Design requirements for hot strip mills rolling thin continuously cast slab sections are outlined. Advantages of a planetary mill for this application are described.

Hot strip mills for thin slab continuous casting systems

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CONTINUOUS casting of steel slabs has been widely adopted during the past several decades throughout the world for production of plates and hot strip. Slab thickness has been decreased during this period, depending on the type of steel being cast and slab width. The general guideline has been that the thickness should not be less than ⅛ the width of the slab or, with certain curved molds, $^1/_{10}$ the maximum width.

In recent years, several projects have been undertaken in Europe, the U.S. and Japan for developing continuous casters to produce thinner sections than previously considered possible. To date, slabs with thickness to width ratios in the $^1/_{30}$ and $^1/_{40}$ range have been produced with acceptable metallurgy and good surface quality. Work is also being conducted on thinner sections with ratios less than $^1/_{100}$ which eventually will lead to direct casting of hot strip. Meanwhile, however, development and successful operation of thin slab casters can be expected.

Hot strip mills must be adapted to suit these new casters. Accordingly, mill designers must examine the characteristics of thin slab continuous casting systems and determine how to design appropriate hot strip mills that will provide safe, reliable, economical operation, high product quality and the ability to process several types of steel for different purposes.

The advantages of Sendzimir mills for such applications are presented in this article.

Planetary mill

The most important advantage of the planetary mill over the conventional mill is that it can roll a slab of indefinite length and produce a coil of indefinite size in a single reduction of over 95% in the roll bite, producing strip in one pass. This means that the process can be continuous; there are no front ends or off-gage material, and the strip has the same shape, metallurgical structure and surface throughout its length.

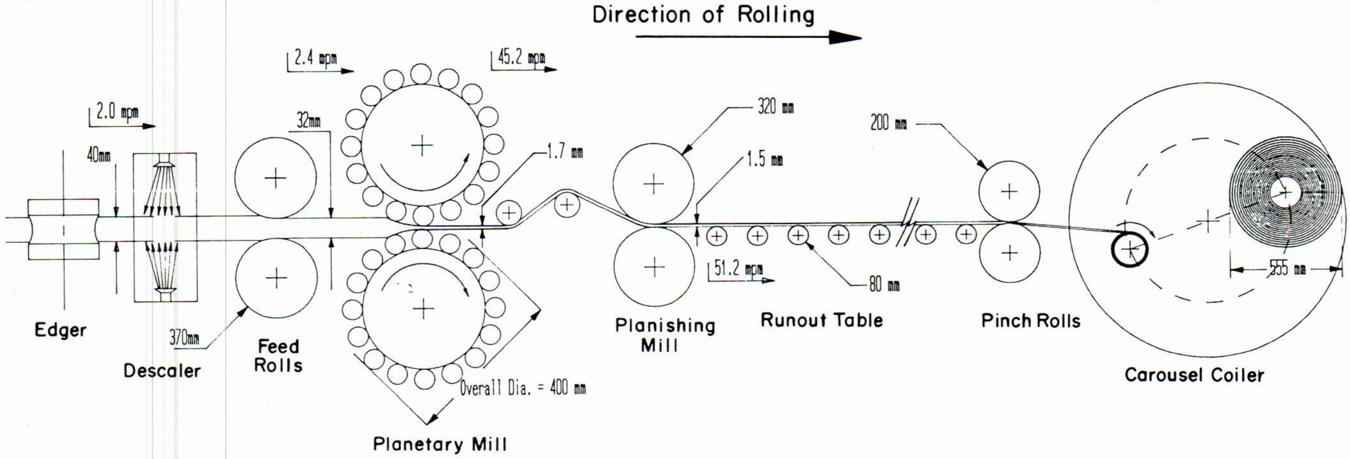
Sendzimir planetary mills are radically different from conventional rolling mills. A planetary mill layout, which can have one or two feed rolls, is shown in Fig. 1. A cross-section of the feed rolls and planetary assemblies is shown in Fig. 2. The feed rolls push the slab, taking a small reduction, through a guide into the planetary rolls, where the main reduction is accomplished by two backup rolls surrounded by a number of small work rolls held in cages at their extremities. These cages are synchronized by external means so that each pair of work rolls passes through the vertical centerline of the mill at precisely the same time and that their axes are always parallel to the backup roll axes.

The angular velocity of the backup cage is less than half that of the backup roll. The direction of rotation of the upper backup roll is clockwise when the slab is fed from right to left. The cages holding the upper set of work rolls also turn clockwise. However, the work rolls themselves turn counterclockwise around their own axis.

The roll-bite geometry of a planetary mill is shown in Fig. 3. Two pairs of work rolls are shown. The first pair is close to the point where it leaves the strip and where the material is nearly reduced to its finished gage. The second pair has just touched the slab at its initial thickness H and has penetrated deep enough to establish a full width of deformation zone BA. The work rolls establish this condition at an angle α from the vertical.

The rolling process is cyclic. Rolls make contact with the unworked portion of the slab, then work downward gradually, making a rolling pass in the deformation zone and finally breaking contact with the material where it has reached final thickness after the next pair of work rolls has contacted the slab. The cycle repeats itself approximately 200 times/min.

Fig. 1 — Planetary mill layout.



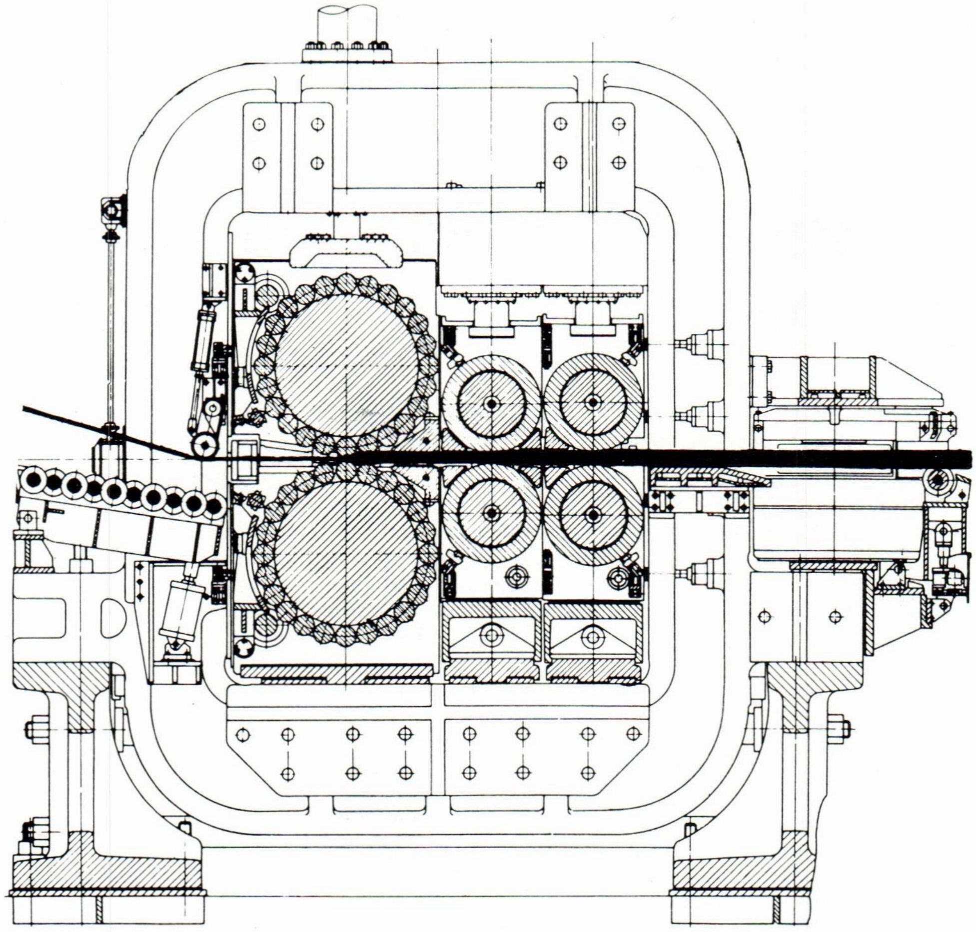


Fig. 2 — Combined planetary/ feed roll unit.

The work rolls remain in contact with the workpiece throughout the roll bite, as well as maintaining contact with the backup rolls. Power is supplied by the backup rolls, which turn the work rolls as well as propel them forward by frictional contact along common line of contact such as *G*. For each pair of work rolls passing through the bite, the slab is fed by feed rolls a small distance represented as *f* in Fig. 3. After reduction, this slab length is transformed into a strip length *F*.

When the slab is in the roll bite (Fig. 4), the metal travels through the deformation zone quickly, usually within $1\frac{1}{2}$ to 4 s. While in the zone of plastic deformation, the metal is subject to two opposing effects, the relative influence and magnitude of which should be carefully evaluated. One is the increase in metal temperature due to the energy of plastic deformation, which averages 40 kwhr/ton for low carbon steel and 55 kwhr/ton for stainless steel, which should be capable, theoretically, of increasing the metal temperature by several hundred degrees. At the same time, however, heat is rapidly removed from the surface of the metal within this zone by contact with the relatively cold work rolls. In practice, the temperature of the strip is usually higher at the planetary mill exit than the temperature of the slab at the mill entrance.

A planetary mill should be operated continuously, with slabs being fed one butting against another and with the continuous, high temperature, high heat input furnace located in tandem with the mill. Slab temperature can be kept constant within precise limits and close gage control of the finished strip is easily obtained. In fact, commercial cold rolling tolerances can be obtained directly from the hot mill, end to end, without any long, heavy leading or trailing ends. With automatic gage control at the planishing stand, an even finer adjustment will be obtained.

A typical planetary mill installation is illustrated in Fig. 5.

Fig. 3 — Roll bite zone of planetary mill.

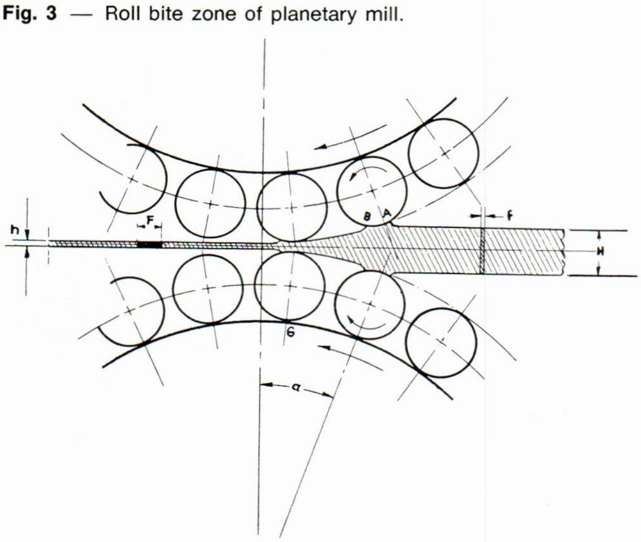
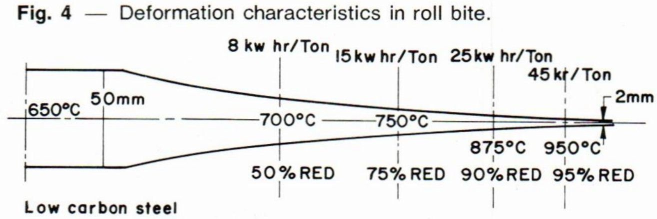


Fig. 4 — Deformation characteristics in roll bite.



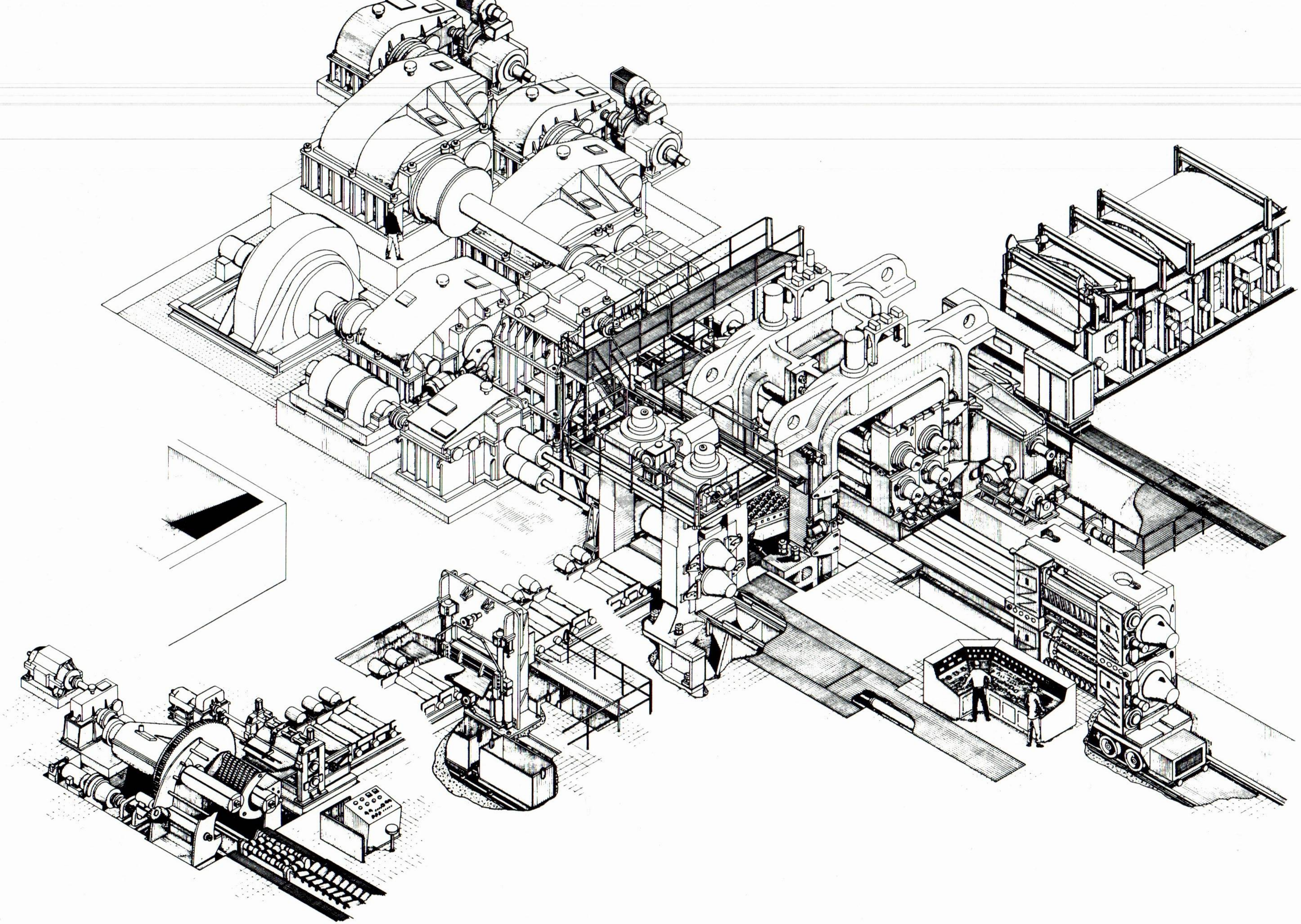


Fig. 5 — Typical planetary mill installation.

On exit from the planetary mill, the strip passes through a planishing mill and, after cooling, is coiled by a carousel coiler (Fig. 6).

The planetary mill allows considerable flexibility in rolling schedules. Also, strip quality is excellent. Because the temperature of the strip exiting the mills is constant, the same characteristics prevail throughout the coil.

Other advantages of the planetary mill include high yield, lower heating costs, smaller scale loss, lower roll costs, lower power consumption, less floor space and lower capital investment per annual ton of production.

Early operation, 50-in. range

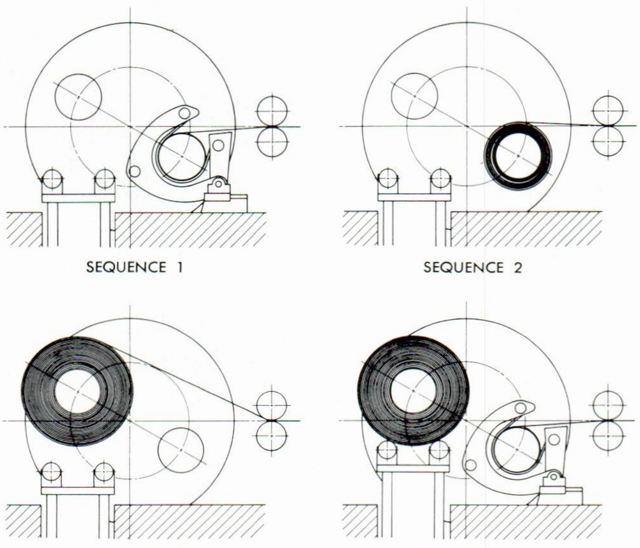
Two mills rolling low-carbon steel in the 50-in. width range, one in Italy (Fig. 7) and one in Sweden, produced hot rolled strip and light plate for manufacture of pipe welded sections. Occasionally, part of the production was cold rolled. For one mill with a 46-in. roll face, slabs were obtained in the open market, and the furnace was limited to 3 or 4-ton slabs. For the other mill with a 52-in. roll face, slabs were obtained from the plant's own steelworks and a blooming/slabbing mill, which produced 4-in. thick slabs.

Two other mills rolling stainless steel, one in Canada and one in Japan, both had a roll face of 57-in. initially. The one in Japan was later widened to 68 in. Both mills were fed with slabs produced by continuous casting machines. The caster in Japan was of the straight mold design, with no bending rolls, and the slab was cut with a maximum weight of 8 tonnes. The caster in Canada was of the curved mold design and the slabs could be cut with a maximum weight of 27 tons. These slabs had to be cooled, surface ground and reheated for planetary rolling.

In one instance, on a trial basis, an entire 60-ton heat was cast as one slab, surface conditioned in one piece and rolled on the planetary mill also as one piece. Later, it was divided into coils which could be handled in the downstream operation.

These stainless steel casters were producing 6-in. thick slabs in a vertical mold and 5-in. thick slabs in a curved mold, a record width:thickness ratio of 1:10 at the time the curved mold was built.

Fig. 6 — Operating sequence of carousel coiler.



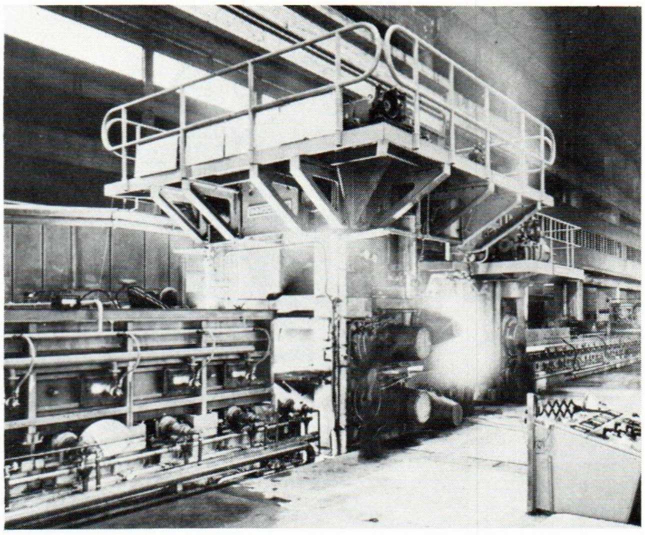


Fig. 7 — 46-in. wide planetary mill in operation rolling low-carbon steel.

Experimental tandem operation of casters and planetary mills

More than 20 years ago, attempts were already being made to continuously roll slabs with the objective of converting the entire heat of the furnace into hot coils (Fig. 8). Numerous metallurgical, handling, reheating and surface problems were encountered. Balancing the output of the caster proved difficult together with handling the slab on the runout table, entry into the furnace, and operation of the planetary mill and coiler.

An initial mold size of $2\frac{1}{2}$ x $17\frac{1}{2}$ in. was tried in Germany. It was too small and the speed of casting too slow for successful hot rolling downstream. With a slab speed of 4 to 5 fpm, the slab edges were black when entering the rolling mill. However, when everything was working properly, 80-in. OD coils were produced.

Next, a high-tonnage, proven continuous caster coupled with a planetary mill in the U.S. provided slabs which entered the mill at 16 to 18 fpm. The heat balance was correct and 60-ton hot coils were produced on an experimental basis.

In a third attempt, in Austria, the objective was to put the planetary mill back to back in tandem with the caster, eliminating the heating furnace but considering use of an equalization hood and possibly an edge reheater. This scheme would have required allowing the dummy bar head from the caster to go through the planetary mill and be cut off by a flying shear just ahead of the coiler. Experiments were conducted with a planetary roll bite made directly into the cast section, with the mill screwdown coming on blocks to achieve the desired gage. The experiments were successful; a tapered section after the dummy bar head proved that only a small amount of the metal would have to be scrapped.

New attempts in the future will utilize past experience and, at the same time, permit working with thinner cast sections from newer types of casters. For example, a mill is under consideration for rolling continuously cast sections of 2 x 50 in. and $1\frac{1}{2}$ x 50 in., but with both systems able to roll cast sections as thick as 3-in. for special products.

Most casters must balance the pouring rate and, therefore, casting speed with the cooling time of the liquid steel in the ladle. The liquid steel has a limited amount of superheat and the process must be completed before the metal freezes. Because of size considerations, the metal flow must be within approximately $2\frac{1}{2}$ tons/hr/in. of width, which represents casting speeds in the range of 15 to 20 fpm. These speeds may be increased in the future.

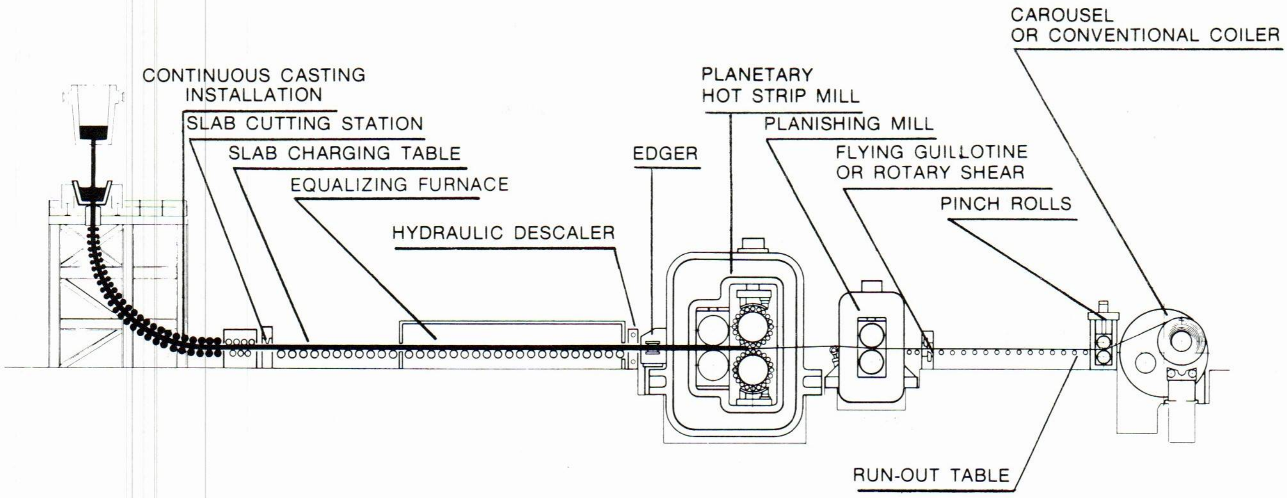


Fig. 8 — Continuous casting/planetary mill combination.

Mill design parameters must be based primarily on production of low carbon steel. However, the final product for which the steel will be used must also be considered; production of nonsophisticated grades of steel for making checker plate differs significantly from production of hot rolled strip for manufacture of tinplate.

Mill design parameters should also exploit the advantages of continuously casting thin sections. The slab is thin and is delivered from the caster at a high speed. It is hot, but not of uniform temperature. It needs a soaking zone with, perhaps, reheating near the edges by high frequency electric means or gas flame. Presumably, the caster will provide a good rollable surface on top and bottom sides. Although there should be little time to form secondary scale, the slab should be protected from oxidation, thereby perhaps eliminating a high-pressure water scalebreaker. Space should be allowed, but a mechanical mill surface scalper might be developed such as the type used in the nonferrous industries. Experiments conducted several years ago using ceramic and high-speed steel knives alternately provided good results.

Design for thin-section casters

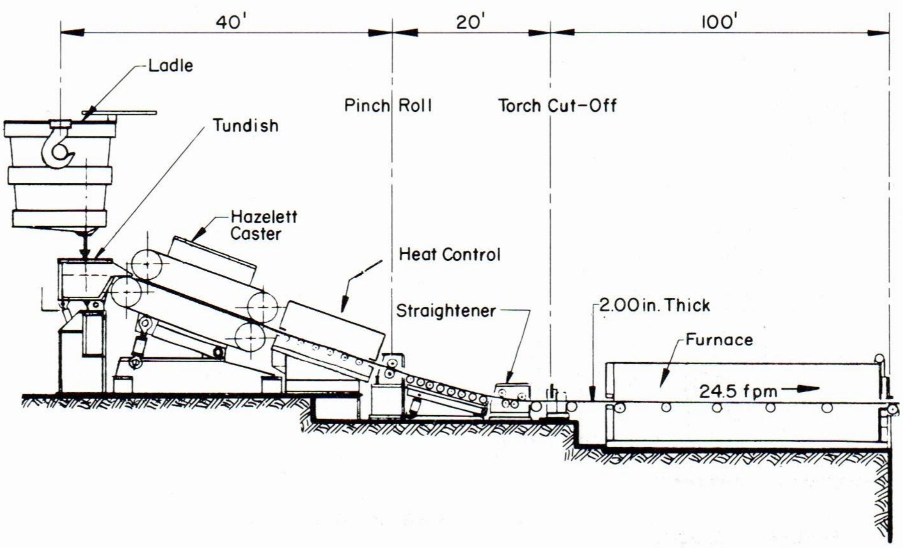
Specific parameters to be used in designing a planetary mill for thin-section casters become apparent when analyzing the passage of a thin-section slab through the roll bite. An example of a line for producing 60-in. wide strip at a rate of 300 tons/hr, which is equivalent to 5 tons/hr/in. of strip width, is illustrated in Fig. 9. A Hazelett caster is used to produce 2-in. thick slabs which pass through a reheat furnace before entering a planetary mill followed by a planishing mill. Strip exits the planetary mill at a nominal thickness of 0.150 in. and from the planishing mill at a nominal thickness of 0.135 in. The slab exits the Hazelett caster at 24.5 fpm with the strip exiting the planetary mill at 327 fpm and the planishing mill at 364 fpm.

With thin-section casters, the slab section moves into the planetary mill at a much higher rate of speed than with conventional thicker slabs. The feed rolls will take less reduction but will have to be regeared to match the increased rate of speed.

Edging of the thin slab should be considered. Although the amount of reduction can be only minimal, incorporation of an edger ahead of the planetary mill could have numerous advantages, eg, an edger insures that the slab enters the mill exactly in its centerline. However, an additional slab center correction point should be located upstream to insure straight alignment throughout the rolling mill and to prevent camber in the exiting strip.

The edger should work the cast structure on the slab sides to provide a more homogeneous strip edge. It can calibrate slab width within narrow tolerances and provide a round edge profile that will yield a smooth edge after the planetary mill.

Fig. 9 — Thin-slab caster (Hazelett)/ planetary mill combination.



Edging rolls should be driven by a d-c motor of the same speed range as the feed rolls and should have a symmetrical power screwdown to cover the entire range of widths to be cast. Edging-roll diameter can be small, eg, 14 or 16 in., and roll grooves should be smooth.

On exiting the last furnace hood, the slab should be protected by shielding to minimize heat radiation losses, and a neutral gas such as nitrogen might be applied through low-pressure nozzle banks to envelop the slab during passage through the edger and onto the feed rolls.

In the roll bite, because of the thinner incoming slab section, the point at which the work rolls meet the slab on this section is much further into the roll bite than on the thicker section. When the rolls touch the slab surface in the thinner section, the rolls that had been performing the rolling have already left the strip surface. Consequently, the rolling load (roll separating force) is suddenly reduced to zero. During this period, the slab can easily advance without restriction, which is advantageous because the thinner section slab has less resistance to a column effect. In addition, the back force on the slab at the initial point of contact is less. Thus, with a good roll bite established, the nonslip or equilibrium point will be reached quickly. Thereafter, the planetary work rolls will extrude metal in front of the rolls until they leave the strip.

Although each pair of work rolls will take a substantially larger feed of slab per roll bite, the scallop length at the end of the bite will be of approximately the same pitch as on conventional mills. It will differ in length depending on the gage rolled.

In designing the planetary mill, adjustment must be made for the complete load/no load condition in the mill housing. Prestressing the screwdown to 140% of the maximum roll separating force must be included in the design and the mill must have a roll gap opening adjusted by the wedges with a suitably strong screwdown for up and down motion.

There are several ways to arrange for synchronization and parallelism of the work roll cages including use of newly designed basket cages together with a juxtaposed beam anvil. Direct synchronization with basket cages insures that each pair of work rolls will touch the slab at the same time and that the rolls will be parallel. Use of the beam anvil, which simultaneously contacts the antipodic work roll, insures that the cages achieve synchronized speed before entry of the first slab and also provides for rigidity of the roll bite.

In addition, the beam anvil construction provides rigidity of the planetary roll assembly. This permits using much smaller diameter backup rolls and smaller diameter work rolls, which, in turn, reduces the size of the main chocks and mill housing. The roll separating force is absorbed directly by the beam anvil which must be designed with sufficient strength to resist deformation. Moreover, the beam anvil can be counter crowned to prevent roll deflection and produce good finished strip shape.

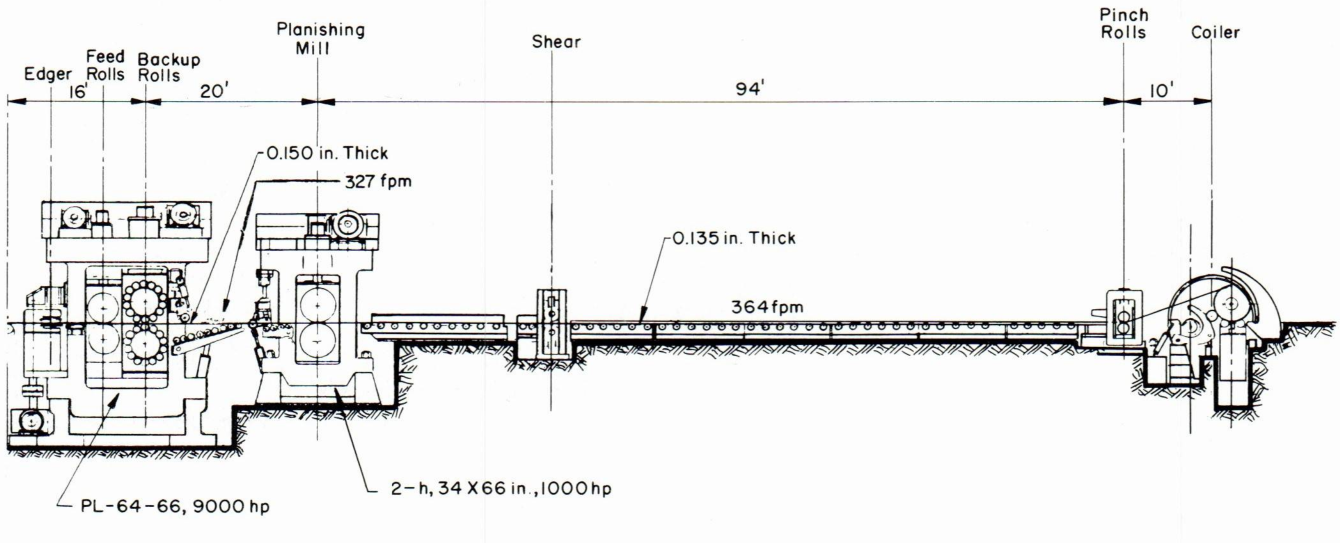
In addition to the mill screwdown, a separate screwdown must be provided for the beam anvil. It is adjusted only after rolls are changed in the mill. The beam anvil moves up and down with the chocks and is activated by the main screwdown.

Other parameters involved in designing a small planetary mill for thin strip casters include the power to be transmitted. This will depend on the width of the slab to be rolled, type of steel, steel temperature, maximum and minimum gage which the mill must handle, and work roll diameter. These factors will govern the minimum diameter of the backup roll and the spindles which can be utilized for a given application. The mill size will, therefore, have to be adjusted to the backup roll parameters.

Another factor to be considered is the desire to roll sequential heats in a continuous mode and operate as long as possible without interruptions. Work roll wear will depend on the minimum gage produced. As a general rule, work roll life will be reduced by more than half if the thickness rolled is reduced by half. For example, on one 25-in. wide planetary mill, 800 or 900 tons of 0.100-in. thick low carbon steel can be produced before the work rolls must be reground. However, when rolling 0.060-in. thick low carbon steel, only 300 to 350 tons can be produced before regrinding is necessary. Both gages are obtained from a 2¼-in. input size.

Thus, operators may prefer a planetary mill with larger roll diameters and a larger number of work rolls to extend the life between assembly exchanges and obtain longer runs. Sufficient life for 20 to 22 hr of continuous operation for that type of mill would be a reasonable goal, leaving 2 to 4 hr/day for maintenance of the caster and planetary mill. Under these conditions, both units would be working at 100% load and the overall operating efficiency would be nearly 90%.

Planishing mill — Downstream from the planetary mill, it may be desirable to include one or more planishing mills, depending on factors such as if the product is simple or sophisticated, whether the hot strip will be used directly or will be cold rolled, if metallurgical cleanliness or low cost is dominant in steel production, and whether the steel is a special type such as low alloy high strength, high alloy, silicon or stainless. In deciding to include planishing mills, the need for heavy reduction after the planetary mill must be balanced against added investment cost and hot strip quality.



A 10% reduction in the planishing mill might be sufficient for many applications, eg, galvanized steel. Reductions of 35 to 50% might be appropriate for hot strip to be used for building construction where light reflection will accentuate surface detail.

Normally, a simple 2-h mill could achieve a 10 to 12% reduction and eliminate most of the scallops. Although 3-h mills give reductions of up to 20%, work roll wear would make this solution questionable for mills operating continuously for 20-hr periods. This could also apply to mills such as the 4 and 6-h type used at the Nippon Yakin 68-in. wide installation. Although these two types of mill could achieve reductions of 30 to 35% and provide good shape (especially the 6-h), work roll wear and the need for exchanging rolls would limit their application for long continuous runs.

Another mill that might be considered in the future is the turret mill. This mill resembles the planetary mill and has spare work rolls incorporated in cages around the backup roll. The mill itself works as a 4-h, and the other rolls are pushed by the springs away from the backup roll. Essentially, these rolls in the revolver position are spare rolls. They can be of different diameter, crown or length to suit a given width of product. With the turret mill's fast opening screwdown, work rolls can be exchanged in 5 or 6 s.

After the planishing mill, there should be a flying shear and a coiler. The coiler can be of the carousel type or two separate coilers can be used to handle the uninterrupted flow of strip.

When the strip is parted by the shear, the trailing end must be accelerated away from the succeeding coil. A gap of 10 to 15 ft is desirable so that the front end can be caught in the coiler without creating a stoppage.

Investment and operating costs — A 50-in. planetary mill for rolling slabs of normal thickness might cost $18 to $20 million for mechanical equipment. The comparable cost of a small planetary mill for thin-section slabs might be only ⅓ as much. The electrical equipment for thin-section slab rolling would consist of a single-speed synchronous motor and d-c drives. The largest of these would be the feed-roll motor of approximately 350 hp. A 5000-hp, a-c mill motor would give an output of 100 tons/hr for a normal range of gages. Planishing mills would require a d-c drive.

Operating costs would depend on the product quality required. One 50-in. wide planetary mill operating overseas and producing 125 tons/hr requires only four operators for the entire installation. Data from a small planetary mill producing low carbon steel in the U.K. are shown in Table I.

Maintenance and spares — For round the clock operation, four sets of planetary assemblies would be required: one in the mill; one for standby; one in the roll shop being assembled; and one being processed for the grinder. Usually, two or three sets of work roll changes would be needed before backup rolls are reground. With clean steel and a small amount of scale, work roll life between changes would increase.

With fully continuous operation and no front ends or trailing ends, yield should approach 100%; a yield of 99.9% should not be unusual. The only pieces to be scrapped in regular operation would be 3 or 4 ft from the original front end and a piece of slab between the feed rolls and the planetary mill when the caster is stopped.

TABLE I Data from small planetary mill producing low-carbon steel operating from 1953 to 1981

Portion of total operating cost, %	
Production labor (£1.20/hr)	22.8
Maintenance labor (£0.85/hr)	8.2
Manufacturing supplies (oils, greases, etc)	1.4
Repairs and renewals	17.4
Roll depreciation	6.8
Roll grinding	2.8
Electricity (£0.01/kw)	10.8
Furnace gas (£0.03/therm)	17.9
Water	0.5
Management and staff salaries	3.2
Other direct charges (rates, insurance, depreciation)	8.2
Portion of overall costs, %	
Variable costs	72
Fixed costs	28
Production	
Yield, %	99
Efficiency, %	90
Rated tons/hr	10
Actual tons/hr rolled	14.5
Average tons/hr (at 90%)	13
Total rolling hours/5-day week from two mills	160
Total average tonnage/5-day week	2100
Scheduled total annual tonnage from two mills	100,000
Product usage, %	
Presswork, (car and cycle industry)	60
Building (scaffold clips, Z purlins, etc)	10
Welded tube industry	15
For cold rollers	5
For section rollers	5
For industrial casters	2
Miscellaneous	3

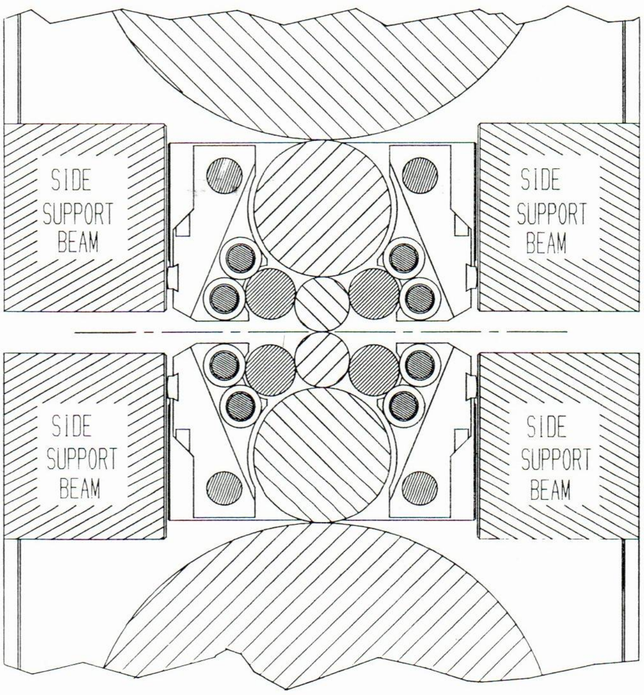
Discontinuous operation

Thin-section casting systems could also be operated in more conventional ways using hot coilers and one or more reversing mills.

A 2-h mill could be put in line with the caster to achieve some reduction and to coil strip approximately 1 in. thick.

A combination mill might also be used—two 2-h mills in one housing or a 2-h and a 4-h in one housing with a 2-h pushing the slab into the 4-h for maximum reduction. This combination could achieve intermediate finish thicknesses but the wear of the 4-h work rolls would be disastrous. This arrangement could be desirable for certain short casting periods and for thicker finished gages.

Fig. 10 — Hot Z-high mill with small work rolls.



Another possibility would be to use two, three or four 2-h mills in tandem. This system would insure longer runs, but the minimum gage attained would be limited. Several 4-h, 6-h and/or hot Z-high as the downstream finishing mills could be considered.

Another approach would be to provide for a 2-h reduction mill with a hot coiler at 1-in. thickness and then transfer the material to a reversing mill equipped with two hot coilers (hot steckel solution). It would be essential that the second mill have sufficient speed and power to accomplish its reversing operation—even to the thinnest gages—well before the next coil is forthcoming. This approach would require elaborate, expensive electrical equipment. For continuous operation, two hot coil boxes would be needed.

For the latter approach, the reversing mill could be a 4-h or a 6-h mill. Sendzimir has developed the hot Z-high mill (Fig. 10) using a relatively small work roll ($5\frac{1}{2}$ to 7 in. dia) for a 50-in. strip width. This would permit heavier reduction in each finishing pass, thinner gages (eg, 0.040 in.) and better gage accuracy. The mill would need sufficient power and speed not only to roll to thinner gages but also to allow a work roll change between coils. With automatic handling, such a work roll change should be possible in 60 s. The life of all the intermediate rolls should be well within a day's operation.

Variations of the foregoing concepts are numerous and could be selected so as to provide the best solution for each individual project.

Summary

The use of planetary mills for hot rolling thin continuously cast sections appears to offer numerous advantages, including the possibility of reducing the cast slab directly to finished thickness in one pass in tandem operation with the caster. Also, hot coils of indefinite size can be produced and continuous operation may be maintained over long periods. For discontinuous rolling of thin sections, hot coilers and conventional reversing mills could be used to advantage in certain applications as well as the new hot Z-high mill. ▲

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