HOT CHARGING AND DIRECT ROLLING OF CONTINUOUS CAST STEEL: IN-PROCESS CHARACTERIZATION AND CONTROL


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ABSTRACT

This paper focuses on work in progress at the Middletown plant of Armco, Inc. to utilize the known quality, yield and energy advantages of hot charging continuous cast steel slabs. Earlier efforts concentrated on exploiting those advantages for ingot produced material. Improvements in furnace efficiency and productivity attributable to opportunistic hot connection proved difficult to verify and led to the development of a fully integrated control system for the slab reheating and hot strip processes. That system requires an estimate of the initial slab temperature profile; the need for such information is well recognized in the industry, and is one of the target applications for an AISI collaborative sensor development. The imminent phasing out of steel ingot production reinforced the need to intensify hot charging of caster produced slabs. One of the approaches under consideration will make use of this same sensing methodology to monitor the temperature profile in the solidifying slab. That sensor and the current plans for a demonstration site will be described.
INTRODUCTION

We will be discussing work in progress at the Middletown plant of Armco Inc. to exploit the known quality, yield and energy advantages of hot charging continuous cast steel slabs. Those advantages have been well documented in the literature and were the objectives of our early activities to optimize the processing of ingot produced material. We will briefly review some of that work because many of our current approaches are extensions of methods developed at that time.

We have demonstrated the efficacy of some simplistic approaches to solving hot charging and direct rolling problems, and it is that progress we will describe to you. Be forewarned that we will also be using the problem to illustrate approaches to sensing and control which have more general applicability. The hot charging problem serves to introduce some very recent developments in an AISI collaborative effort to develop a sensor which monitors the temperature distributions inside solid and solidifying materials during processing. We will first outline the control problem and the economic incentives.

EMERGING TECHNOLOGIES & ECONOMIC "OPPORTUNITIES"

Recently, there have been a number of technical innovations which have made the task of controlling processes far more feasible, and other less welcome economic trends which make such control imperative.

On the technical side we have seen the emergence of improved sensors and methodologies which provide more insight into the details of the process. These techniques often rely on indirect measurements, mathematical process models and algorithmic approaches to infer the parameters of interest, and make heavy demands on computing resources. The proliferation of inexpensive, powerful, and intrinsically more reliable computing systems has added considerable impetus to these efforts. The availability of adequate computing power at the process level has led to remarkable improvements in the supervisory control of processes and in the ability to share information among processes through communication links and hierarchic networks.
On the economic side, the industry is facing increasing pressures to improve quality and productivity at a time when economic resources for modernization are especially limited.

There is a growing emphasis on quality, and on the requirement to monitor and control processing parameters which influence quality.

There is a relentless move towards combining processes to eliminate redundancies and handling which serve no discernible metallurgical purpose. Production facilities, product lines, plants, and companies are being subjected to similar scrutiny.

There is an ongoing, concerted effort to simplify and to rationalize product lines through the use of "generic" materials. The particular attributes required by the customer in the final material are developed by specialized and needless to say - intimately controlled processing in the latter stages of production.

MATERIALS CHARACTERIZATION & PROCESS CONTROL

These trends suggest a need to characterize and control more precisely than ever the parameters which can influence product quality and processing efficiencies:

Characterization involves a number of parameters which must be closely controlled to develop the attributes critical to the material end use. Those properties are the net result of a series of chemical, thermal, and mechanical processing steps aimed at the development of the appropriate microstructure, geometry, and surface characteristics.

Control is often tenuous because accurate, reliable and sufficiently rapid sensing systems are simply not available. The problem is further compounded by difficulties in adequately maintaining and calibrating equipment with limited accessibility in hostile environments.

THE GENERIC HOT CHARGING PROBLEM

These considerations influenced our approach to the hot charge problem. We sought to develop an integrated control system which would use information on the energy content of
slabs at charge, the furnace heating and pacing conditions, and the "rollability" of processed material. This system would employ algorithmic approaches to estimate slab temperature distributions in the furnace and seek to control firing conditions and pacing to match reheating and hot rolling process requirements. Our ideas were very definite and a natural extension of our earlier activities to optimize hot charging of ingot produced slabs.

**HOT CHARGING & DIRECT ROLLING OF INGOTS**

Both ingot and strand cast slabs must be processed at Middletown Works. Our original effort concentrated on improving ingot to slab yield. We developed a computer based Ingot Processing System to oversee the flow of material and information between the melt shops and the soaking pits (1). This system had at its heart a process model of the cooling and solidification processes in ingots between teeming into the mold and reaching a rollable condition in the soaking pits. This embedded model allowed purposeful shifts in operating practices, much earlier stripping times, and massive reductions in energy consumption and soaking pit residence times. That work culminated in the development of a Liquid Centre / Hot Centre Rolling (*) practice which fully utilized the latent and residual energy content in solidifying ingots. Concomitantly, this practice also improved yield and internal product quality.

The Liquid Centre and Hot Centre Rolling strategies also offered special advantages for direct rolling, incremental heating, and hot charging applications because excess energy persisted at the centres of the slabs for an extended time after slabbing. That energy, properly shepherded, could be used to reduce or eliminate the need for reheating before hot rolling. A few trials were completed at Middletown Works using this approach on "non-critical" items which could tolerate cold edges. No skid marks were present (naturally), and the finish mill could be accelerated (zoomed) to compensate for temperature "rundown" along the length of the bar; the apparent strip temperature - as measured along the strip centreline - was more uniform than that of conventionally produced slabs. Limited production use of direct rolling of non-critical
slabs was instituted without the requirement that these be necessarily Liquid Centre rolled.

For most ingot produced material, however, the requirements on temperature uniformity across the strip were more stringent than we could maintain without equipment modifications. We inserted some slabs into the exit end of a reheating furnace to redistribute the excess energy from the centre and reheat the colder edges. These trials showed that a holding furnace could be effective, but several would have to be built and modifications made to the hot strip mill scheduling. We determined that much of the benefit of direct rolling could be realized by a hot charging procedure which simply interjected slabs with significant residual energy and appropriate width into the normal cold slab production stream without modifying the pre-ordained hot strip mill schedule.

Hot connection was enhanced by scheduling a part of the melt shop production and controlling the flow of material into the slab yard. At first, manual expediting was used to select candidate slabs for hot charging; furnace firing rates were observed to decrease and enhanced productivity was anticipated. Hot charge incidence reached 30% of ingot slab production, but improvements beyond that level were problematic because the slab and strip mill schedules were not coordinated.

To justify modifications to the scheduling procedures we first had to demonstrate feasibility - which we were able to do -, and document the benefits - which we could not. The anticipated improvements in furnace efficiency and productivity attributable to opportunistic hot connection proved impossible to verify! Apparently, the furnace operator did not have sufficient information to take advantage of the sporadic hot connected slabs.

**SLAB REHEATING PROCESS CONTROL**

The recognition of this inherent limitation led to a concerted effort to develop a comprehensive approach to the control of the slab reheating and hot strip processes. Problems abounded in process monitoring and control; operational difficulties were often countered by modifying furnace firing. The objective was to ensure that hot slabs would be
available for rolling. Often, high heating rates were used to the detriment of slab quality and energy efficiency; the effect on energy usage was obscured because credit was allowed for the recovery of waste energy in the form of steam. This subterfuge meant that no benefit could be claimed for changes which conserved only fuel, because a comparable loss in steam credit would also result. Improvements in quality, yield, and throughput were the only viable objectives.

A body of knowledgeable individuals was recruited from both staff and operations to resolve these problems. Their mission was to improve performance and consistency, paving the way for the installation of the control system. If the operating conditions could be made more consistent the control problem would be simpler and fewer contingencies would need to be considered. This cooperative effort culminated in the development of a Slab Processing System operating in real-time and making use of in-process measurements and inferential models for the reheating and strip processing steps.

The overall material and data flow in this control scheme are diagrammed in Figure 1. The arrows represent information flows into and out of subsystems which transform that information. This diagram has been divided into slab reheating and hot rolling segments. Hot charging is accommodated by Module 1, which requires information on slab dimensions, chemistry, and temperature distribution at charge, furnace geometry, hot face temperatures and pacing rates. This module estimates the temperature profiles in the individual slabs at each point in the furnace, and projects the future pacing rates and furnace zone setpoints that would be required to heat the slabs to a specified "rollability". This specification includes any time-at-temperature soak requirements.

Module 2, in Figure 1, estimates the furnace hot face temperatures from the furnace thermocouple measurements, firing rates and the geometry of each zone of the furnace and passes that information to module 1. Module 7 dictates furnace firing and pacing rates using slab temperature profiles estimated by module 1 while accommodating policy constraints and delays and apprises an operator of his available options.
The associated hot rolling segment consists of several modules which project temperature distributions as the slab is converted to strip. These projections provide feedback to the reheating segment and targets for dynamically modifying of the reduction and cooling steps.

This approach has been used virtually without change in several plants on different product lines with varying chemistries, geometries, and metallurgical requirements. Those applications were on seamless pipe (since rationalized) and silicon and stainless steel processes.

**HOT CHARGE TEMPERATURE**

The Slab Processing System accommodates hot charging but needs an estimate of the slab temperature profile, average temperature or energy content at charge. The estimate does not have to be particularly accurate, but at no point would a measurement of surface temperature alone be sufficient because the slabs have varying degrees of scaling. At charge these slabs are subjected to a high pressure water spray which removes the accumulated surface debris; the surface temperature drops precipitously, then rebounds over the next several minutes.

Better marshalling of hot slabs, more efficient handling, quicker transfers, storage using heat retaining chambers and enclosures, and the gathering and processing of information on slab identity, location, and elapsed time at each step offer a partial solution. At Middletown Works, information on the identity and location of each slab is now available, and when combined with slab surface temperature measurements will provide a basis for estimating the energy content at charge needed by the Slab Processing System.

Conventional instrumentation combined with computer tracking and heat loss algorithms provide a means of estimating the energy content in hot slabs. Alternatively, one could employ a sensing system which measures the temperature distributions inside the slabs. Such information would augment or supplant tracking and estimating. The need for such a sensing device is well recognized in the industry and this hot charge problem is one of the target applications of an AISI collaborative
development effort. That work and the current plans for a demonstration site will be described below.

"ROLLABILITY"

"Rollability" describes the relative ease with which a workpiece can be deformed during a mechanical transformation. Typically, this might be monitored as a function of roll separation forces, reduction ratios, and grade during hot rolling. Rollability implies a minimum energy content, and suggests a temperature distribution with a specified maximum gradient. We routinely extend this concept to define a through thickness temperature distribution at certain points during processing. The slab processing system estimates rollability at charging, at the threshold of each furnace zone, at extraction, and at each significant rolling and cooling stage during hot rolling. These estimates are compared with the information on surface temperatures, mill motor power and extensometer readings, etc. Often, this information is noisy, not accurate, not complete, and not available in real-time. "Rollability" measurements in the furnace are recognized as important sensing needs.

HOT CONNECTING CONTINUOUS CAST SLABS

During the development and installation of the slab processing system, the manual expediting of ingot produced slabs for hot connection was augmented with communication and computer links and extended to include strand cast slabs. The impending phasing out of steel ingot production underscored the need to intensify hot charging of strand cast material. This was particularly a concern because the slab furnace throughput had benefited markedly from hot connection. As an interim rationalization of front end production facilities, lost ingot production would be compensated with either ingots or slabs transferred cold from a sister plant. The substitution of ingot produced slabs with a high probability of hot charging by cold slabs with none reduces the effective furnace heating capacities. This impairment can be redressed by revising "rollability" criteria and making hot connection of strand cast slabs more effective by:
- modifying caster operating practices to produce slabs with greater residual energy,
- modifying stacking and marshalling practices to conserve the residual energy content,
- expediting information transfer between melt shop and slab yard so that the full hot charge potential can be realized,
- upgrading furnace firing capacities,
- modifying scheduling strategies to more efficiently integrate hot charge slabs into the hot rolling stream.

Some of the problems of coordinating schedules between the melt shops and the hot strip mill can be alleviated by modifying equipment and practices in both facilities. Two overriding considerations in hot connecting strand cast slabs are the slab surface quality and the ability to adequately match the strict width schedules of the hot strip mill.

Strand caster quality control must ensure that defect-free slabs can be produced and carefully differentiate slabs in which defects may be found. Those slabs must be inspected and will lose any hot charge advantage. There are many approaches to monitoring and controlling the quality of strand cast material and these often rely on statistical process control approaches (2). The parameters of interest are inferred from production variables and other indirect indicators of the process dynamics.

Restricted scheduling by width is an attempt to counteract the excessive roll wear induced by the colder edges of the workpieces in the hot strip finishing mill. This wear has a detrimental effect on roll contour and strip geometry. Slab widths are generally scheduled from wide to narrow and the width pattern is repeated only after worn rolls have been replaced. The need to constrain widths restricts hot connection unless the production facilities can be appropriately coupled. For ingot produced material at Middletown Works, this restriction was mitigated by scheduling the soaking and slabbing processes to match the independent hot rolling schedules. The recent installation of variable width molds on the strand caster at Middletown will permit better scheduling. Although caster width changes are
made slowly and infrequently, variations in width in transition slabs present problems for pusher type furnaces. Modified hot rolling techniques such as side shifting work rolls, and heavy duty edging are alternatives which would require substantial capital investment and/or significant yield loss.

**STRAND CASTING PRODUCTIVITY ENHANCEMENTS**

Approximately 35% of all slabs are hot charged at the present time, including 35% of all strand cast slabs and 50-60% of ingot source slabs. For quality assurance reasons, transitions slabs and those produced outside statistical process control (SPC) bounds are set aside for hand scarifying and lose their residual energy content. The success rate on slabs originating as ingots from a sister plant can be greatly improved by maintaining an ingot inventory so that appropriate widths can be selected to meet the hot mill schedule width restrictions.

A direct approach to improved casting productivity would make use of the sensing methodology now being developed collaboratively by AISI member companies. That approach is to monitor temperature profiles in solidifying material to permit true optimization of the casting process and better productivity while maintaining slab quality standards. The energy benefit of the unsolidified hot centres could be preserved by delaying solidification as late as metallurgically feasible. The shape of the solidifying boundary could also be influenced to provide a more favorable energy distribution in the slabs destined for hot charging (3).

We will now turn to a discussion of the collaborative sensor development effort which is addressing some of these problem areas. We do not want to leave the impression that this has been solely an Armco development - it has been an industry development with a great deal of help from government laboratories and with government and industry funding.

**SENSING THE PROCESS: NEEDS AND SOLUTIONS**

It has long been recognized that the control of many industrial processes is being compromised by inadequate sensors. In 1979, the American Iron & Steel Institute (AISI) developed a comprehensive list of sensor needs. This list
included some which already existed but required further refinement, several for which the measurement principles had been demonstrated, and others for which the need could be stated, but the means were open to conjecture.

The common attribute was that none of these sensors were likely to become available without a substantial commitment to research and development. The economic incentives for an instrument manufacturer were somewhat limited - given the high risk potential and the specialized requirements of the end users. On the other hand the end users themselves, with a siege mentality and operating in a "survival mode", were unlikely to undertake any longer range developments. A strong case was made for collaboration; task groups were established with industry support to promote the development of specific high priority sensors. These groups took an active role in generating the financial support and coordinating the technical efforts and are the means by which this technology will be transferred to the industry.

I have already described to you several sensor needs in hot connecting and direct rolling strand cast slabs. Those needs included sensors which would:

- for the strand caster permit precise control of the solidification process to maximize the residual energy content and improve hot connection efficiency. Provided suitable rolling equipment are available this sensing approach would aid direct rolling applications;

- provide more precise estimates of the internal temperature distributions in slabs prior to reheating (or direct rolling). Such information would be used by slab processing control systems to optimize efficiency, throughput, and product quality in the charging, firing, and pacing of furnaces;

- provide "rollability" estimates during reheating on slabs inside the furnace, and at extraction;

- provide "rollability" estimates during hot rolling processes to correct the reheating control system and to dynamically modify rolling and cooling steps.
One of the AISI task units has been working towards the development of a sensor which can meet some of these needs. This device will determine the temperature distribution inside solid and solidifying hot bodies and it will make this determination in real-time and by non-contacting means. The system uses prior information on geometry, process routing and chemistry, and ancillary measurements if available on surface temperature, geometry, etc.

This is a collaborative research effort involving the active participation of eight different steel companies, the National Bureau of Standards (NBS), and Battelle's Pacific Northwest Laboratories (PNL) and has been funded by AISI through member contributions, the Department of Commerce and the Department of Energy.

The developmental effort has been coordinated by the on-site participation of AISI member companies at PNL through the DOE visiting scientist program, and at NBS by means of their research associate program.

THE NBS CONNECTION

The work at NBS has been a multi-faceted, exhaustive scientific endeavor (4). Both eddy current and ultrasonic methods have been shown effective in interrogating internal temperature distributions. The eddy current method depends on electrical resistivity and magnetic permeability, while the ultrasonic approach relies on elastic moduli and density.

The eddy current approach is well suited to aluminum and a collaborative effort with the Aluminum Association is now underway at NBS. The approach may also prove workable on steel products above the Curie temperature.

The work on steel at NBS relies primarily on ultrasonic methods, and has emphasized:

- the refinement of calibration data on the variation of ultrasonic velocity with temperature in various grades of steel,

- the experimental measurement of ultrasonic time-of-flight in cylindrical and rectangular bodies of steel to 800 Celsius.
the development of algorithms to reconstruct temperature distributions from such information,

- the investigation of a wide range of related technologies in EMAT (Electro-Magnetic Acoustic Transducer) design, signal processing, error propagation analyses, etc.,

- the investigation of uniquely innovative approaches using surface waves, and dimensional resonance.

Work is underway to understand the dependence of ultrasonic attenuation and dispersion on grain structure, solidification boundaries, and the mushy zone. The influence of varying solidification rates is being approached using an aluminum analogue. The boundary dynamics of a full repertoire of steel solidification structures from planar to dendritic can be simulated by adjusting the chemistry of an aluminum silicon melt injected into a hollow aluminum mold. Analogous behavior in steel alloys would then be projected from an intimate understanding of the behavior of ultrasound.

For austenitic steels, the variation of the longitudinal wave ultrasonic velocity with temperature turns out to be virtually linear, as shown in Figure 2. The corresponding dependences for ferritic steels are more complex and exhibit considerable hysteresis (Figure 3) at intermediate temperatures. This complexity occurs near the Curie temperature, and is influenced by the microstructure, grain size, grain orientation, defects, and porosity. The sensitivity to these solid state phenomena is a complication for the internal temperature sensor, but offers an avenue for continuing inquiry into fundamental metallurgical phenomena. The amount of hysteresis depends on cooling rate and is not expected to be a serious hindrance to sensing system accuracy.

The experimental arrangement for measuring temperature distributions in cylindrical samples is shown in Figure 4. A Nd:YAG LASER pulse impinging on the surface generates ultrasonic pulses which propagate through the material to be detected by an EMAT. Ultrasonic waveforms are digitized and stored for subsequent analyses and the extraction of time-of-flight data.
The arrangement for rectangular geometry is comparable (Figure 5). The LASER beam is rapidly scanned across one face while ultrasonic time-of-flight data are gathered using an array of receivers on the opposite face. The beam geometry is then rotated 90 degrees to scan the orthogonal face and data are acquired using a second array of receivers. The information, processed and stored, becomes a tomographic representation of the velocity of ultrasound within the sample. Calibration curves and algorithms describing the temperature fields are then invoked to reconstruct internal temperature distributions.

This experimental apparatus has been fully automated to allow the precise and rapid acquisition of data (5). Refinements in reconstructive algorithms are underway with particular emphasis on the inclusion of prior information and ancillary measurements. The progress on this sensing system has reached the point that the only impediment to the development of a practical instrument seems to be the temperature tolerance of the EMAT device.

DOE AND PNL INVOLVEMENT

The Department of Energy recognized this need and has been sponsoring a complementary program at Pacific Northwest Labs. That effort is concentrating on the engineering aspects with the intent of demonstrating a practical instrument in a steel mill environment. Recent effort has focused on the development of a simple, inexpensive EMAT receiver capable of both momentary and continuous application on real steel samples with surface temperatures in excess of 1300 C (6).

You will recognize that the EMAT is inherently a non-contacting device, but the distinction of non-contacting is arguable when distances of a few millimeters are involved. This lift-off distance is a very important consideration, particularly if one needs to overcome small surface irregularities and scaling phenomena.

The PNL EMAT design uses a pulsed current to generate the bias magnetic field, and is quite small and potentially inexpensive - possibly even a throwaway! The "breakthrough" technology is embedded in the control package and in the materials from which the EMAT is
constructed. Several versions have been tested and much refinement is likely. The device has been successfully applied to austenitic 304 stainless steel samples with surface temperatures in excess of 1300 C. The experiments used a ruby LASER with a pulse duration of 25 nanoseconds. Liftoff distances of more than 1 cm were demonstrated at room temperature. Similar results on ferritic low carbon 1018, and 4130 steels have been recorded to 800 C. Above this temperature, surface scaling on the samples blocked the relatively low power LASER source. This scaling occurred because the samples were heated slowly to elevated temperature using an underpowered furnace and inadequate cover gas.

PNL is now working to improve the EMAT design and the signal processing. They are attempting to replace the LASER source with an electromagnetic pulser. This pulser borrows much of the pulsed EMAT detector technology and may prove to be a very important contribution of this collaborative effort.

TEST AND DEMONSTRATION SITE

Our AISI sensor task unit is proposing to design and operate a test and demonstration site in an actual steel plant. This testing is a necessary step in the refinement of the technical approaches, particularly for materials with unsolidified centres. Experimentally producing test specimens with unsolidified portions approaching that found in practice is a difficult and expensive proposition. NBS is approaching this problem using aluminum analogues and extrapolating the results to steel. Simply "piggybacking" a prototype device on an industrial process will avoid the need to create synthetic samples and allow us to immediately address mill environment issues which are critical to the ultimate acceptance of the sensing approach. This approach is one of expediency and will not begin to address the fundamental questions which the NBS approach is intended to answer. The objectives are to provide:

- a test site to scrutinize the effectiveness of the selected technology in a real steel mill application,
- a means of capturing suitable "real" data for further analyses and refinement of signal processing and reconstructive approaches,
- a focal point for the integration of appropriate technology from NBS, PNL, AISI members, and various consultants,
- a resource site which can provide continuity for future related investigations,
- a demonstration site for refining prototype systems which integrate portions of the development.

After much consideration of alternative sites, the Task Unit is proposing to install a test and demonstration facility on a commercial horizontal continuous caster at the Specialty Metals Division plant of ARMCO, Inc. located in Baltimore, Maryland.

The demonstration aspects will complete our commitment to select and oversee the evolution of this sensing methodology. Our motivation was to complete the scientific and developmental tasks and show that the approach could be viable. We would like nothing better than to transfer this technology to an organization which would complete the product development and market a package suitable for our needs. The economic incentives are phenomenal, and the technology can be made available to appropriate partners. We are actively looking for partners to fully commercialize the results of this collaborative effort.

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REFERENCES

(*) Hot Centre Rolling is a registered trade mark of ARMCO, Inc.


5. R. Heinrick, One On One Designs

ULTRASONIC VELOCITY/ms$^{-1}$

HEATING
COOLING

SLOPE = -0.68ms$^{-1}$°C$^{-1}$

TEMPERATURE/°C

MATERIAL
304 STAINLESS STEEL

ELEMENT
C Mn Si Cr Ni Mo

wt% 0.066 1.56 1.02 18.1 8.9 0.14
FIGURES

FIGURE 1: Data flow diagram for slab processing system at Middletown Works (Armco, Inc.). System has been separated into reheating and hot rolling segments and accommodates hot charge but requires estimate of initial charge temperature.

FIGURE 2: Dependence of longitudinal ultrasonic velocity on temperature for austenitic material (courtesy of NBS). Note extreme linearity.

FIGURE 3: Dependence of longitudinal ultrasonic velocity on temperature for ferritic materials (courtesy of NBS). Note complexity near Curie Temperature and hysteresis (see text for explanation).

FIGURE 4: Experimental configuration for cylindrical samples showing Nd:YAG Laser source, EMAT receiver (courtesy of NBS).

FIGURE 5: Experimental configuration for rectangular geometry showing scanning Nd:YAG Laser source and EMAT receiver. Two independent sets of receivers are used on orthogonal faces of sample (courtesy of NBS).