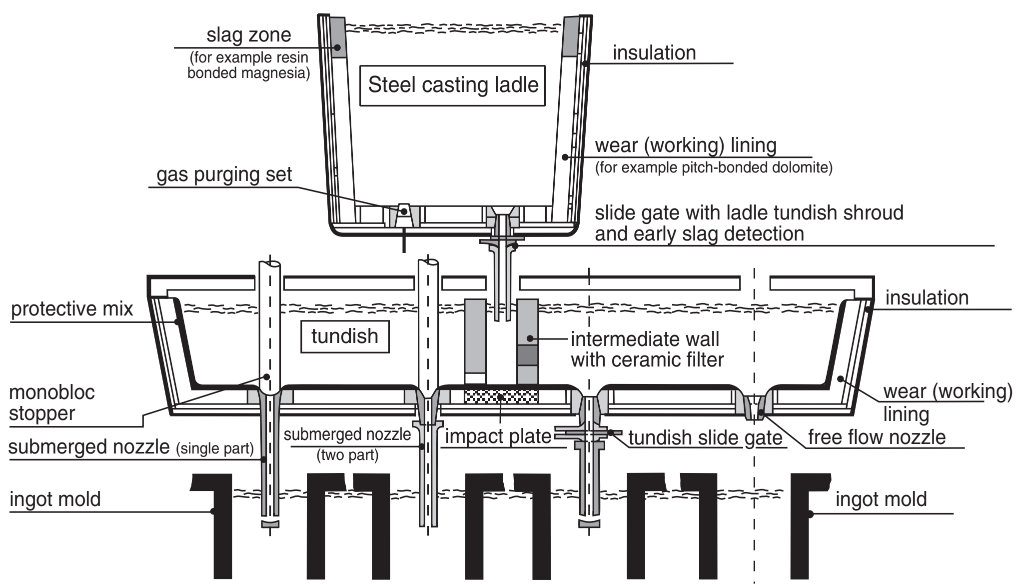


Fig. 1.16 Main processing stages in continuous casting and their relevance to product quality, schematic. *From Ref. 39.*



(a)



(b)

Fig. 1.17 (a) Refractory-lined vessels for liquid steel handling and transport, and (b) schematic outline of ladle and tundish refractories. *From Ref. 40.*

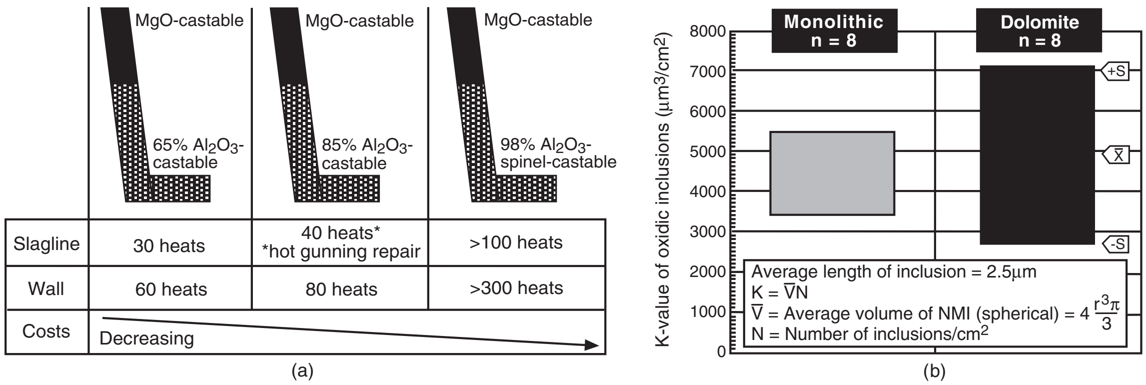


Fig. 1.18 (a) Example for life enhancement in ladle linings and (b) improved steel cleanliness by monolithic refractory. *From Ref. 43.*

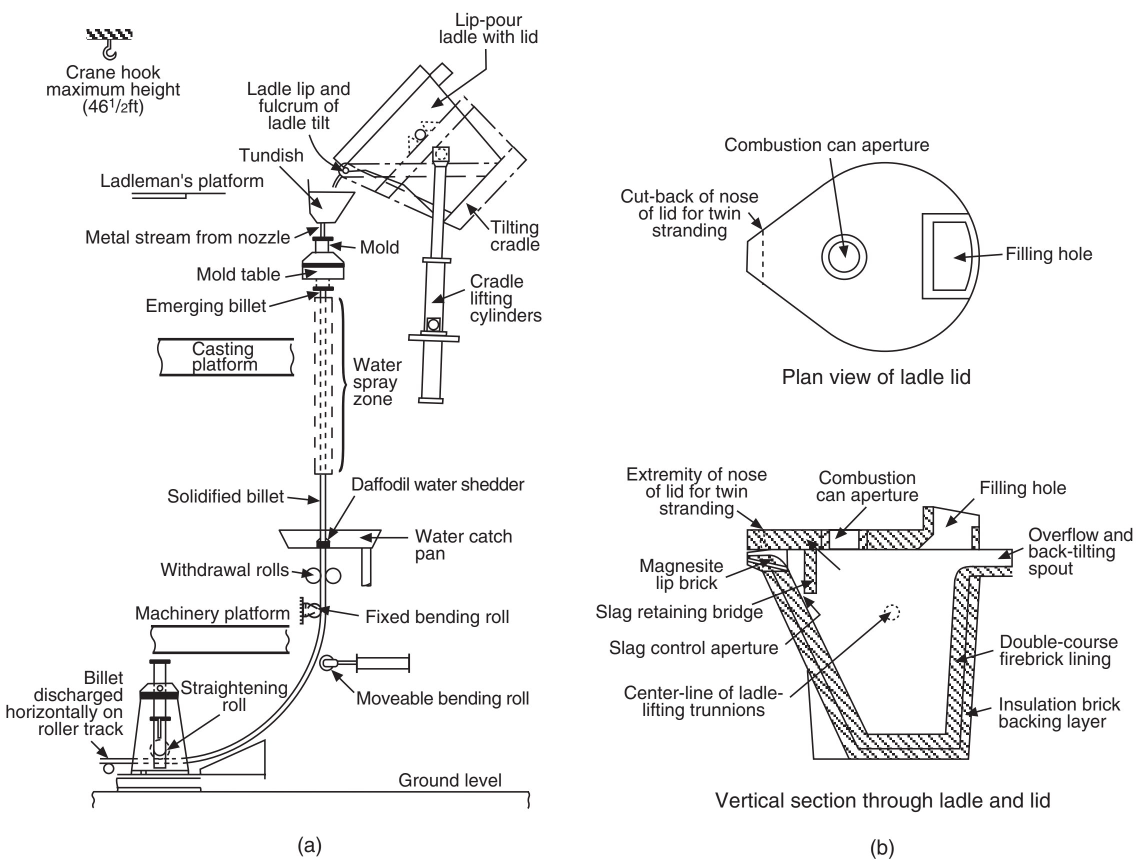


Fig. 1.19 (a) Caster profile and (b) lip-pouring ladle with heating during casting at Barrow. *From Ref. 44.*

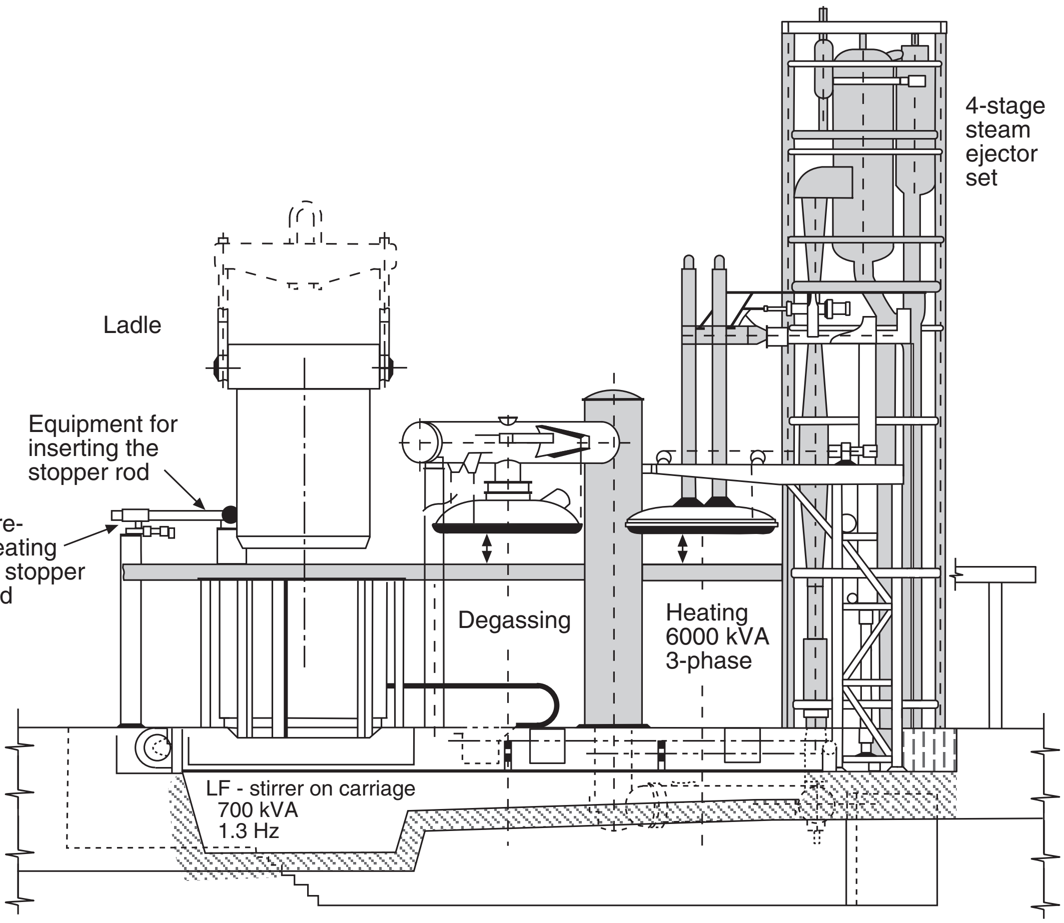


Fig. 1.20 Example of early ASEA/SKF ladle furnace at AB Bofors, Sweden. *From Ref. 45.*

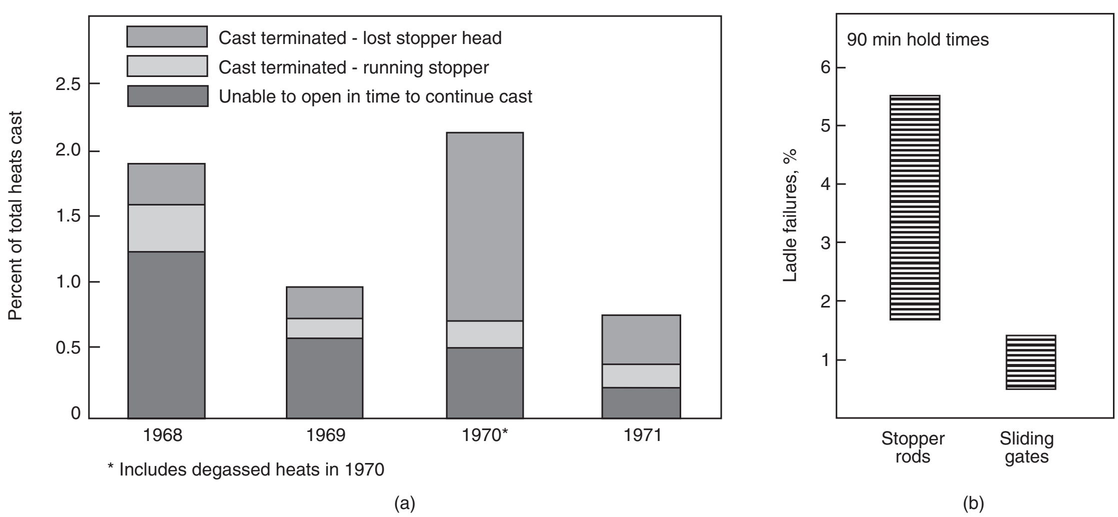
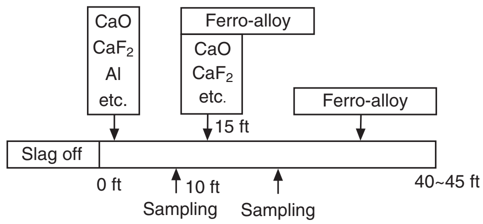
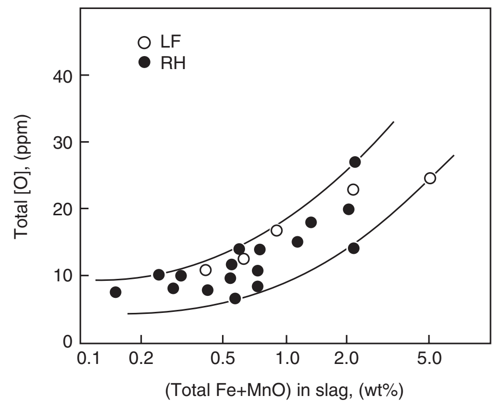


Fig. 1.21 (a) Example for evolution of ladle stopper performance *(from Ref. 46)* and (b) comparison with slidegate performance *(from Ref. 47).*



CaO	SiO_2	Al_2O_3	MnO	MgO	Total Fe	Cr_2O_3	P_2O_5	CaF_2	S
57.8	13.3 ~8.0	15.0 ~20.4	<0.1	4.3	<0.6	<0.1	<0.1	7.8	1.1

(a)

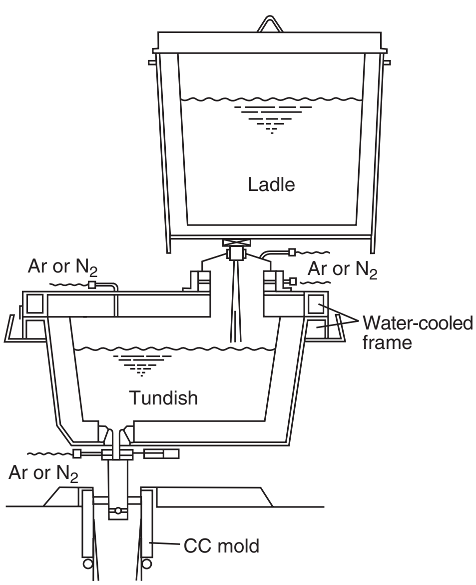


(b)

Fig. 1.22 (a) Example of ladle slag composition and deoxidation practice of SAE 52100 bearing steel *(from Ref. 48)* and (b) effect on total oxygen content in medium-carbon engineering steels *(from Ref. 49).*

rather late, i.e., in the 1980s, apart from some earlier solitary efforts with either a long tubular[52] or a short hood-type shroud.[53] A rigorous approach for highest cleanliness requirements, e.g., bearing steel SAE 52100, is shown in Fig. 1.23,[54,55] where complete tundish inertization is assured right from the start of casting by virtue of an airtight tundish cover with water-cooled frame. The application of tundish slag is not necessary in this case, and ladle slag carryover is prevented by always retaining some steel in the ladle. Otherwise, an automatic ladle slag detection system is indispensable for assurance of cleanliness.[56]

Since all these precautions still need to be implemented to a wider extent, the main effort in tundish operation so far focuses on inclusion flotation rather than prevention. For this purpose, tundish capacities have become increasingly larger to ensure a longer average residence time; and complex weir/dam combinations are often added for improved inclusion separation through a plug-type flow pattern. However, it also must be realized that larger tundishes lead to more steel being contaminated in the case of reoxidation events,[57] particularly during transients, i.e., mainly ladle



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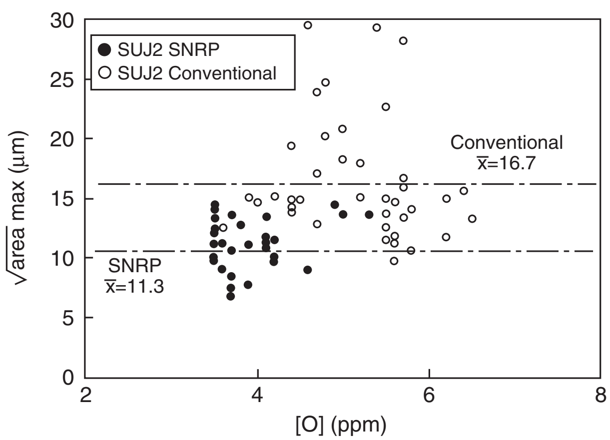


(b)

Fig. 1.23 (a) Example of clean tundish operation *(from Refs. 52 and 54)* and (b) cleanliness results for SAE 52100 bearing steel *(from Ref. 55).* (Note: SNRP = Sanyo new refining process.)

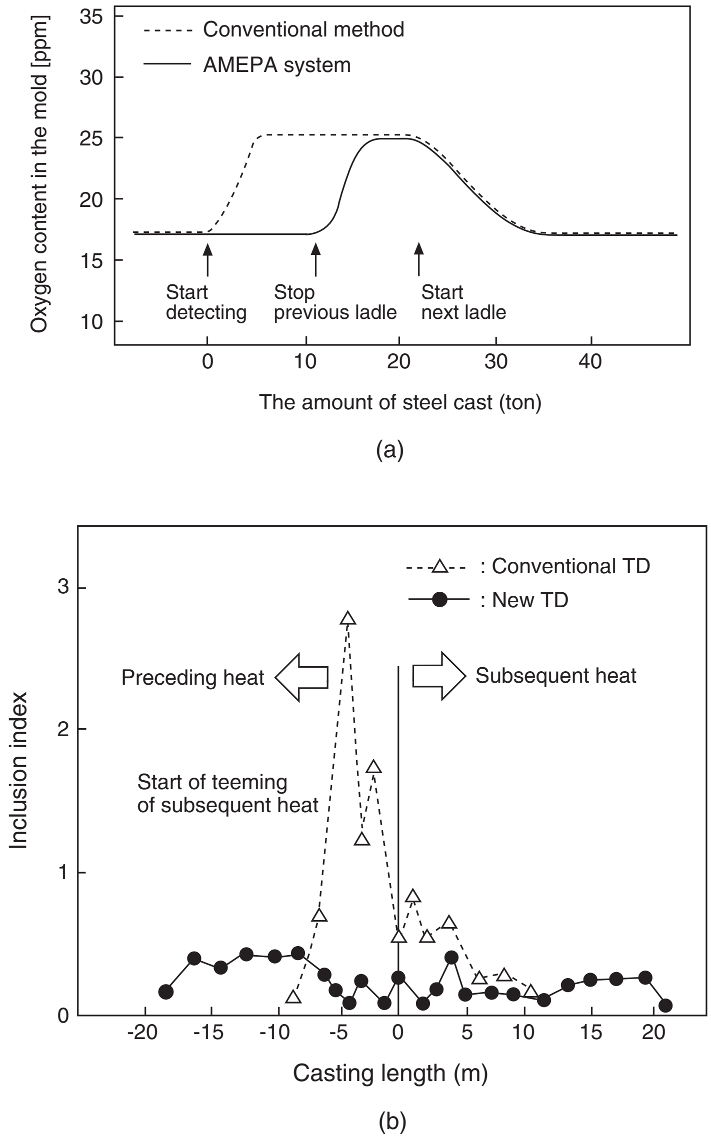


Fig. 1.24 Transient slab cleanliness with 80-tonne tundishes: (a) without heating *(from Ref. 59)* and (b) with heating *(from Ref. 60).* (Note: AMEPA = inductive ladle slag detector.)

change; here, inclusion flotation is hampered by a flow inversion due to colder steel affecting thermal buoyancy.[58] Such instabilities can be overcome only by tundish heating during transients, and its beneficial effect on cleanliness assurance is clearly obvious from the examples in Fig. 1.24 comparing transient cleanliness in slab casting through 80-tonne tundishes with and without tundish heating,[59,60] the former case relying solely on ladle slag detection. Tundish heating is also effective at preventing tundish skulls, apart from the further beneficial metallurgical effects on surface quality and inner soundness from tight steel superheat control, and has been pursued in the course of CC history at various instances, e.g., Fig. 1.25.[61] However, tundish heating is still not widely recognized as a key technology for caster operation and steel cleanliness. Also, the argon injection through the tundish bottom appears to have considerable potential for convection control and inclusion separation, but it still lacks routine application.

Of course, for low-quality requirements like CQ steel billet casting, tundish handling becomes rather simple, and long lives can be achieved by nozzle changing on the fly. To keep refractory costs low for bloom and slab casters, multiple usage of tundishes by the “back-flying” and “hot-cycling”

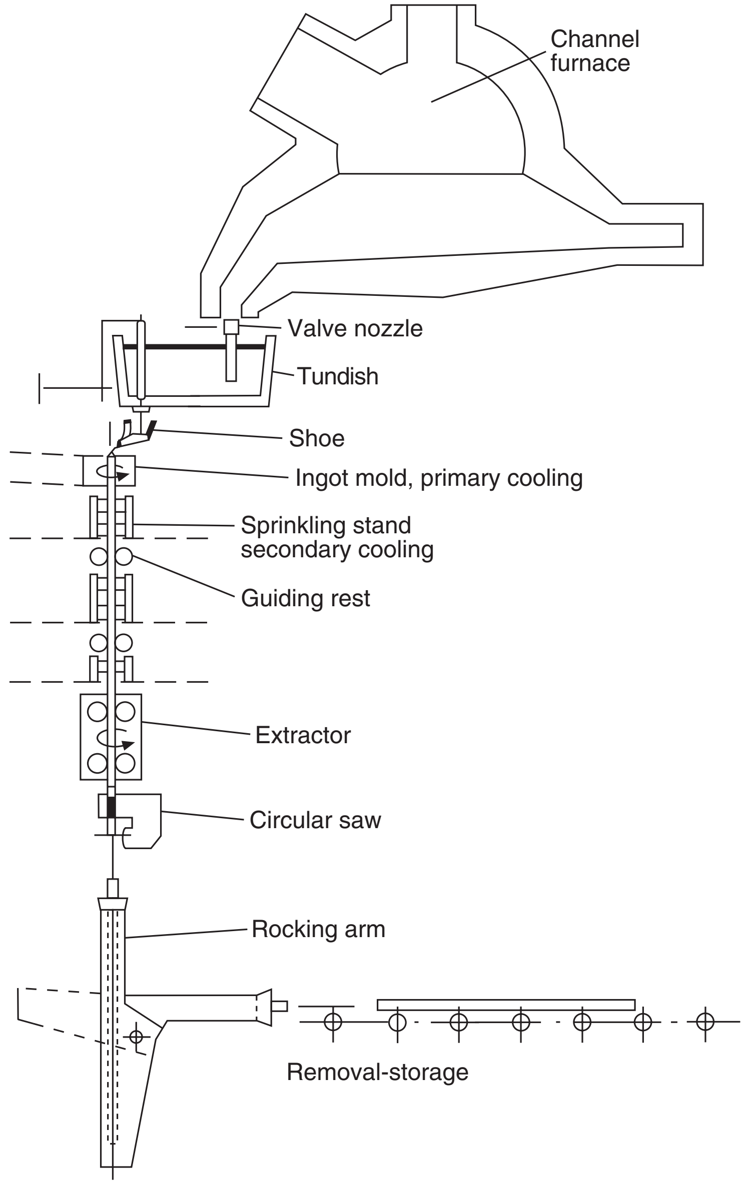


Fig. 1.25 Example of inductive tundish heater for vertical rotating round billet caster. *From Ref. 61.*

methods is increasingly applied but requires particular care to minimize initial steel contamination by oxides remaining from the previous cast (Fig. 1.26).[62]

One side effect of larger tundishes via height increase was initially inadequate stopper performance, which then favored the development of the tundish slidegate, especially in the U.S. and Japan. For attenuation of nozzle clogging, argon injection through either stoppers or slidegates or through the submerged entry nozzle (SEN) is very effective. The development of in-situ SEN changing devices circumvents the nozzle clogging effect for attaining longer sequences. However, it must be pointed out that, in the example of Fig. 1.23, a sequence length of 30–50 heats (maximum 70 heats = 10,000 tonnes) is regularly achieved without changing the tundish or the SEN,[48,54] demonstrating the still large potential for a really clean tundish operation for the assurance of steel cleanliness in conjunction with advanced ladle metallurgy.

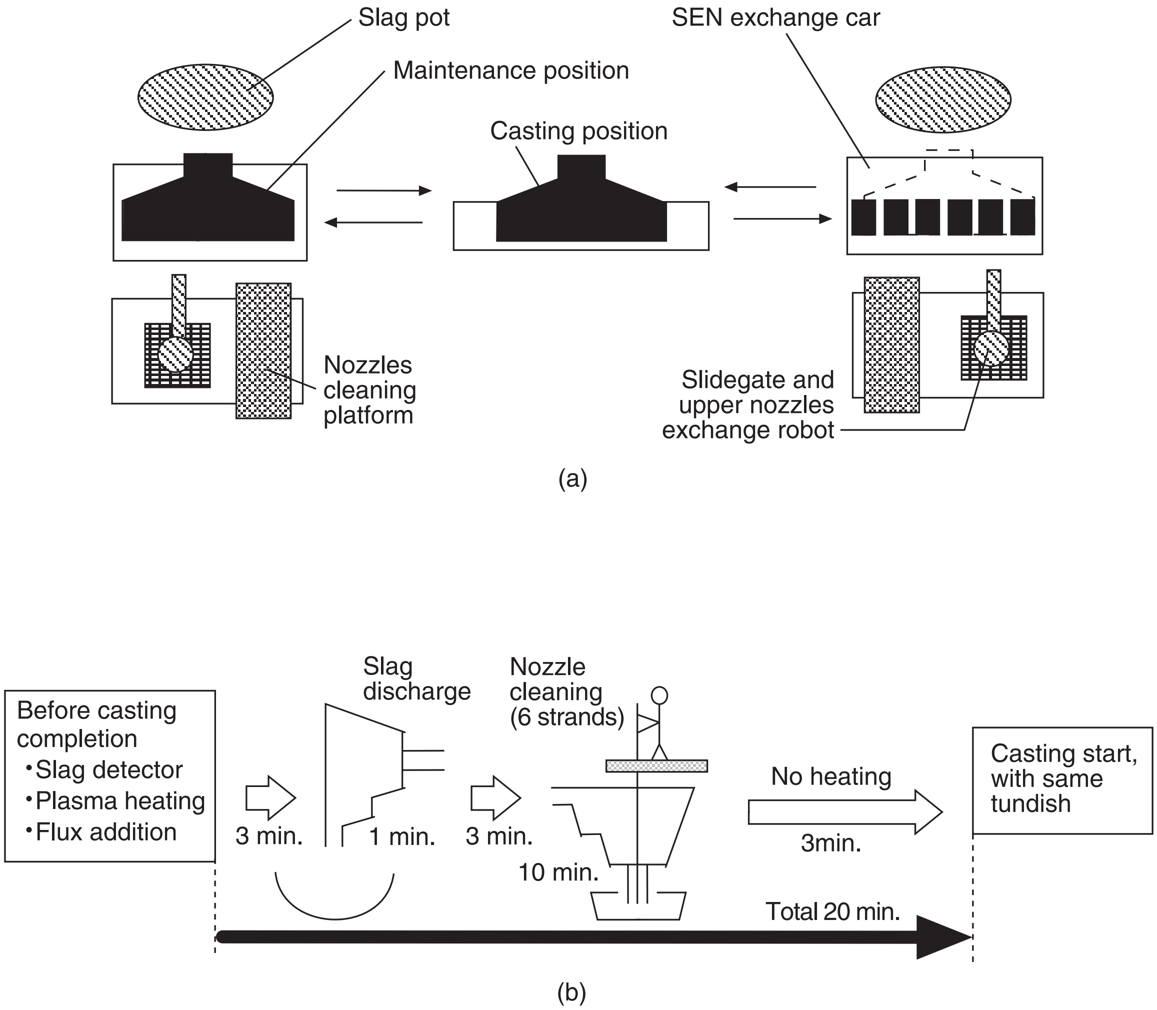


Fig. 1.26 Example of tundish hot cycle practice with quick slag draining at end of cast: (a) layout and (b) schematic of procedure. *From Ref. 52.*

1.2.2 Mold Technology

While initial shell formation is decisive in strand surface quality (Fig. 1.16), the progress of shell growth in the mold must provide adequate breakout safety in order to assure high caster productivity. In both respects, the control of mold heat transfer and lubrication are two major functions.[63] Historically, it was believed that heat transfer is enhanced by the intimate shell/mold contact of a fixed (non-moving) mold, as pursued by the majority of the early pilot casters. Even with the Junghans-Rossi-type mold oscillation, no relative movement was imparted during downward motion, extending over three quarters of the total cycle. As this impeded lubricant infiltration, Halliday perfected mold oscillation technology by introducing his negative strip concept, i.e., moving the mold slightly faster than the strand during the downstroke of the cycle (Fig. 1.27).[44] This has been vital to minimizing shell sticking under the conditions of imperfect mold level control prevailing at that time, since any shell defect caused by meniscus shell overflow (Fig. 1.28)[64] may easily lead to shell tearing under the effect of mold friction. Much more safety is anticipated from a meniscus-free mold technology, which would permit strand withdrawal without lubrication and without oscillation (like the electromagnetic casting in the aluminum industry); however, practically feasible solutions are still to be developed.[1,63]

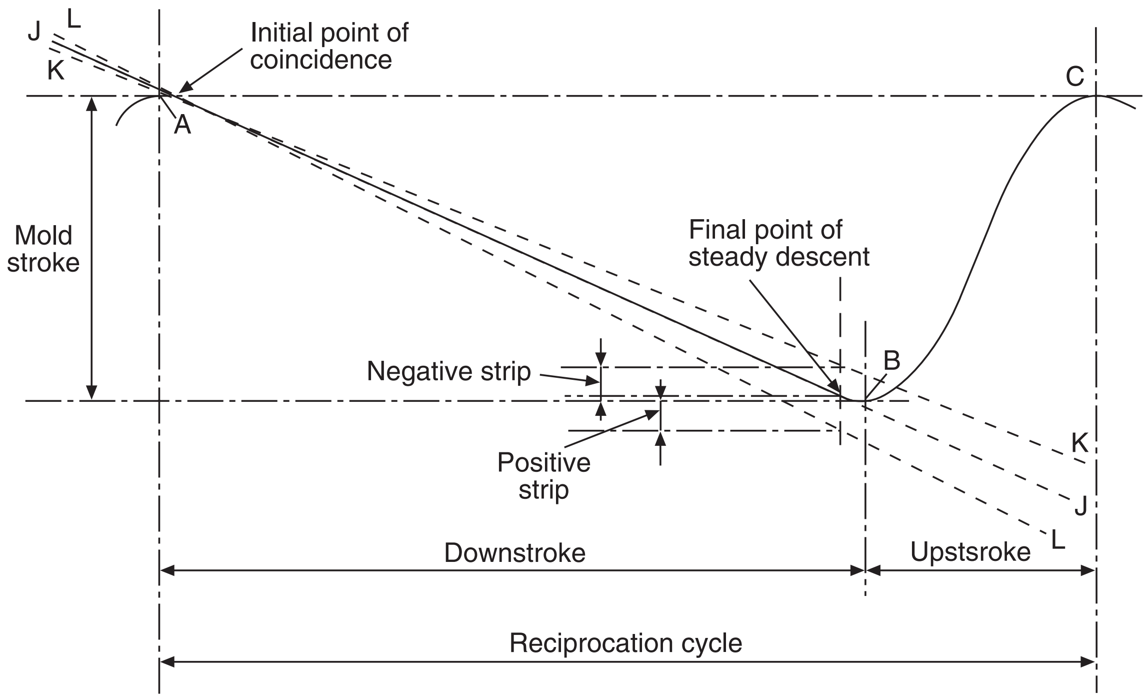
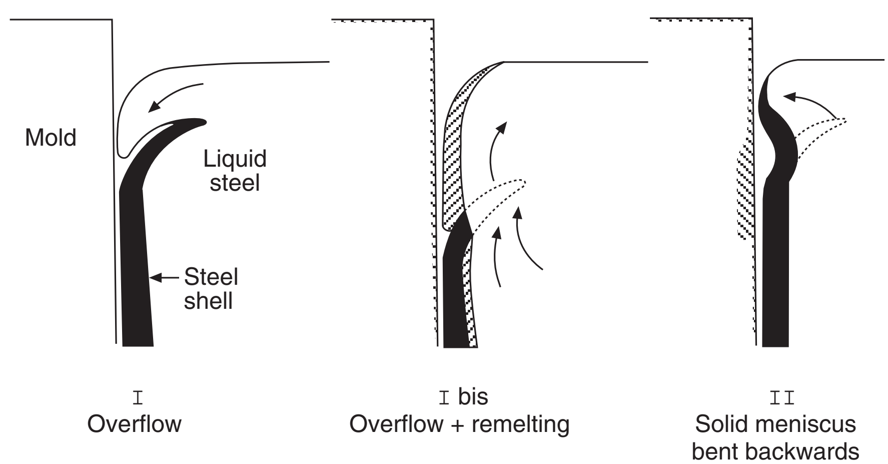


Fig. 1.27 Principle of negative strip introduced by Halliday at Barrow Steelworks in 1954. *From Ref. 44.*

Control of mold friction by oil lubrication is found to be quite effective, provided that oil losses due to burning are retarded by an oil flash point exceeding the mold wall temperature (Fig. 1.29).[65] This requirement has favored the development of tubular molds with relatively thin walls, keeping a "cold" hot-face temperature. Nevertheless, when mold powder was introduced as a lubricant in the early 1960s,[66] this proved to be a much more effective and stable technology to keep mold friction low and strand surface quality high (Fig. 1.30).[67,68] However, in the transition to mold powder usage, it had been simply overlooked that conventional mold level sensors (optical or radiometric) are not compatible and only steel level detection by electromagnetic sensing is viable—a fact that is still not sufficiently recognized. By the same token, adequate mold powder performance is assured only by continuous feeding in order to maintain a stable pool of liquid slag on top of the steel level (compare Fig. 1.31).[69] Again, however, very few casters apply automatic powder feeders as yet, although the process has been simplified by gravity feeding of granular powder (Fig. 1.32).[70] Thus, surface defects as well as breakouts are still to a large extent "handmade," i.e., by

Fig. 1.28 Various cases of meniscus shell distortion. *From Ref. 64.*



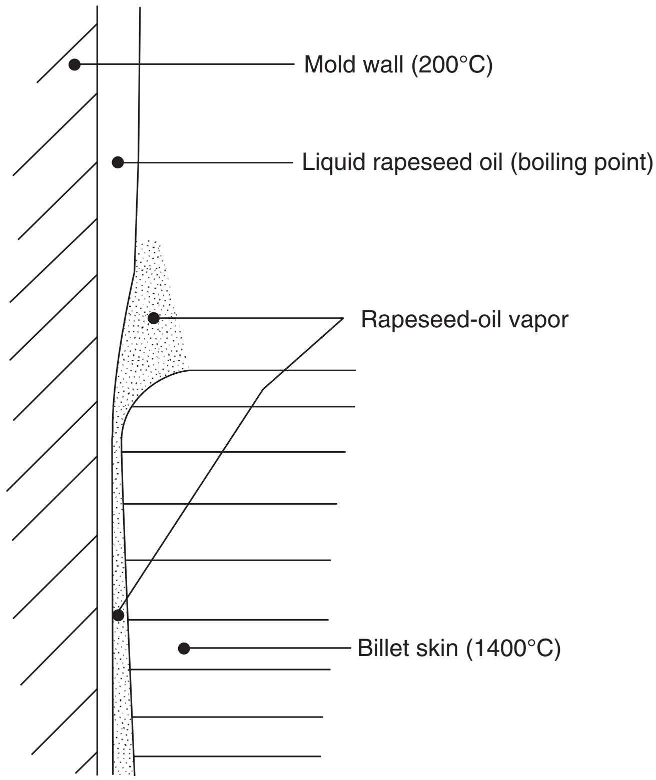


Fig. 1.29 Conceptual presentation of mold lubrication by rapeseed oil. *From Ref. 55.*

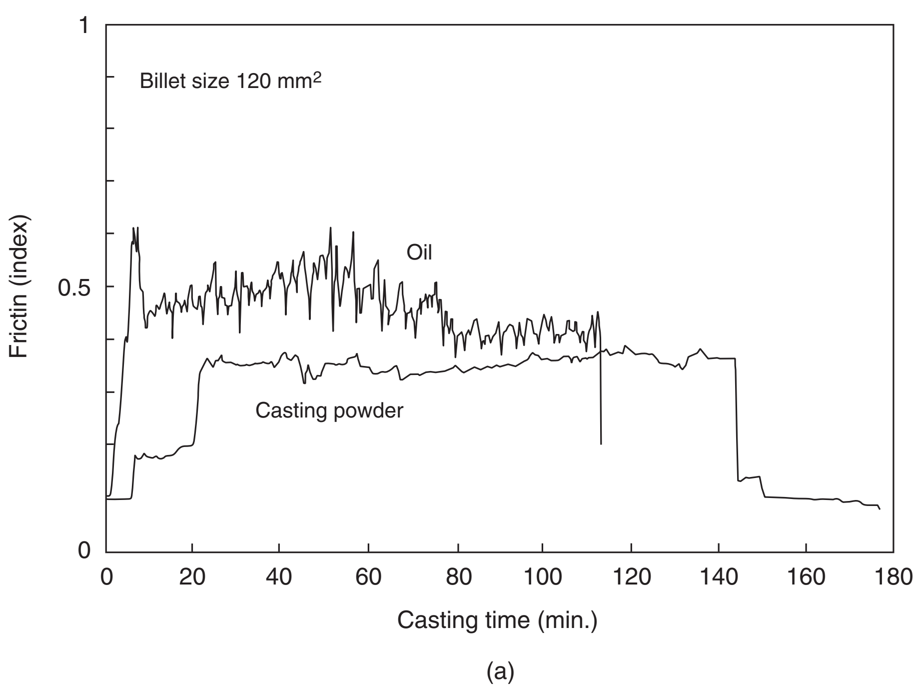


Fig. 1.30a Comparison of oil versus mold powder lubrication in billet casting: mold friction. *From Ref. 67.*

manual mold powder feeding in irregular intervals, especially in the case of the very sensitive peritectic steel grades.[71]

To ensure adequate breakout safety, especially at higher casting speeds, the optimization of mold length is a critical issue.[72] While early billet casting tests at 50 mm^2 at Barrow already reached record speeds of up to 14.7 m/min with an 860-mm-long mold,[44] slab casters, especially in Russia, featured mold lengths up to 1500 mm at low speeds of 0.6 m/min.[73] On the other hand, in Western technology, slab molds gradually grew in length concurrent to the casting speed increase (Fig. 1.33).[74] Meanwhile, breakout safety has been dramatically improved by the control of two main irregularities in shell growth:

- Shell sticking can be detected early by a particular algorithm in local heat transfer, monitored by thermocouples embedded in the mold wall.[75]
- Local off-corner shell thinning is clearly reduced by a nonlinear (“multi-”) taper of the mold wall.[76]

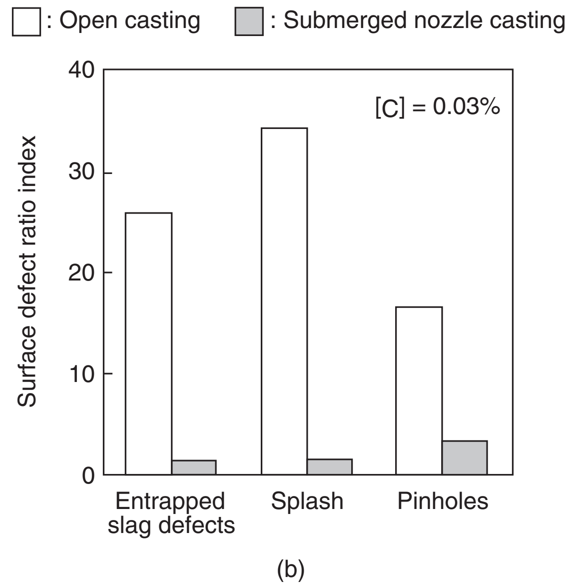


Fig. 1.30b Comparison of oil versus mold powder lubrication in billet casting: strand surface quality. *From Ref. 68.*

Thus, casting speed levels of up to 8–10 m/min are thought to be ultimately feasible for billet and thin slab sections based on the oscillating mold with mold lengths between 1200 and 1500 mm (Fig. 1.34)[72] from the viewpoint of adequate breakout safety.

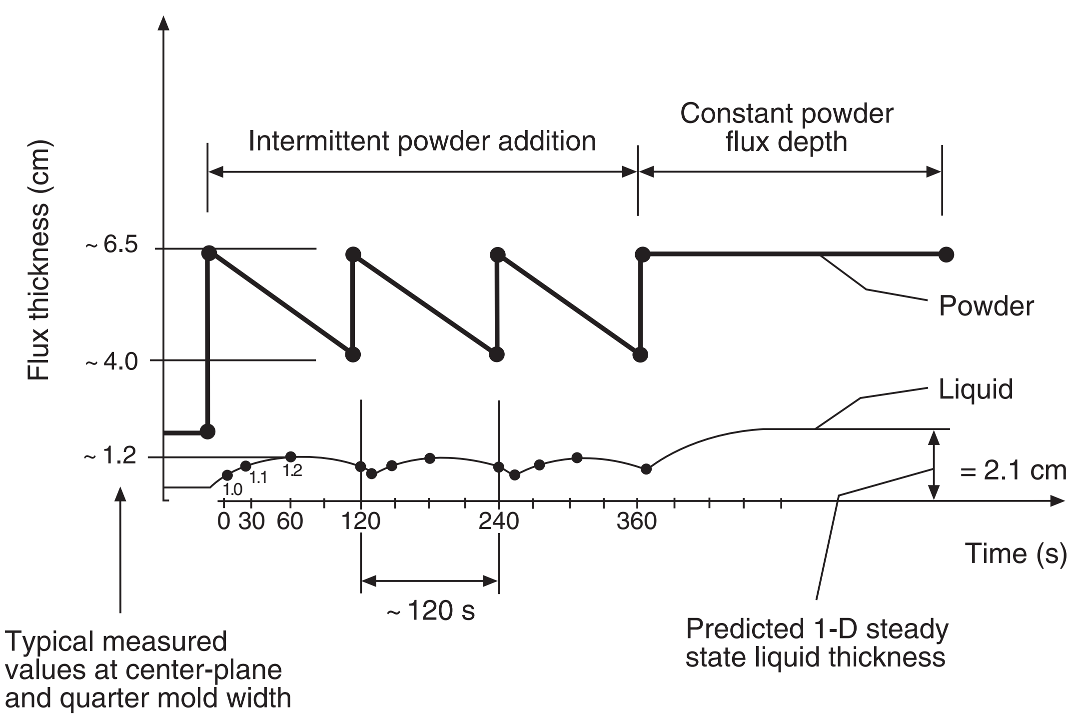


Fig. 1.31 Mathematical modeling of liquid slag pool thickness as function of total powder layer depth for intermittent and continuous powder feeding. *From Ref. 69.*

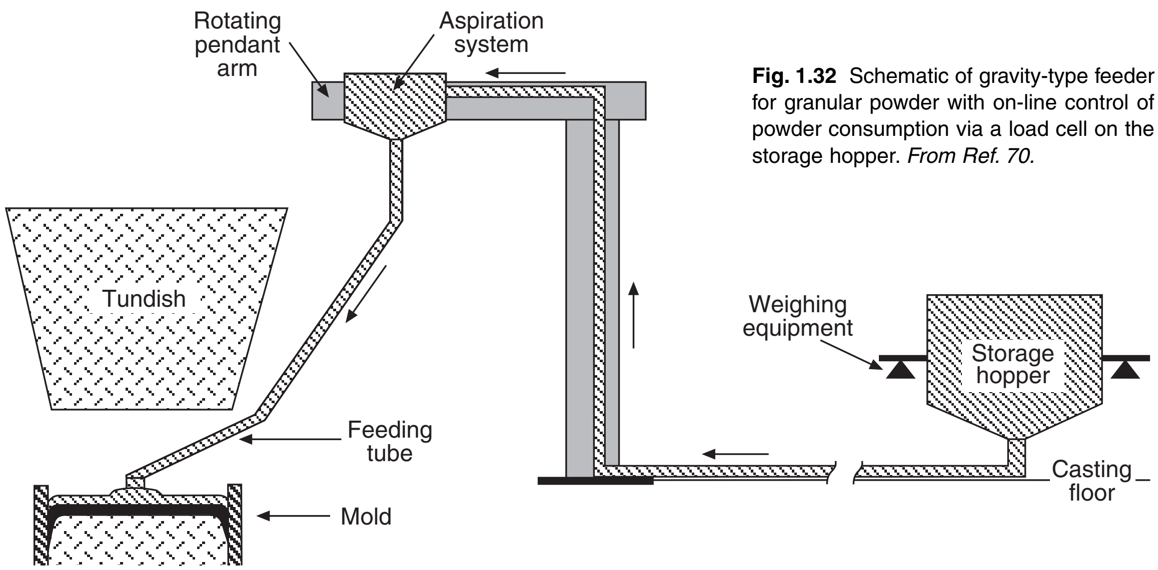


Fig. 1.32 Schematic of gravity-type feeder for granular powder with on-line control of powder consumption via a load cell on the storage hopper. *From Ref. 70.*

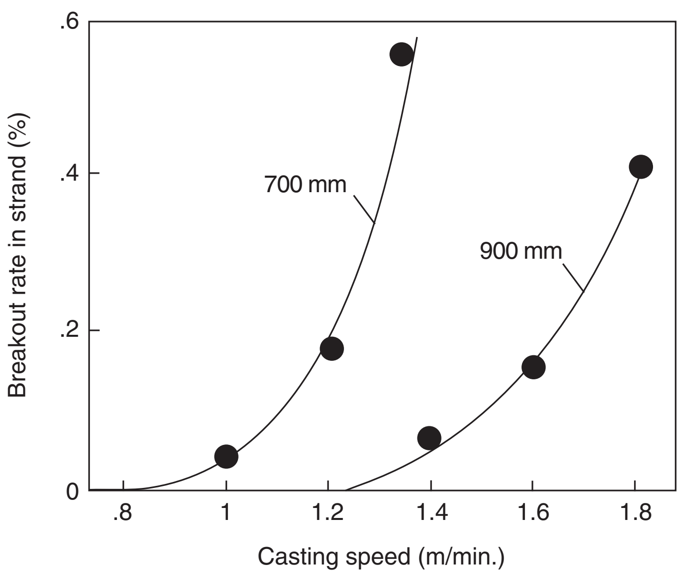
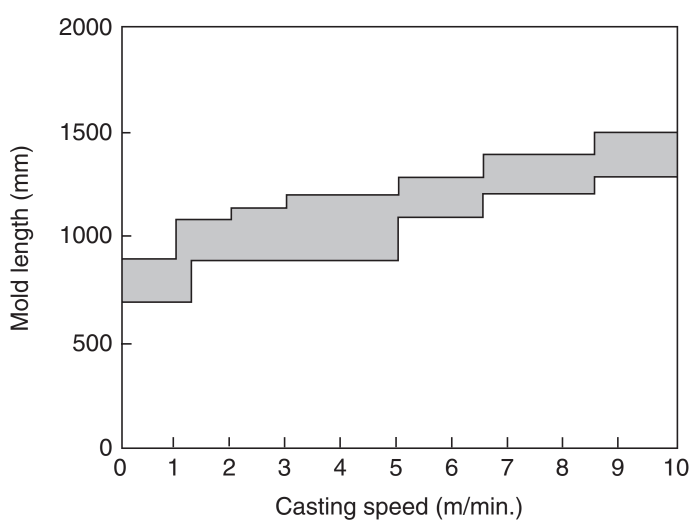


Fig. 1.33 Breakout rate versus casting speed for two slab mold lengths. *From Ref. 74.*

Fig. 1.34 Guideline for mold length versus casting speed. *From Ref. 72.*



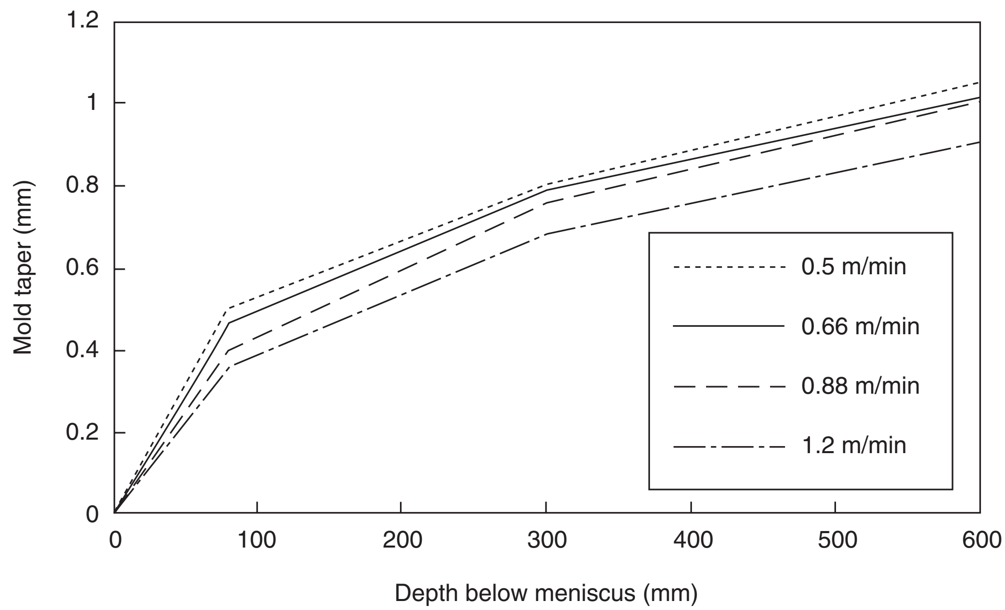


Fig. 1.35 Ideal mold taper calculated for 280-mm-diameter rounds at various casting speeds. *From Ref. 77.*

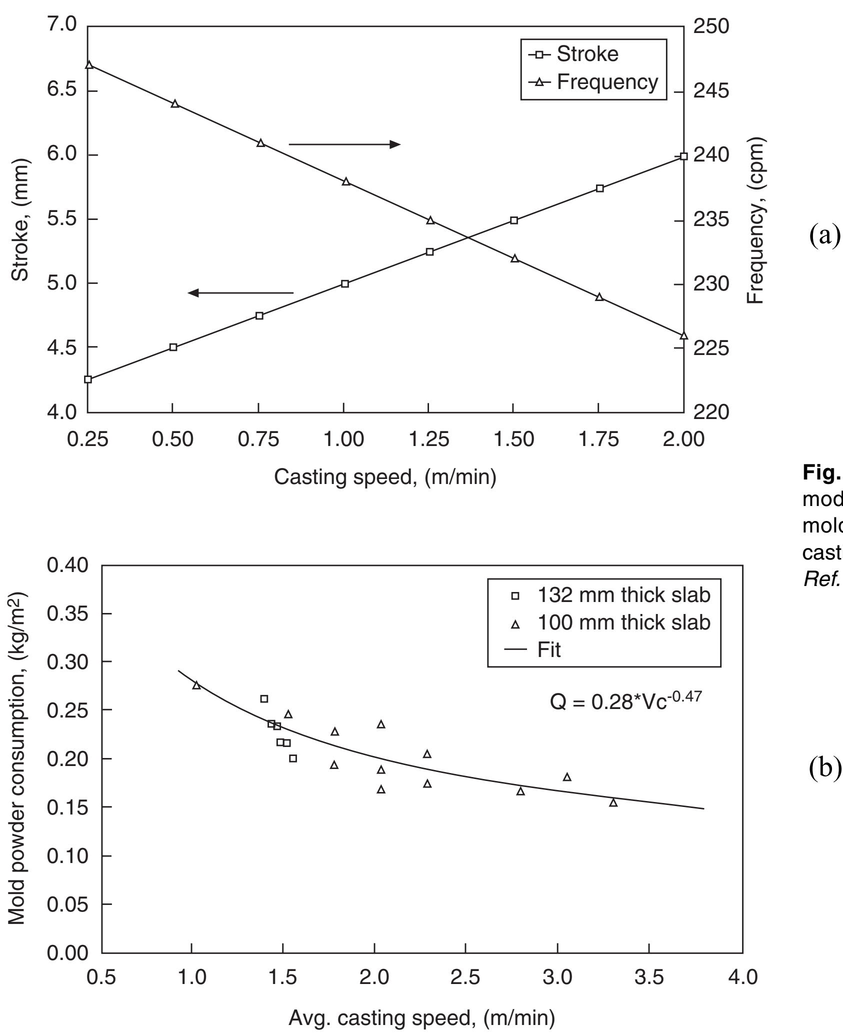


Fig. 1.36 (a) Optimized control modes for mold oscillation and (b) mold powder consumption versus casting speed in slab casting. *From Ref. 80.*

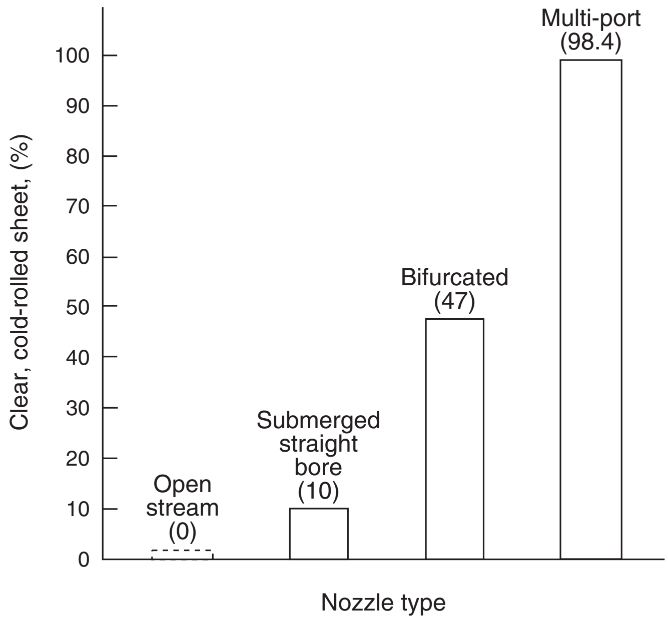


Fig. 1.37 Sheet surface quality from unconditioned slabs in LCAK-steel as function of SEN configuration. *From Ref. 82.*

As hinted at above, shell growth uniformity is really the key requirement to a defect-free strand surface and sticker prevention. Apart from continuous powder feeding under conditions of stable mold level control, mold taper optimization in accordance with shell shrinkage presents the other vital task. While this has been difficult in early CC development due to limitations in mold manufacture, great flexibility is offered today by advanced methods such as numerically controlled mold machining or explosion forming. Mold taper design is of particular importance to round sections, which tend easily to local gap formation between points of shell/mold contact (polygonalization); such behavior can be counteracted by a steep taper during initial shell formation (Fig. 1.35).[77] By the same token, taper optimization during on-line slab width change is a task of similar importance;[78] such continuous width change was boldly conceived by researchers at NSC Nagoya Works in 1974.[79] In the effort to optimize mold heat transfer and lubrication, concurrent developments in mold oscillation point to on-line stroke variation synchronous to casting speed (on account of hydraulic mold actuation) and inverse frequency control as the most effective approaches to ensure fairly constant lubricant infiltration and consumption over a wide speed range (Fig. 1.36).[80]

Initial solidification and progress of shell growth in the mold, as well as the incidence of subsurface pinholes and slags, are strongly affected by liquid steel convection. The guiding of steel flow toward the meniscus by four- and six-hole SEN configurations[81] has yielded significant gains in surface quality (Fig. 1.37).[82] The ultimate perfection in solidification uniformity results from superimposed forced rotational flow by magnetohydrodynamic (MHD) means, i.e., mold electromagnetic stirring (MEMS),[83] which was conceived by Junghans and Schaaber with the intent of improving solidification control in the continuous casting of rimming steel (Fig. 1.38).[84] Commercial MEMS application[85] has been perfected over the years and is now a standard feature in bloom and billet casting of high-grade steels, with similar favorable effects on surface quality assurance more recently reported in slab casting, too.[86]

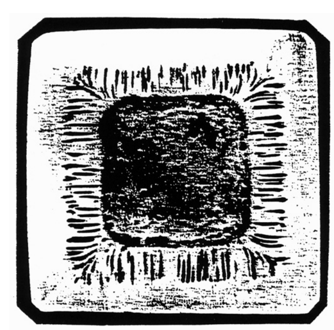


Fig. 1.38 Rimming steel section 200-by-240 mm cast on Mannesmann Huckingen pilot caster. *From Ref. 84.*

On the other hand, a static magnetic field in the slab caster mold is proposed to reduce downward flow, i.e., the electromagnetic brake (EMBR)[87] (Fig. 1.39), in order to reduce the loose-side quarterband accumulation of macroinclusions and argon bubbles typical for curved mold slab casters. The use of static or traveling fields based on MHD forces also intends to stabilize the mold level in the case of high-speed and high-rate slab casting, with a view to maintain an undisturbed initial solidification and also to prevent mold slag entrainment.

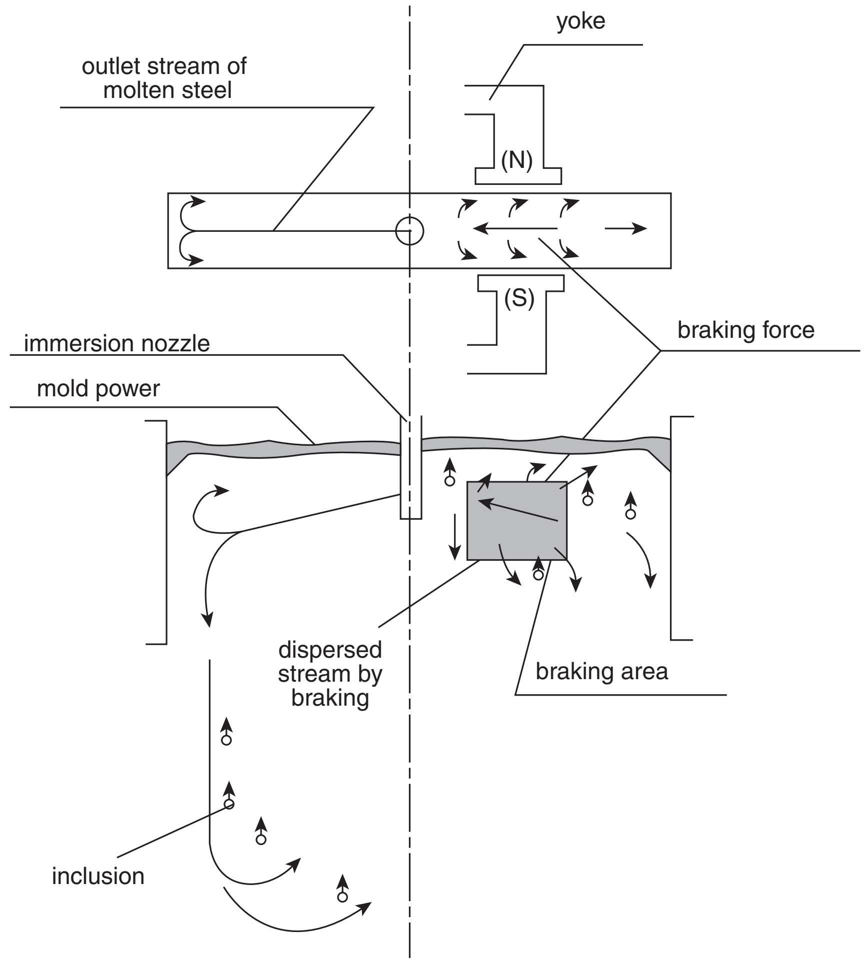


Fig. 1.39 Principle of reduced stream penetration by electromagnetic braking. *From Ref. 87.*

1.2.3 Caster Profile, Strand Guide, Discharge and Further Processing

The vertical caster is the natural machine design, casting with gravity and also assuring a symmetric macrostructure; but caster productivity is severely limited by machine height. Hence, several efforts in CC history are noteworthy to extend machine length at low building height by strand bending and straightening, e.g., the billet caster by Rowley (Fig. 1.8) and a more advanced proposal by Tarquinee and Scovill,[88] which even includes strand in-line sizing after temperature equalization (Fig. 1.40), a design concept that subsequently had been realized first by U. S. Steel for the South Works pilot (1961) and the Gary Works No. 1 slab caster (1967), respectively. To prevent inner cracking, several rules for caster design, based on critical strain and strain rate at the solid/liquid (s/l) interface, had been developed (Table 1.3),[89] which has led to distinct bending and straightening zones extending over several roller pairs.

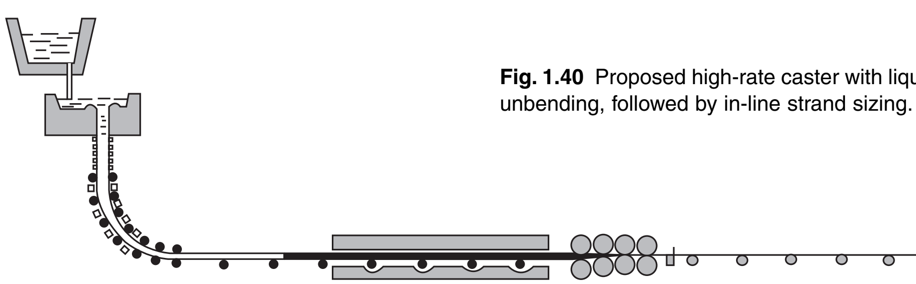


Fig. 1.40 Proposed high-rate caster with liquid core bending and unbending, followed by in-line strand sizing. *From Ref. 88.*

Table 1.3 Review of Patented Methods for Strand Bending and/or Unbending with Liquid Core. *From Ref. 89.*

Year	Inventor	B/S-Method†	Specification‡
1960	E.A. Olsson	B: stepwise (or progressive)	none
1961	E. Schneckenburger	B: progressive (continuous)	klotoid (catenary)
1961	C. Bondanelli	B: stepwise or continuous	hyperbola
1963	A. Bungeroth & H. Schrewe	S: stepwise	$\varepsilon_i < \varepsilon_c$
1964	A. Bungeroth	S: stepwise	"recovery" between steps
1965	G.L. Khimich et al.	S: continuous ("curvilenar")	none
1970	E.J. Gelfenbein et al.	S: continuous	$\dot{\varepsilon} << \dot{\varepsilon}_c$
1973	Anonymous (Voest-Alpine)	B/S: continuous transition	$\dot{\varepsilon} << \dot{\varepsilon}_c$
1981	A. Vaterlaus	B/S: continuous (floating rolls)	$\dot{\varepsilon} < \dot{\varepsilon}_c$; $\tau = 0$

† B = bending; S = straightening
‡ ε = strain; $\dot{\varepsilon}$ = strain rate (i = instantaneous; c = critical); τ = shear stress

With the advent of the curved mold casting principle, introduced simultaneously by the pioneering plant trials at Mannesmann Huckingen and Von Moos Stahl in 1963, the required building height was substantially reduced. This caster type initiated rapid growth of CC application, especially in small billet casting shops that could use the existing buildings. Thus emerged the classical mini-mill, based on a curved mold billet caster that is fed by an EAF unit. Still today, curved mold machines are the standard caster type in billet and bloom casting.[90]

In slab casting, however, the widespread use of curved mold design came to a clear halt in recent years on account of the accentuated quarterband accumulation of macroinclusions and/or argon bubbles (with inclusions attached) (Fig. 1.41),[91] which leads to high reject rates on cold rolled sheet of ultra-low carbon (ULC) steels. Thus, apart from new casters now being exclusively built as straight mold/bending (V-B) type, existing curved mold machines are increasingly revamped at a high cost and substantial loss of production in order to meet the ever-more-stringent requirements on product cleanliness.

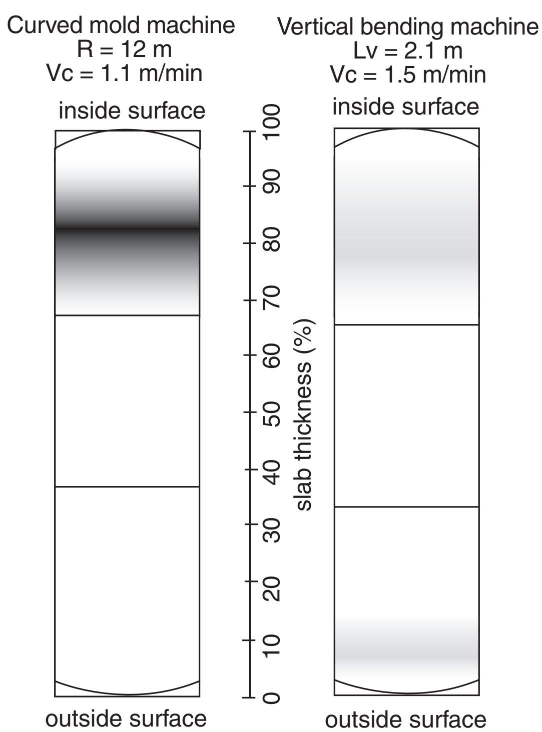


Fig. 1.41 Through-thickness distribution of macroscopic inclusions in CC slabs detected by ultrasonic scanning (Midas method) for two caster types. *From Ref. 91.*

To assure undercritical shell deformation, strands with liquid core must be supported until they are self-containing. This is true already below the mold for rounds and small billets of square section. Rectangular sections require roller support, especially on the wide face for a certain distance; in the case of slab sections, until the very crater end (Fig. 1.11). However, care must be taken to prevent strand squeezing by driven rolls in the withdrawal system. This also must be combined with uniform secondary cooling in order to prevent excessive shell deformation due to thermal stress. Hence, over the years the design of cooling profiles as well as roller support arrangements has been perfected to a great extent, with operating success

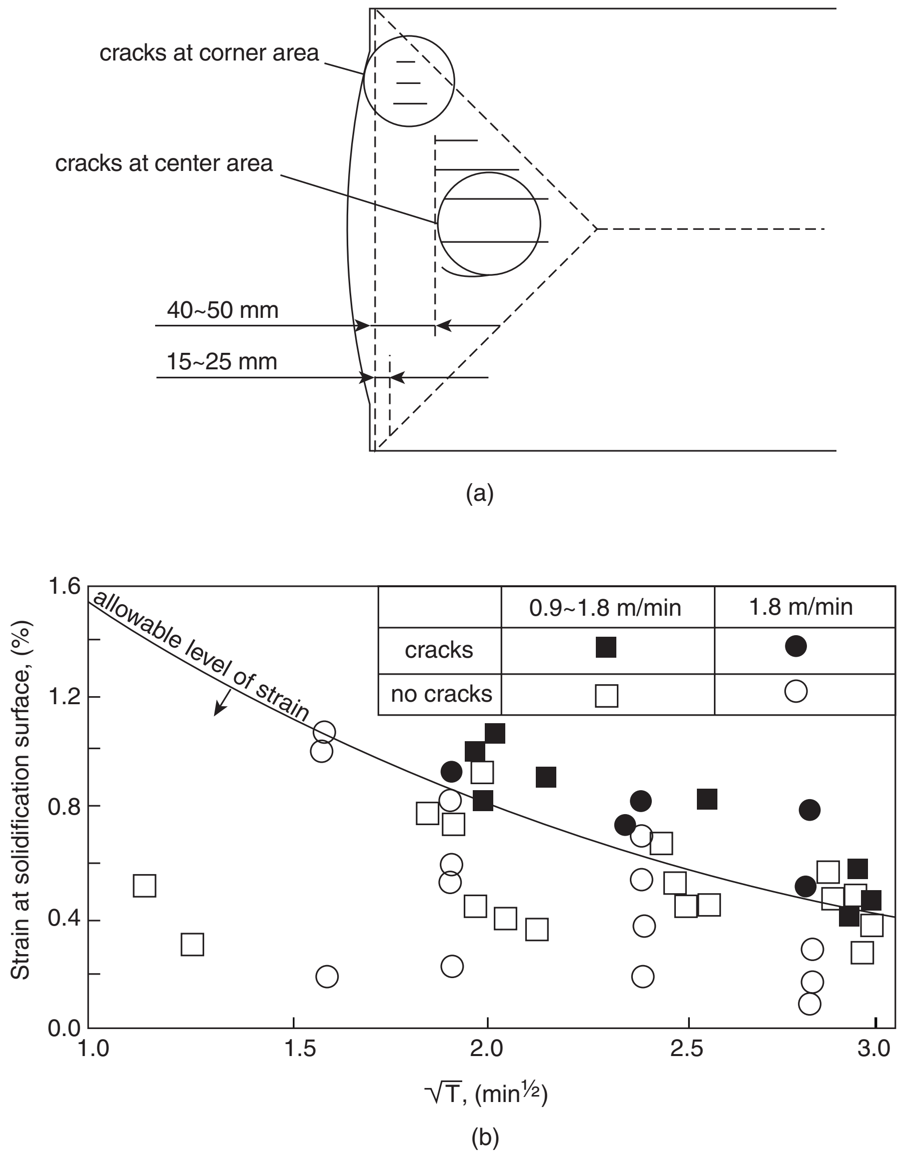


Fig. 1.42 (a) Example of inner crack occurrence in modern high-speed slab caster and (b) derived critical strain at s/l interface versus solidification time for 0.15% C steel. *From Ref. 92.*

essentially depending on caster maintenance. Nevertheless, under the critical conditions of high-speed casting, the incidence of inner cracking is still obvious even in the case of perfectly controlled caster alignment and cooling uniformity (Fig. 1.42); only stronger cooling intensity is an effective measure.[92]

Another phenomenon detrimental to product inner soundness is the so-called mini-ingot formation, i.e., intermittent center porosity and macrosegregation. The main contributor in self-supporting sections is dendrite bridging in the case of columnar growth, and liquid core "pumping" due to strand bulging near the crater end in the case of slab sections. In the former case, inducing columnar-to-equiaxed transition (CET) by electromagnetic stirring in the mold (MEMS), often combined with strand stirring (SEMS) and/or near the final solidification (FEMS), is a well-established countermeasure (Fig. 1.43).[93] For slab sections the so-called (mechanical) soft reduction, controlled strand squeezing near the crater end proposed by NKK in 1974,[94] prescribes a maximum strand reduction of 2% each for at least two roller pairs. This technology has been found most effective at improving center soundness and is increasingly applied to large bloom sections. For small bloom

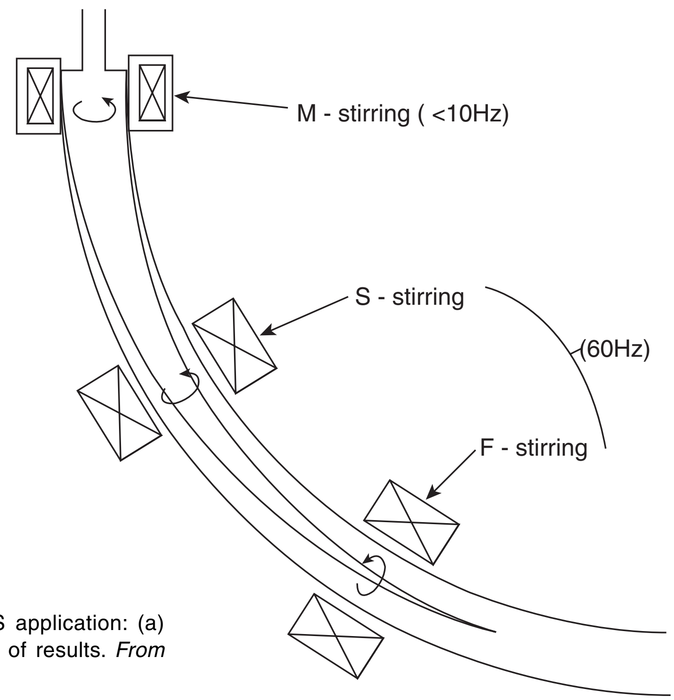
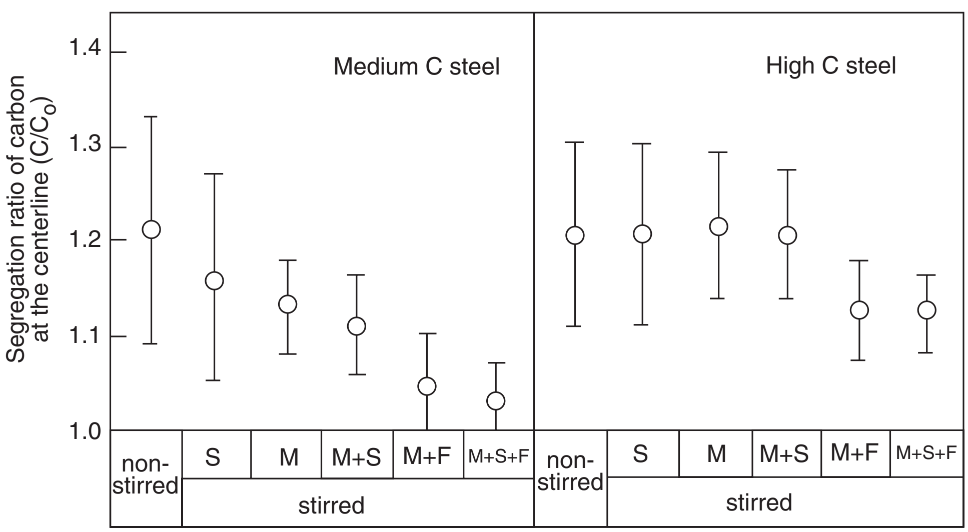


Fig. 1.43 Multi-stage EMS application: (a) schematic and (b) example of results. *From Ref. 93.*

(a)



(b)

and billet sections, hard spray cooling near the crater end appears to be equally effective. This method, termed thermal soft reduction,[95,96] still requires further development work.

After complete solidification and cutting to length, it is preferable to transfer the as-cast product directly to the rolling mill in order to use maximum heat content for the saving of reheating energy and, thereby, reducing carbon dioxide emission, apart from shorter lead time and smaller stock volume. In order to omit product inspection, quality assurance is increasingly based on the quality prediction derived from computerized on-line monitoring of the process variables by means of an

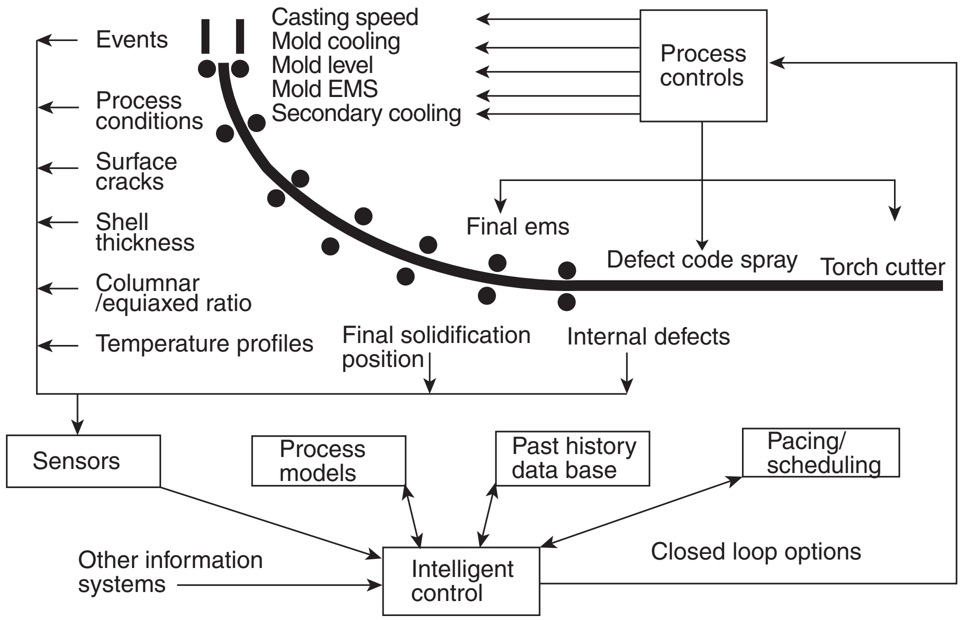


Fig. 1.44 Example of expert system for on-line quality prediction in bloom casting. *From Ref. 97.*

expert system (Fig. 1.44).[97] In the case of Al-fine-grain steel, intermediate cooling below the austenite-to-ferrite transformation temperature may be required for grain refinement prior to reheating in order to prevent surface defects during hot rolling and to assure final toughness properties of the as-rolled product. Products requiring surface conditioning prior to reheating may need controlled cooling to ambient temperature if hardenability is high. The computer-assisted quality assurance system also allows dynamic scheduling, i.e., diversion to other orders, if steel cleanliness or inner soundness is predicted as not conforming to original order requirements.

1.3 Concluding Remarks

The conventional CC process has developed, by all the efforts throughout past history, into a highly mature and safely manageable technology, as best illustrated by records in sequence casting with an outstanding performance of up to seven weeks of uninterrupted operation (Table 1.4).

Concurrent endeavors rationalize process knowledge further in view of closed-loop computer control.[98] However, rather little has been achieved as yet in this respect due to various conditions of process instabilities, highlighted by the following examples:

- Despite clean steelmaking through enhanced ladle metallurgy, steel contamination, mainly during transients (start of cast and ladle change), brings about erratic cleanliness control in the product.
- Furthermore, such random loss in steel cleanliness may lead to adverse consequences for operational stability, such as chemistry change of mold powder and nozzle clogging, the former causing enhanced shell sticking while the latter affects steel flow and mold level control.
- The control of argon injection to combat nozzle clogging relies purely on operator judgment, which is unsafe since it also influences steel convection.
- Argon injection as well as SEN submergence would require a dynamic control system adapted to changes of section sizes and casting speed, too.

Table 1.4 Record Sequence Casting in Heats as of May 2000

Caster	Country	Billet	Bloom	Slab
AK Steel, Ashland	U.S.			1721
National Steel, Great Lakes 2	U.S.			1317
British Steel, Llanwern 1	Great Britain			1165
Sumitomo Metal, Wakayama 3	Japan		1129	
Sumitomo Metal, Kokura 2	Japan		1065	
U. S. Steel, Gary 1	U.S.			1025
Kawasaki Steel, Mizushima 5	Japan			927
U. S. Steel, Edgar Thomson	U.S.			887
U. S. Steel, Gary 2A	U.S.			880
AK Steel, Middletown	U.S.			825
LTV Steel, Cleveland East	U.S.			661
Thyssen Stahl, Ruhrort 2	Germany		632	
Siderar, San Nicolas 3	Argentina			517
Nippon Steel, Kimitsu 1	Japan		508	
Daido Steel, Chita 1	Japan		502	
British Steel, Port Talbot 1	Great Britain			403
National Steel, Great Lakes 1	U.S.			402
Voest Alpine Stahl, Donawitz 2	Austria		365	
LTV Steel, Indiana Harbor 2	U.S.			351
Nucor Steel, Plymouth	U.S.	349		
Nisshin Steel, Kure 2	Japan			345
Sicartsa, Las Truchas 3	Mexico	319		
GS Industries, Georgetown 3	U.S.	310		

- Mold slag infiltration into the strand/mold interface as a function of oscillation conditions is still poorly understood. Hence, it is mostly based on trial-and-error optimization and is often hampered by the additional instability created by manual mold powder feeding.
- While local heat transfer monitoring with embedded thermocouples has proved to be vital for sticker detection, the more general use of predicting surface quality is still in its infancy.
- By the same token, prediction of inner soundness based on the on-line machine condition monitoring has not much developed as yet.

Anticipating that such disturbances and lack of controllability will be resolved through future development, a fully integrated computer system for closed-loop CC process control may be envisioned for maximum stability of caster operation as well as product quality assurance.[99]

Such challenge increases in urgency with higher casting speeds, as realized by the novel processes of near-net-shape casting in particular. Especially in the case of direct strip casting, a fully automatic operation is mandatory. For improved process stability, one key feature in general could be the development of Al-free steel grades, for which the so-called concept of "oxide metallurgy" offers one novel approach[100] (Fig. 1.45), which would assure not only better castability but also enhanced structure control.

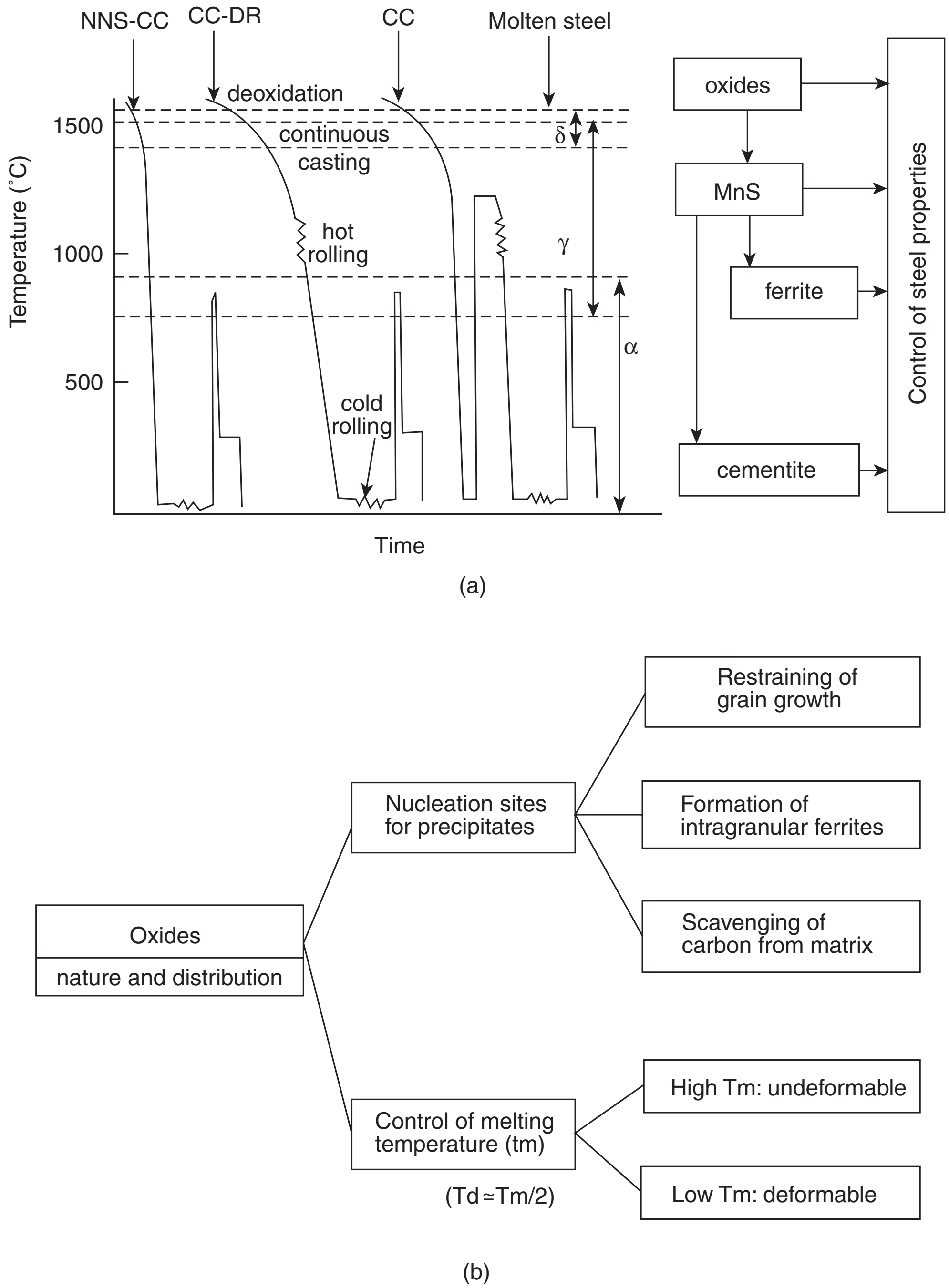


Fig. 1.45 (a) Outline of "Oxide Metallurgy" schematic with typical thermal history of various CC processes and (b) interaction with oxide effects. *From Ref. 100.*

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