Castrip LLC

FASTER

SMARTER

THINNER

BETTER

Application of Fundamental Research at Project "M"

By
W Blejde and R Mahapatra, BlueScope Steel, Port Kembla, Australia
H Fukase, IHI, Yokohama, Japan

The Belton Memorial Symposium
Sydney, Australia
January 10-11, 2000

2100 Rexford Road, Charlotte NC 28211

Telephone: 704.972.1820 Facsimile: 704.972.1829

www.castrip.com

Application of Fundamental Research at Project ‘M’

by
Walter Blejde & Rama Mahapatra
BlueScope Steel, Flat Products Division

Hishahiko Fukase
IHI, Production Systems

Key Words: Strip casting, twin rolls, solidification, metal delivery, microstructure, mould distortion

INTRODUCTION

The production of steel strip directly from liquid steel has been the dream of steel industry technologists for over 150 years.

Since 1989, BHP and IHI have been collaborating on the development of strip casting technology on a full scale development plant at Port Kembla, Australia. The capability to produce commercial quality low-carbon steel coils (2 mm x 1345 mm) was demonstrated in 1998. Cast material has been successfully side trimmed, pickled, cold rolled, metal coated, painted and roll formed into a number of sections. These sheeting products are currently in use in actual building projects. Cast material has also been directly converted to pipes and tubes. The main features of the development plant, the cast strip quality and product processing results, have been reported elsewhere[1)]. Since 1999, development has concentrated on the production of thinner gauge material (<1.4 mm).

An aggressive support research program was introduced from the beginning of the project to gain a good basic understanding of process fundamentals in order to minimize development time and cost.

This paper focuses on the role played by fundamental research in Project ‘M’.

PROCESS OVERVIEW

Strip casting enables the elimination of intermediate process steps which exist in conventional strip production resulting in a process that is not only simpler, but in many respects more challenging from the process point of view.

Unlike conventional slab casting, strip casting is carried out without mould flux resulting in direct contact between the liquid steel and the mould surface (Fig. 1). This regime is accompanied by much higher heat fluxes and solidification rates as summarized in Table I.

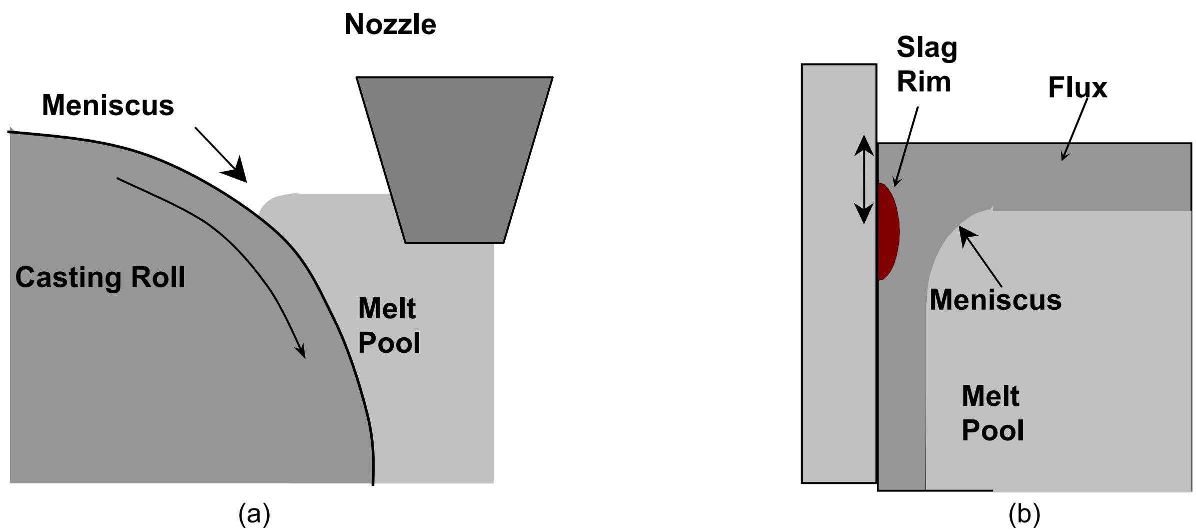

Fig. 1: Schematic representation of moulds (a) twin roll strip casting (b) slab casting.

Table I: Key process differences between twin roll and conventional slab casting

	Strip	Thin slab	Thick slab
Strip thickness, mm	1.6	50	220
Casting speed, m/min	80	6	2
Average mould heat fluxes, MW/m^2	14	2.5	1.0
Total solidification time, s	0.15	45*	1070**
Average shell cooling rate in mould, °C/s	1700	50	12

*k factor = 29
** k factor = 26

PRODUCT OVERVIEW

Fig. 2: Summarizes key strip attributes that are used to specify commercial quality strip.

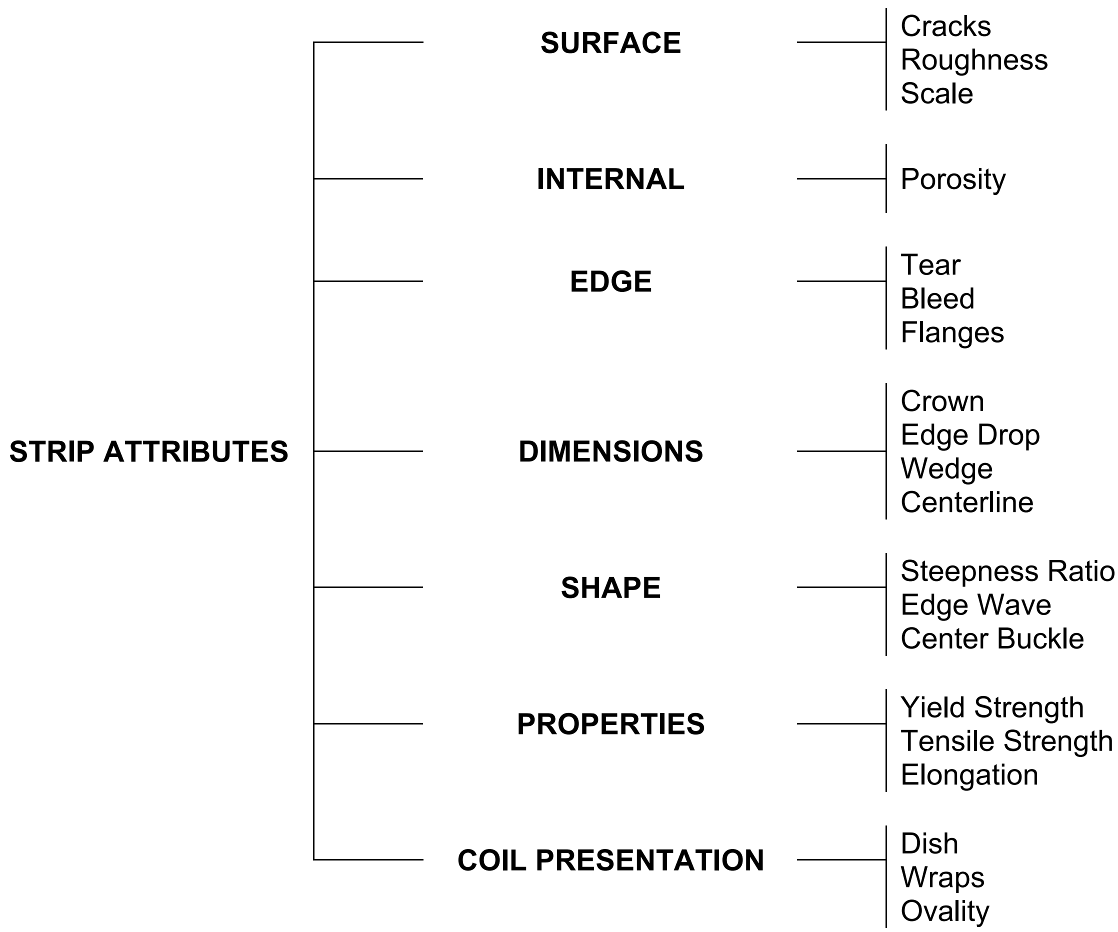

Fig. 2: Key Strip Product Attributes

Satisfactory strip (quality) attributes can only be produced through careful control of metal delivery, mould heat extraction and microstructure evolution.

In an effort to accelerate acquisition of knowledge on process fundamentals, support research within Project 'M' was divided into the following areas:

- Solidification fundamentals
- Metal delivery
- Melt/refractory interactions
- Mould distortion
- Microstructure evolution and properties

SOLIDIFICATION FUNDAMENTALS

Although the overall solidification time is of the order of 100 to 200 ms, surface quality is predetermined by the events in the first 20 to 30 ms. Initial liquid steel/mould surface contact has a profound impact on nucleation characteristics, heat transfer and solidification behavior. The meniscus is thus the most crucial region for quality. Considerable attention has been devoted towards obtaining a precise understanding of the heat transfer and solidification mechanisms in this region [2,3].

Solidification Simulation Experiments

A special apparatus which enabled millisecond resolution of heat fluxes was built to simulate the solidification process occurring in a twin-roll casting environment. The apparatus arrangement is shown in Fig. 3.

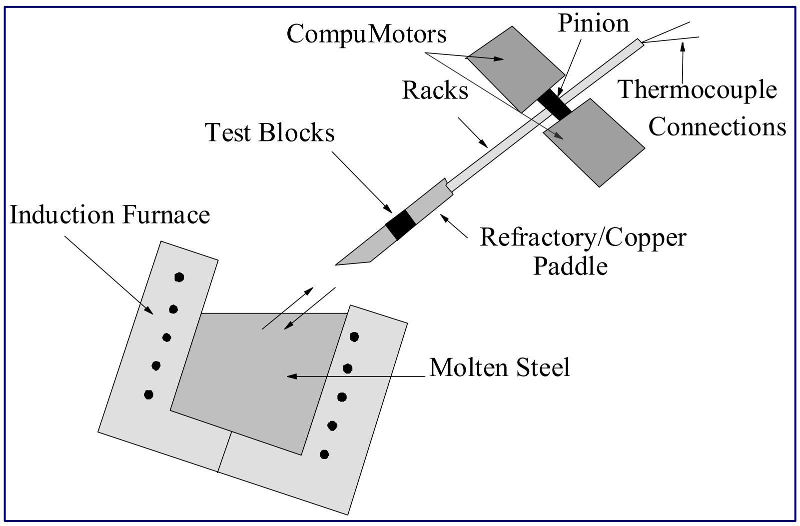

Fig. 3: Schematic representation of apparatus used to simulate solidification in the meniscus region.

Details of this apparatus has been reported elsewhere.

This facility has been extensively used to define solidification strategies with respect to roll textures, melt chemistry, casting speeds, melt temperature and other process variables.

The casting roll surface is nuclear to the solidification process as the roll texture fundamentally defines heat transfer rates. Typical heat flux curves for two different textures are shown in Fig. 4. The magnitude of the peak heat flux characterizes the effectiveness of the initial contact and these values correlate well with the nucleation density measurements.

From a practical standpoint, the fundamental challenge has been to control the heat flux with appropriate roll textures to meet economic productivity rates without producing cracks through excessive stress generation in the solidifying shell.

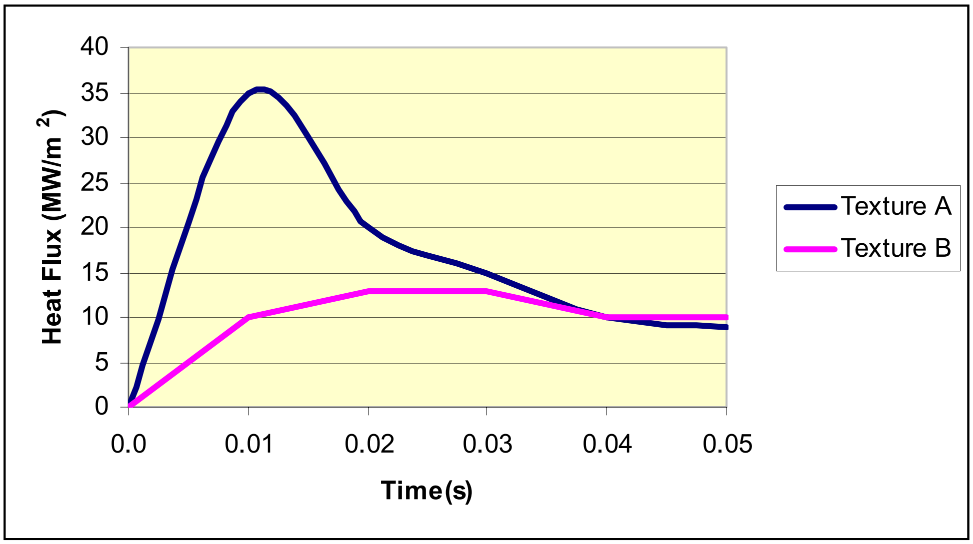

Fig. 4: effect of roll tecture on heat fluxes.

Control of shell uniformity over the roll surface is critical as localized thinner regions are more prone to cracking due to stress buildup. Unevenness in the shell will inevitably result in internal porosities which are caused by the shrinkage of the liquid trapped between the two shells below the nip as illustrated in Fig. 5. Existence of internal porosities is of concern as initial cold rolling trials indicated that this defect can cause severe operational problems during cold rolling under tension.

Solidification simulation experiments revealed that uneven solidification can be overcome with appropriate roll textures and melt chemistry.

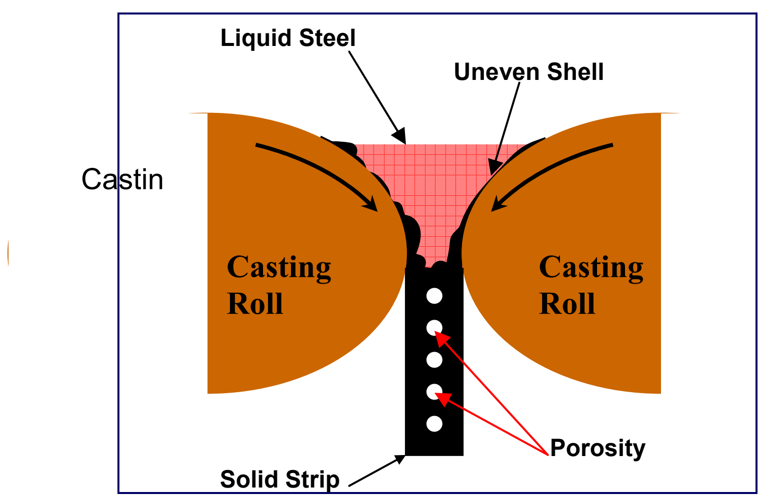

Fig. 5: Formation of internal porosities caused by uneven solidification

Solidification Modeling

In parallel to the experimental efforts described above, mathematical models have also been developed to obtain fundamental process insights. Solidification behaviour has been modelled at a microscopic level to predict interfacial heat transfer rates, shell growth, stress evolution and shell buckling [4)]. Modelling work has also highlighted the significance of roll texture. Fig. 6 illustrates the effect of casting roll texture on the degree of shell evenness. Clearly, roll texture optimisation is critical to achieving uniform solidification.

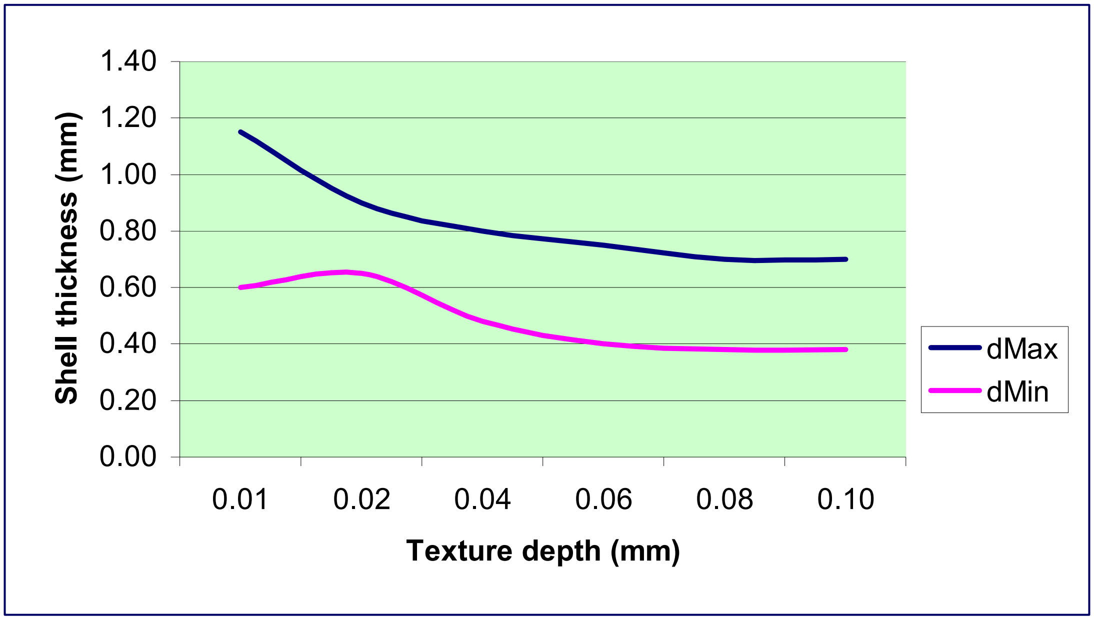

Fig 6: Model predicted effect of roll texture on shell evenness

METAL DELIVERY

Fluid flow patterns in the mould have a significant impact on strip surface quality. The input stream energy per unit pool volume in strip casting is around five to ten times greater than that in slab casting processes, thus the effects of general pool turbulence, surface waves and shell washing in strip casting are more pronounced.

Metal delivery systems must be capable of simultaneously meeting flow requirements in the meniscus area, the bulk of pool, and also the edge region. Final designs were developed through extensive use of computer modeling, water modeling and plant casting trials.

Meniscus Area Flow Control

The supply of hotter steel to the meniscus area is essential to prevent freezing related defects (Fig. 7). Excessive flow on the other hand will increase turbulence and the tendency to form cracks.

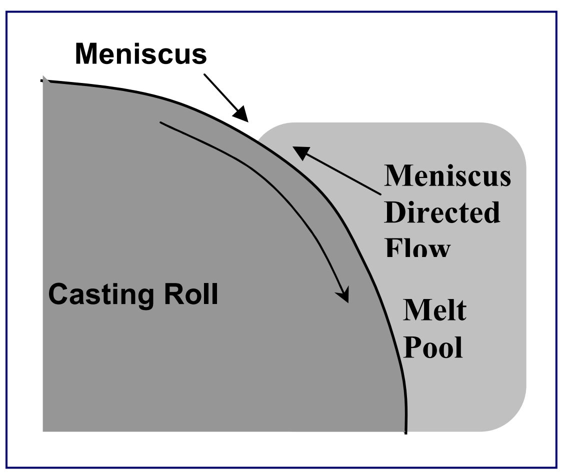

Fig 7: Meniscus directed metal flow

Bulk Flow Control

Design efforts have also been directed to developing delivery devices capable of distributing the metal as uniformly as possible across the entire pool with reduced stream velocities. Stream impingement on the solidifying shell must be avoided to prevent localized shell remelting which produces a defect referred to as nozzle mark. An example of this defect is shown in Fig. 8.

Edge Flow Control

Pre-heated refractory plates (side dams) are applied against the roll edge for metal containment as shown in Fig. 9.

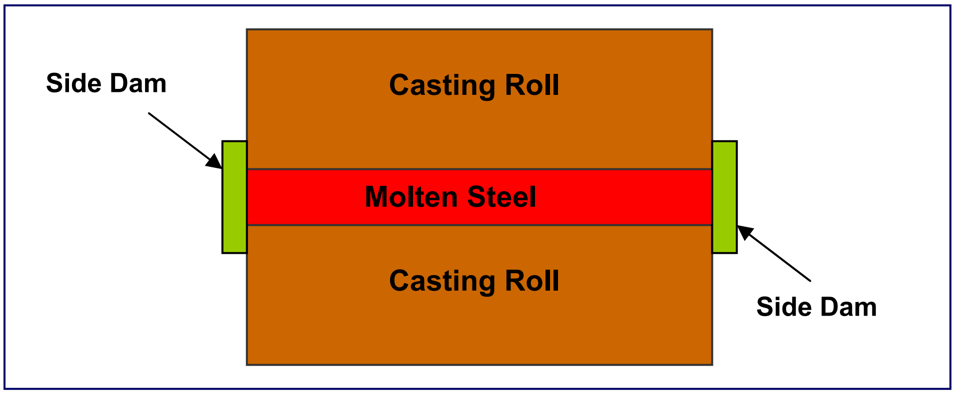

Fig. 9: Schematic representation of side dam application against roll.

The region of the side dam in direct contact with the roll is cooled dramatically (Fig. 10). Thus at the edge region of the side dam, the steel is more prone to freezing and thus skull formation. This results in poor edge quality and in some cases, can cause severe operational problems. This problem has been overcome by appropriate nozzle design features which enable supply of more heat in this region.

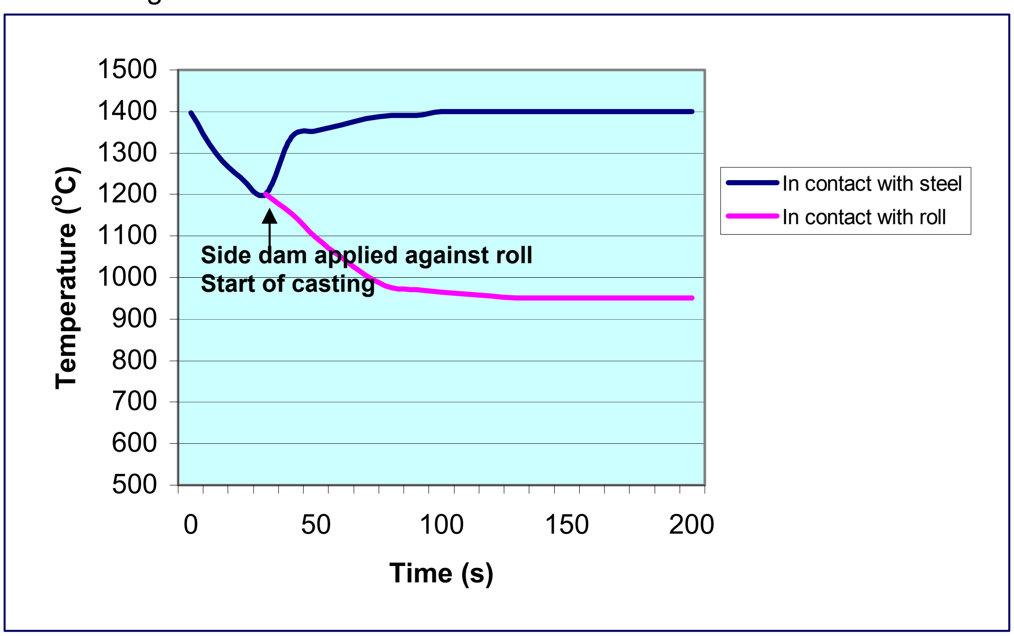

Fig. 10: Side dam temperature as per model calculations

MELT-REFRACTORY INTERACTIONS

Alumina-graphite refractory nozzles are used in the mould area. Although there are no operational issues associated with this material, there were strip quality issues caused by a reaction at the nozzle/melt interface. These reactions, which resulted in the evolution of carbon monoxide bubbles were capable of inducing disturbances at the meniscus which produced defects as shown in Fig. 11.

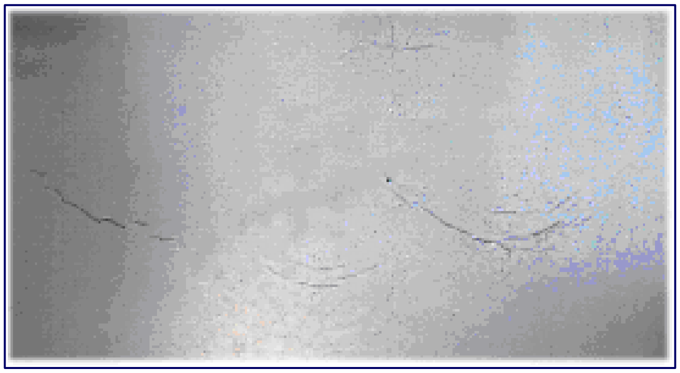

Fig. 11: Photo of defect on strip resulting from meniscus disturbances induced by CO bubbling

In-situ high temperature visualisation experiments coupled with off-gas analysis have been utilised to quantitatively characterise reaction kinetics. Details of this experimental facility have been described elsewhere [5)]. The effect of one of the key parameters namely refractory material composition on CO generation is shown in Fig. 12. There is a dramatic reduction in CO generation with refractory material B when compared to A.

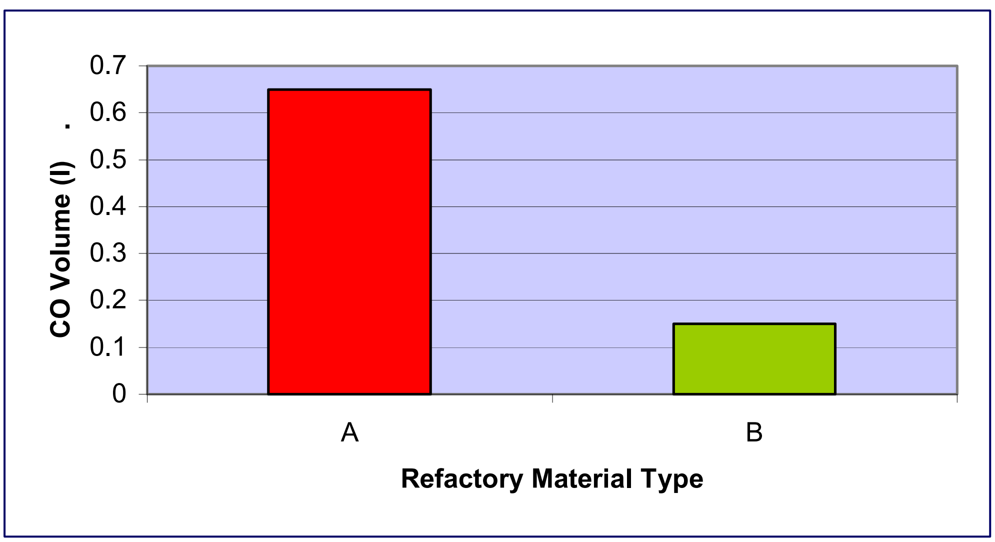

Fig. 12: Effect of refractory material on CO evolution

Defects caused by CO bubbling have been eliminated through appropriate selection of refractory materials.

MOULD DISTORTION

Cast strip dimensions have to be controlled within tight tolerances to ensure that the coils can be successfully processed in downstream operations such as cold rolling and other direct applications. Key dimensional requirements include strip profile (crown and edge drop) and thickness variations as shown in the three-dimensional strip thickness contour in Fig. 13. Solidification time control is fundamental to achieving constant thickness. Strip thickness variations (both transverse and longitudinal) are predominantly influenced by the roll gap dimensions at the nip.

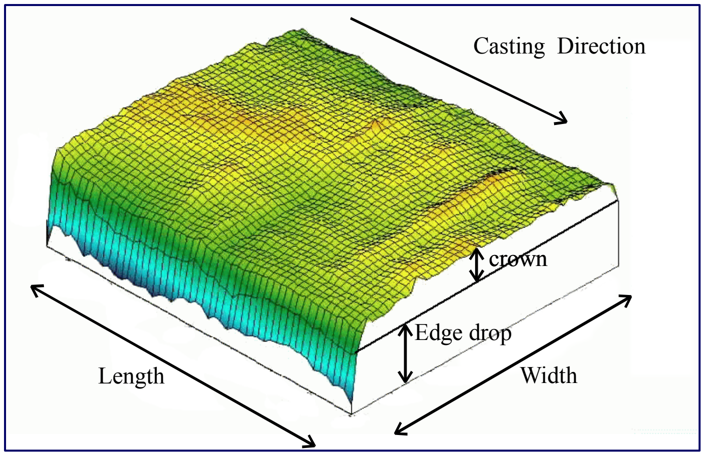

Fig. 13: Strip dimensional requirements

In addition to extreme heat fluxes, the rolls are subjected to cyclic thermal loads producing rapid changes in temperature and roll dimensions (Fig. 14). A fundamental understanding of the impact of roll dimensional transients on heat transfer and solidification has been developed to control strip dimensional performance.

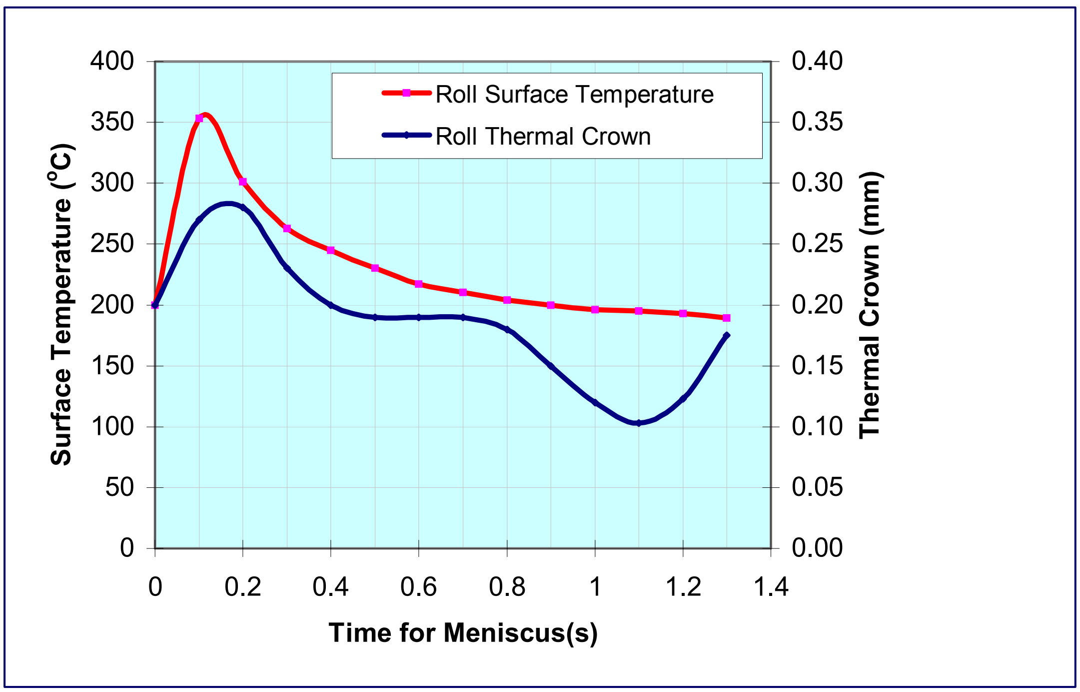

Fig. 14: Changes in roll surface temperature and thermal crown over one roll revolution

Strip Profile

The strip profile is determined by the geometry of the roll gap and the shell contour at the nip. Casting with flat rolls will produce a concave strip where the central region is thinner compared to the edges as shown in Fig. 15a. Thicker edges are due to bulging of the shell below the roll nip due to the existence of a liquid core in this region. Casting rolls have therefore a machined crown to compensate for the thermal crown developed during casting as illustrated in Fig. 15b.

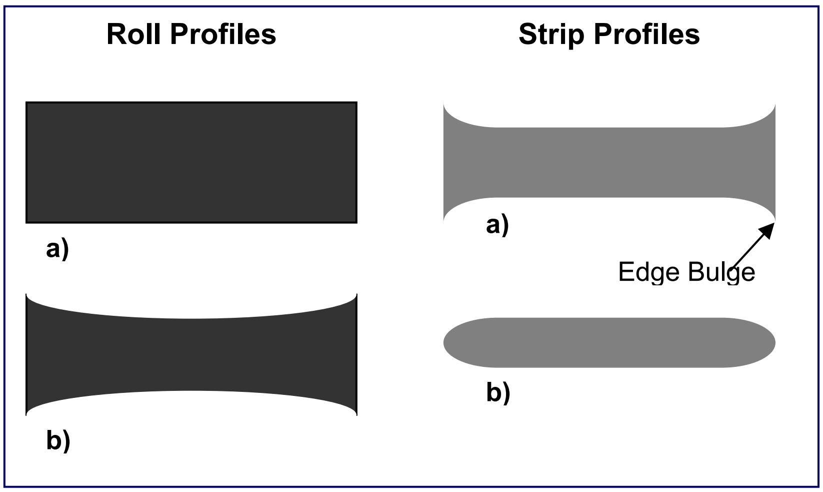

Fig. 15: Effect of roll crown on strip profile. a) Flat roll b) roll with machined crown

An understanding of the heat flux distribution across the roll width is critical to controlling strip crown and edge bulge. Fig. 16 presents actual roll surface temperature measurements which show that there is a significant drop-off in temperature towards the edges indicating lower heat fluxes in this region. This leads to considerable thinning of the shell near the edges. The above conditions are taken into consideration when designing machined crowns for the casting rolls. Heat flux attenuation towards the edge is believed to be caused by a combination of roll distortion, shell shrinkage and lift-off.

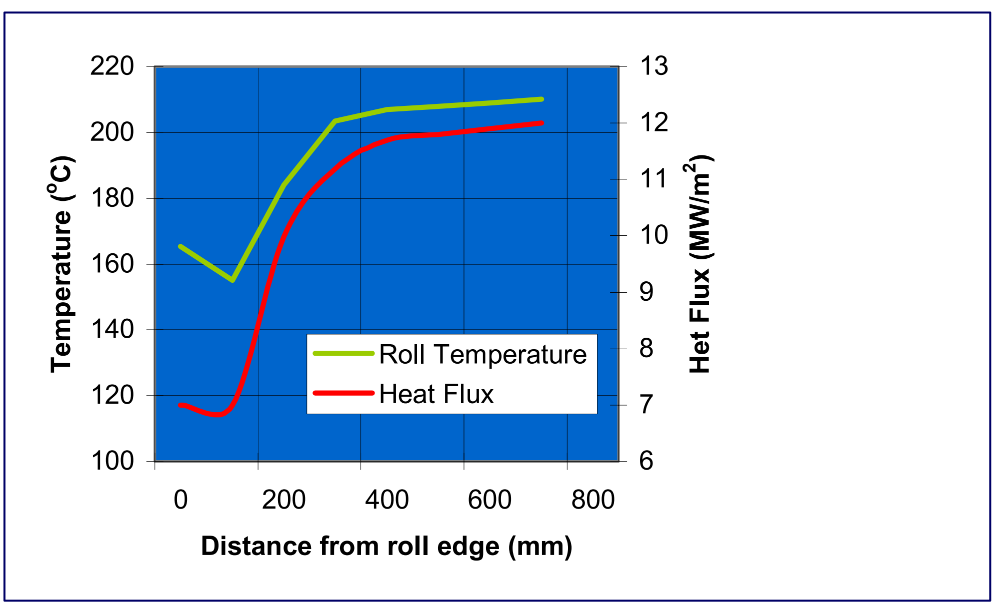

Fig. 16: Measured temperature across roll width and calculated heat fluxes

MICROSTRUCTURE EVOLUTION AND PROPERTIES

The process of microstructure evolution in strip casting is fundamentally different from that in conventional hot strip mills. Fig. 17 shows the difference in final microstructure for the two strip production routes. Hot strip mill products exhibit fine equiaxed ferritic microstructure (Fig. 17a) whilst cast strip microstructure is predominantly a mixture of coarser polygonal and acicular /widmanstatten ferrite (Fig. 17b).

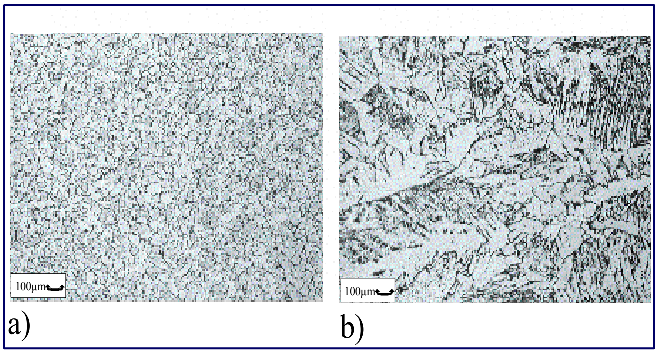

Fig. 17: Comparison of final strip microstructures produced by a) Hot Strip Mill and b) Strip Casting.

Microstructure Evolution

Hot strip mill products undergo large reduction which breaks up the structure and also enhances re-crystallization kinetics resulting in significant refinement of austenite grains, which upon further transformation produce finer equiaxed ferritic grains. The austenitic grain size in cast strip is entirely governed by the casting process. The observed mixed microstructure in strip casting (Fig. 17b) is an inevitable outcome from the transformation of coarser austenitic grains.

Microstructure development in strip casting is fundamentally coupled to the solidification process. The solidification simulation device described earlier has been extensively used to understand the evolution of microstructures from initial solidification through to the final product. Fig. 18 indicates that there is a strong correlation between the initial solidification nucleation density and the size of austenite grains [6)].

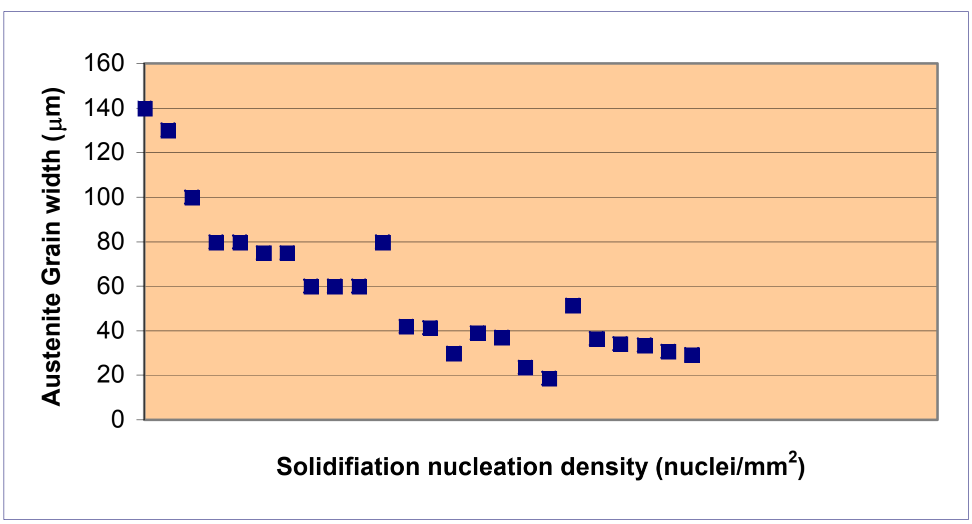

Fig. 18: Effect of nucleation density on austenitic grain size

Properties

The mechanical properties of cast strip are comparable to low carbon strip produced via the hot strip mill route (Table II). The strength of strip cast material tends to be on the higher side due to the presence of acicular/widmanstatten ferrite.

Table II: Summary of strip mechanical properties

	Cast strip	Typical hot band range
Yield strength (MPa)	300	250-360
Tensile strength (MPa)	440	320-440
Elongation%	26	22-35

Unlike conventional processes, where chemistry changes are necessary to produce a broad range of properties, strip casting has the potential to achieve the same outcome with a single chemistry because of its unique coarser austenitic grain structure. This concept is illustrated in Fig. 19 which demonstrates the potential effect of strip cooling rates on yield strength.

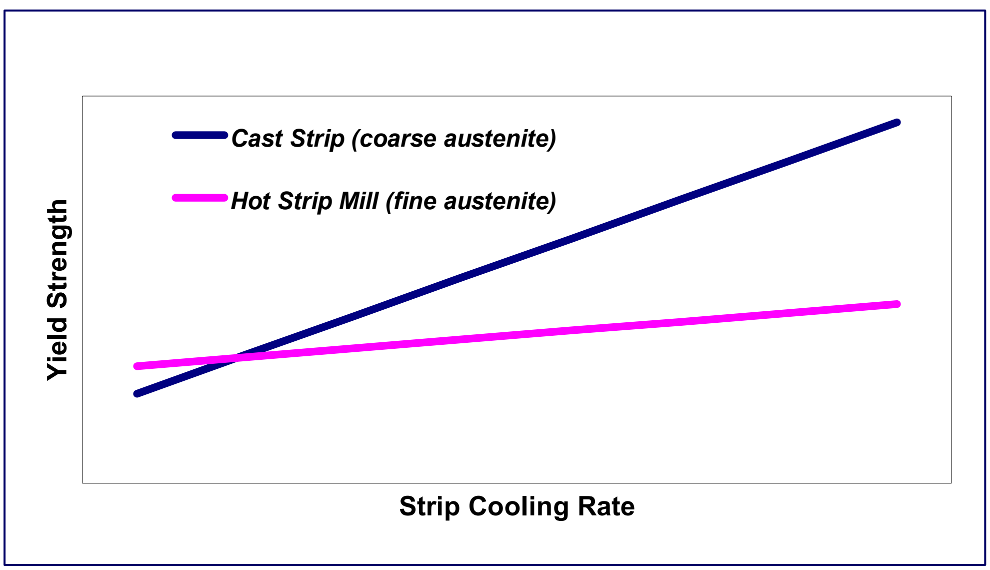

Fig. 19: Response of austenitic grain size to strip cooling

Finer austenitic grains (typical of hot strip mill product) are relatively insensitive to changes in strip cooling rate. Ultra fast cooling rates (in excess of 500 ^{o}C/s) are therefore necessary with hot strip mill products to produce high strength steels [7)].

On the other hand, a coarser austenitic structure (typical of strip casting) can be transformed to microstructures ranging from fully polygonal ferrite to martensite structure (Fig. 20), thus producing a wider range of properties from a single chemistry.

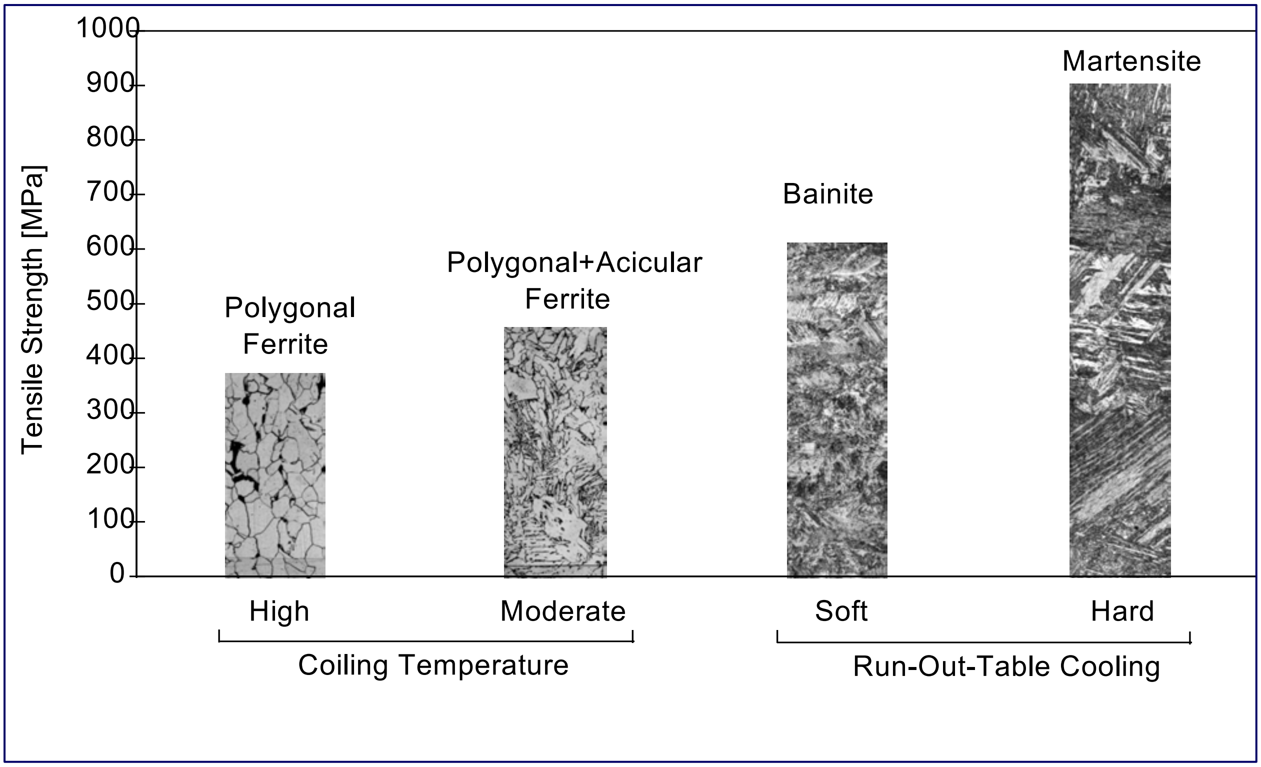

Fig. 20: Microstructure control with strip cast material

CONCLUDING REMARKS

The development of technology to directly cast strip from molten steel has generated a need to expand current fundamental knowledge in the areas of initial nucleation and subsequent solidification behavior. The approach taken by Project 'M' to acquire the necessary fundamental knowledge and apply it to solve quality problems has been presented in this paper.

By virtue of its unique metallurgical regime, strip casting offers the potential to produce strip products that can not be made today using conventional processes leading not only to process simplification, but to the production of unique mechanical properties that are greatly valued by the market place.

REFERENCES

1. W. Blejde, H. Fukase and R. Mahapatra: "Recent Developments in Project M – The Joint Development of Low Carbon Steel Strip Casting by BHP and IHI", International Conference on New Development on Metallurgical Process Technology, METEC Congress, June 1999, pp. 176-181.

2. L. Strezov and J. Herbertson: "Experimental Studies of Interfacial Heat Transfer and Initial Solidification Pertinent to Strip Casting", ISIJ, vol. 38, 1998, pp. 959-966.

3. H. Todoroki, R. Lertarom and A. Cramb: "Initial Solidification of Iron, Nickel and Steel Droplets", Transactions of the ISS, April, 1999, pp. 57-71.

4. H. Fukase: Unpublished Research on "Solidifying Shell Behaviour Simulation System (SBS)", IHI, 1995.

5. C. Wu and V. Sahajwalla: "Influence of Melt Carbon and Sulphur on the Wetting of Solid Graphite by Fe-C-S Melts'', Metallurgical and Materials Transactions, Vol. 29B, 1998, pp. 471-477.

6. K. Mukunthan and L Strezov: Unpublished Research on "Microstructure Evolution in Strip Casting", BHP Research, 1999.

7. P. Simon et al: "Ultra-Fast Cooling on the Run-Out Table of the Hot Strip Mill", La Revue de Metallurgie-CIT, March 1996, 409-415.