THE HISTORY OF THE
RESEARCH DEPARTMENT
OF
BETHLEHEM STEEL CORPORATION

PART 3
1983 TO 2003

Produced and Edited by Kenneth L. Stott, Ph.D. and Francis J. Vasko, Ph.D.

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FORWARD

By Kenneth L. Stott and Francis J. Vasko

First and foremost, we want to congratulate and thank Roger L. Whiteley for producing and editing Volumes 1 and 2 of The History of the Research Department of Bethlehem Steel Corporation (BSC) covering the years 1926-1982. These editors were honored when Roger asked us to produce and edit Volume 3. What Roger stated in Volume 2 is also true of Volume 3, namely, that the contributions in Volume 3 are taken from the records and memories of former BSC researchers. Volume 3 reports on BSC research activities during the time period 1983-2003. This volume consists of two main parts. Part One provides an overview of the major categories of Homer Research Laboratories (HRL) activities—a total of eight categories. Part Two provides descriptions of specific significant project accomplishments—27 articles in all. As will be mentioned in the Introduction by Robert W. Bouman, it was not possible, for several reasons, to detail all the great work done at HRL from 1983 to 2003. However, with the unselfish efforts of the 38 contributors, many of the important HRL accomplishments from 1983 to 2003 are documented in this volume. As you read the descriptions of the various projects, it is important to note that many of the results discussed are still having a very positive impact on the steel industry.

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The editors wish to express their sincere gratitude to all the contributors and thanks also to Richard Woodyatt and Minuteman Press, Bethlehem, PA, for printing this volume,

Ken Stott and Fran Vasko

INTRODUCTION

By Robert W. Bouman

The reorganization of the Research Department in 1982 was a major change. Don Blickwede was retiring and the new director Ed Kottcamp made many changes in the organization structure and personnel. In addition, the Homer Research Laboratory (HRL) mission was changed entirely to support the plants in reducing costs and improving product quality, and our clients in the plants would score the HRL efforts. These were appropriate changes in light of Bethlehem's loss of $1.5 billion in 1982. The newly appointed program managers had the assignment of determining with the plants the most important areas for HRL help. The division managers, program managers and plant technology managers then decided on the goals for the final plan. This cooperative planning with the plants continued to be used for the following years.

The outlook for Bethlehem was not good, mostly because of the rise of mini mills that were producing low-cost steel with scrap and electric arc furnaces. In fact, the Johnstown, Lackawanna and Bethlehem plants would be closed before 2000. There were 67,000 employees in 1982 and this was reduced to 15,000 by 2000, and the cost of pensions and health care for the retired employees was a major financial problem for BSC.

In spite of the poor business outlook, HRL supervisors, engineers and technicians answered the challenges to reduce costs and improved product quality as described in the attached write-ups. These accomplishments were much appreciated by our clients in the plants. In addition, there were many other successful projects that have not been documented mostly because those that did the work are no longer with us.

One of the undocumented efforts was what Dan Kwasnoski did to test granular coal injection in the Burns Harbor blast furnaces. Dan and John Lovis in the engineering department responded to a Department of Energy request-for-proposals to increase the use of coal in industry. They were successful and BSC was awarded a DOE contract to build and test a granular coal injection facility at Burns Harbor. Dan guided the design of the facility, monitored the construction and handled all the DOE reporting requirements. The testing of granular coal injection was totally successful and resulted in record low coke rates and lower hot metal costs at Burns Harbor. Unfortunately, Dan did not get to see the coal injection facility in operation because he and his wife Caroline died in a plane crash while returning from a DOE conference where he reported on the project status.

Another undocumented project was the development and implementation of Turbostop impact pads in the tundish vessel between the steel ladle and caster mold. The impact pads improved steel flow in the tundish and reduced non-metallic inclusions in the cast slabs and, thereby, improved steel quality. The Turbostop pads were developed and refined by Manfred Schmidt and Scot Newman using the water modeling equipment in the C Building melt shop. Manfred and Scot were awarded a patent for Turbostop and this produced significant income as a result of licensing other steel companies.

Even with the Homer Research Laboratories successes in improving steel quality and reducing costs, Bethlehem failed. The International Steel Group (ISG) bought BSC out of bankruptcy in 2003 and ISG became part of the Arcelor Mittal steel conglomerate in 2006. The remaining HRL buildings were sold to Lehigh University and some of the HRL staff moved to Mittal’s operation in Indiana.

Those that worked through the final years at HRL can be proud of their accomplishments, and Volume 3 is a tribute to their hard work, diligence and inventive spirit.

Many thanks to Ken Stott and Fran Vasko for making Volume 3 happen.

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PART 1: OVERVIEW OF MAJOR CATEGORIES OF HRL RESEARCH

SYSTEMS ANALYSIS GROUP 1983-2003

By Kenneth L. Stott

The Systems Analysis Group (SAG) applied engineering, mathematics, and computer science to solve real-world problems for more than 35 years. The Group was made up of about 12 to 14 people that included an approximate balance of engineers and analysts. SAG conducted applied research and development programs using new and innovative approaches to solve decision-making problems for business and technical processes. The work of SAG can best be described as using state-of-the-art technology and solution procedures to maximize the use of available resources to increase profitability without incurring additional costs.

When presented with a problem, the Group first brought structure and a systems approach to defining the problem. As needed, they conducted research to develop new mathematical techniques or algorithms to efficiently solve the problem. History has shown that working closely with the client was vital for the project's success. The Group provided computer systems that are either optimization modules integrated into information systems or stand-alone decision support or expert systems requiring computer software and hardware. The Systems Analysis Group also conducted design studies to determine the best strategy among the various alternatives. These studies had a significant effect on facility design and capital decisions.

Using Combinatorial Optimization

Many Applications in production and operations management are known as combinatorial optimization problems which mean trying to find the best possible solution from many combinations of solutions. The Group developed and published several solution approaches that generated quick and efficient solutions. For example, a seven-day schedule was produced for Sparrows Point's casters that balanced a large number of operating, production scheduling, quality assurance and customer service goals.

Working with Fuzzy Sets

Fuzzy set concepts were used to work with the vagueness of real-world problems. While classical mathematics require that classes of objects must have sharp boundaries, meaning an object is either in the class or not; fuzzy set concepts allowed the object to have a "degree of membership" in the class. The Group applied a fuzzy approach to optimal metallurgical grade assignment. The solution procedure selected the best set of steel grades in a manner that minimizes the number of grades needed to satisfy all orders on-hand and their individual specifications.

Creating Expert Systems

Expert Systems are a type of programing language that embodies the expert's knowledge and experience to solve narrowly focused, but yet complex problems. Expert Systems technology can be applied in both diagnostic and monitoring situations as well as to certain planning and scheduling contexts. Diagnostic applications helped reduce the time needed to pinpoint the cause and to remedy breakdowns in mill motor controllers at the Structural Products Division. A system was designed that improved the consistency of rail shape dimensions at Steelton. These expert systems were developed using IF/THEN logic rules to represent an expert’s known facts and judgment.

To summarize, The Systems Analysis Group’s early work progressed to the point where it helped with “decision-making” skills necessary to solve business and technical problems. Initially, most problems to be solved were proposed by the clients but as the Group and its work matured they was able to identify and suggest problems to be worked on. Throughout the years the SAG continued to grow and was able to keep pace with new technology as it became available.

COKEMAKING, CONTINUOUS CASTING, IRONMAKING AND REFRACTORIES RESEARCH 1997-2003

By Trevor Shellhammer

The subgroups in this part of Primary Process Research changed a few times over this period. It was a large group, at times Ironmaking & Refractories, Cokemaking Refractories, and Continuous Casting & Refractories. The makeup of technicians, engineers and consultants therefore also changed periodically. Key facilities at Homer Research Laboratory (HRL) included the Refractory Lab in building C-3, and what became a water modeling area in C-1. Notable project work is listed below; this is not meant to be a complete list.

Cokemaking

General Support - Bethlehem Steel ceased operation of coke oven batteries at Sparrows Point in the early 1990's, Bethlehem in 1998, and Lackawanna in 2001. The remaining two coke oven batteries were at Burns Harbor. Research work in cokemaking included support for the Burns Harbor operation. This included periodic testing of current and new coals for cokemaking and development of specifications for same, contracting tests at outside test ovens to evaluate coal blends, evaluation of internal coke properties and specifications and as well as other technical support to Burns Harbor. In addition, a major accomplishment, in conjunction with the Systems Analysis Group, was the development of a coal blending model.

Calderon Cokemaking – Bethlehem and LTV Steel were the steel company partners in a project using proprietary technology pioneered by Calderon Energy Company called Calderon Cokemaking. A demonstration plant was built and operated in Alliance, Ohio with assistance from research engineers and technicians. In 2000, engineering was going forward for a $40 M full-scale plant proposed in Cleveland at a former LTV coke plant site. Research investigated the manufacture of the special silicon carbide shapes for the oven body at a refractory supplier in Brazil, but the project was stopped, and the coke plant never materialized.

Burns Harbor Coke Battery Evaluation – Research assisted with the engineering evaluation of a newly rebuilt coke battery that was experiencing signs of premature degradation. Surveys of the battery structure made over time were showing elevation changes and wall movement that were unexpected in new construction and Bethlehem's position was that the contractors had made mistakes in construction and/or commissioning. The contractors insisted this was a normal occurrence. In August 2000, to prove Bethlehem's claim, Research and Home Office engineering supervised the dissection of one of the ovens at the Bethlehem plant A battery. This battery was shut down in 1998 after many years in operation. The result was that this battery was of similar construction and did not exhibit any of the anomalies of the much newer Burns Harbor battery. A settlement was eventually made in Bethlehem's favor.

Continuous Casting

Major projects at Burns Harbor included: support for Steelmaking to transition from a combination of continuous cast and ingot pouring, to 100% continuous casting; the effect of caster operation on slivers; slab cracking and slab quality. These efforts made process improvements in areas of roll life, increased casting speeds, new mold powders, basic tundish flux, improved tundish life and cast sequences, alumina plugging of submerged entry nozzles, dolomitic tundish nozzles, dolomitic submerged entry nozzles, submerged SEN changes, development of tundish mixing models for improved grade changes and reduction of downgraded slabs.

At Sparrows Point, casting work included: 104” wide caster assistance to the plant and Voest Alpine (data collection and analysis, secondary cooling, smart segments and soft reduction improvement); laser-based slab measurement system; implementation of the HRL slab transition model; study of laminations and slivers on D & I grade steels.

In 1987, a unique tundish refractory furniture invention was patented by Manfred Schmidt & Theodore W. Fenicle and named the “Turbo Stop” impact pad. This refractory pad continued to receive royalties from steel suppliers throughout this period and was used at Burns Harbor, Sparrows Point, and Steelton as well as other steel companies. Several projects at the Bethlehem Steel plants included improving steel quality and yield with the use of the Turbo Stop impact pad.

The group provided general support for Steelton’s jumbo bloom caster and Coatesville’s slab caster as requested. Beginning in 2003, support was also added to the Cleveland and Indiana Harbor casters.

Ironmaking

Blast Furnace Stack Lining Wear Measurement – The Refractory Wear Monitor technology used to measure refractory thickness in the stack, patented by HRL in 1980 (Robert A. Strimple, Joseph E. Snyder, Bruce F. Shoemaker), was used throughout this period at all blast furnaces with Research support. With the 2003 addition of former LTV plants in the International Steel Group, the technology was transferred and successfully implemented at both C5 and C6 blast furnaces at ISG Cleveland. The use of radioactive isotopes was also used to measure refractory lining thickness but was discontinued at Sparrows Point L blast furnace with the 1999 reline seeing all remaining isotopes removed by Research personnel. The same isotope removal was planned for Burns Harbor C and D furnaces.

Burns Harbor Tuyere Life Improvement – The closure of the Bethlehem plant’s copper foundry in 1995 resulted in Burns Harbor using an alternate tuyere supplier. When tuyere life dropped from in excess of 1.5 years to only 2 months, this led to a detailed investigation by Research to find the cause and solution. Both new and failed tuyeres were examined, and suppliers were audited. Research into copper quality and specifications, internal water flow, and tuyere coatings was performed. In 1997, a water modeling facility was built using flow test pump system salvaged from the Bethlehem plant foundry and modified by the Research machine shop. A unique apparatus was used to inject plastic beads into the water flow. This bead injector had been built for some previous projects at HRL investigating water flow in blast furnace cooling plates in the 1980’s. That work led to a patent on cooling plate design in 1983 (William E. Gheen, Millet L. Wei). A physical tuyere model was built and tested with this system, tuyere design changes were made, and flow tested. The final work dealt with protective tuyere coatings. Several coatings were evaluated, and a recommendation made. The project resulted in Burns Harbor changing tuyere suppliers, modifying tuyere design, and specifying a coating selected by Research. The end result of the work was successful and Burns Harbor tuyere life returned to match and exceeded its historical average, with tuyeres achieving record life of over 1500 days. Research followed up with a similar project in 2004 at Indiana Harbor blast furnaces.

Burns Harbor Coal Injection – This was a demonstration project co-funded by the Department of Energy to use a particular coal type to replace a portion of the coke used as fuel in the furnace. The system proposed would use granular coal injection (GCI) instead of the powdered coal injection (PCI) that was used at most furnaces that were injecting coal. The goal was to prove the technology was practical and economical. Research provided support during the planning, evaluation and final reporting which was issued in November 1999. The project was very successful and showed substantial benefits to Burns Harbor and the steel industry.

Iron Ore – As Bethlehem Steel was a majority owner of Hibbing Taconite, Research supported Burns Harbor as Hibbing's major iron ore customer by reviewing periodic reports of ore properties and attending quarterly quality reviews with the mine manager, Cleveland Cliffs, at the Hibbing mine in MN, the dock in Duluth, the Burns Harbor plant, or Cliff's headquarters.

A research project at Hibbing involved beneficial reuse of Burns Harbor's blast furnace sludge from wastewater treatment. The sludge contained appreciable amounts of iron and carbon, and the plant had accumulated a significant amount of this material. Trials were conducted at the Hibbing research facility in 1998 to see if pellets containing a percentage of sludge byproduct could be made. Hibbing and Bethlehem research personnel were successful in making batches of green pellets containing recycled sludge and fire them in the laboratory pot grate furnace. While making the pellets was possible, Burns Harbor decided the pellet properties were inferior to Hibbing's regular acid pellets and the project was closed.

Refractories

The Refractory Research group included several technicians working in Building C-3 where the refractory lab was located. These technicians performed testing on samples sent from the plants or refractory suppliers, as directed by the engineers in the group. They also performed work in the plants. The Refractory group supported corporate purchasing in their strategic sourcing efforts with refractory suppliers and different materials. The group was involved in many projects in the plants involving material evaluation and plant testing. They also supported blast furnace relines and lining measurement previously listed. In addition to relines, beginning in 2003, support was provided to regular shotcrete repairs at Cleveland C-5 and C-6 blast furnaces. The furnaces were taken down for repair approximately every 18 months, and research personnel monitored the actual mixing and application of refractory for uniformity, as well as assisted in the installation of new refractory wear monitors in the stack.

The Refractory group was involved in evaluation of refractory in many areas: furnace and ladle brick, in both iron and steelmaking; monolithic castable linings; materials for Steelton's DC EAF bottom and sidewalls; tundish linings and practices, manual vs robotic spraying; slab reheat furnace linings; coke oven refractory and end wall repairs; caster consumables such as nozzles, ladle shrouds, SEN's, flow control systems (both stopper rod and slide gates systems). With slag splashing extending BOF lining life, Research tracked furnace life and refractory consumption.

Miscellaneous

Water Modeling – This is a generic category to cover water modeling work. For the most part, water modeling was performed during this time in C-1. The tuyere flow test work was already discussed.

A ½ scale model of the Sparrows Point wide caster was constructed in C-1 and it was used to test various operating conditions and grade mixing trials.

A full-scale tundish was also built. This was a single strand tundish obtained from National Steel research in Ecorse, MI. They closed the research lab after being acquired by U. S. Steel. The 30-ton tundish was refurbished and used for several projects.

A full-scale tundish slide gate system was built in Plexiglas and used to observe flow under various configurations of gate design and flow.

The pump system built for the tuyere modeling project included an accurate magnetic flow meter, and the unit was portable, so it was available for other projects. It was moved outside to test a spray header and nozzles for rolling mill project.

Water modeling was backed up with computer modeling using computational fluid dynamics, CFD. However, the computer system and software program (Fluent) were both outdated and the software version was no longer supported or licensed. New computer hardware was purchased along with new modeling software by CFX. Engineers were trained in the program and many different uses were found for the new system: lance stirring at ladle met; vacuum degasser steel flow; tundish, SEN, and caster mold flow; tuyere and tuyere cooler water flow, to name a few. The hardware and software were transferred to Mittal's East Chicago Research.

The group participated in many collaborative efforts with other companies, academia and technical societies. Some included:

Carnegie Mellon University's CISR - Center for Iron and Steelmaking Research (CISR)

Pohang Iron & Steel Co (South Korea) research exchanges – researchers hosted visits in Bethlehem, Sparrows Point, and South Korea, 2001 & 2002.

U.S. Steel research partnership – Splash testing copper coatings; caster oscillation studies

Bethlehem Steel's representative on AISI ironmaking & Continuous Casting Technical Committees

AISI & University of Missouri-Rolla project: Steelmaking Nozzles that Resist Clogging - 2001

Gatekeeper for technology on Alternative Ironmaking

Some of the key Refractory Lab equipment was relocated to East Chicago with the consolidation of research facilities with Mittal Steel in 2005/2006. Similarly, some of the unique water modeling equipment and models also relocated to East Chicago, where they continued to be used.

COLD ROLLED &
LIGHT FLAT ROLLED PRODUCTS 1989-2003

By Keith A. Taylor

Personnel

In 1989, the Homer Research Laboratories (HRL) "Cold Rolled Sheet Development" (CRSD) group was created within John Chilton's Steel Products Division. John Speer became the first CRSD Supervisor and by 1990 had a staff that included a Senior Engineer (Roger Pradhan), three Engineers (Adel Bastawros, Carl VanKuren and Kavesary "KS" Raghavan) and three Analysts (Harold Held, Jim Layland, and Tony Sfarra). John Speer left the company in 1997 for a faculty position at the Colorado School of Mines (where he still is today) and Keith Taylor was promoted to Supervisor. Tin Mill products were added to the group's scope around the year 2000. In 2001, hot rolled sheet was also included within the group's scope, and the group became the Light Flat Rolled Products (LFRP) group. Shortly after Keith became Supervisor, he recruited Todd Nelson, a former BethForge metallurgist who had left Bethlehem Steel for a position at the Ingersoll Rand Materials Technology Center. He later also recruited John Wise, a post doc at the Colorado School of Mines, and John Dong, a lubrication engineer. At its peak, the LFRP group had a staff of twelve.

Facilities

The group maintained three labs: the A2LA-accredited Mechanical Testing Lab managed by Rick Fraley, the Formability Lab managed by Jim Layland and The Lubrication Lab managed by Bernie Bast and, after his retirement in 2000, by John Dong. The Lubrication Lab constantly analyzed process fluid samples from the plants and from vendors to verify that their characteristics were within specified ranges. The LFRP group also had some other specialized capabilities that included surface texture characterization by optical profilometry (Adel was the expert) and metal forming simulation using LS-DYNA finite element analysis (KS was the expert).

Activities

The Light Flat Rolled Products (LFRP) group's principal activities included sheet product development (hot rolled, cold rolled and coated product substrate), automotive sheet-product qualifications, customer technical support, internal technical support and training classes, and collaborative projects with R&D departments from other steel companies such as US Steel and Pohang Iron & Steel Co(South Korea). Just a few examples of activities in these different focus areas follow. *Product Development* – The group supported the development of many cold rolled and coated sheet products, including interstitial free steels, bake-hardenable steels and dual phase steels. A noteworthy achievement during the 1990s was the development, patenting and customer-qualification of a bake-hardenable, hot-dip coated sheet product suitable for exposed autobody panels. This product was quickly adopted by Chrysler who used it for more dent-resistant galvannealed door outers for the Dodge Durango SUV. That business came about largely because of the very good relationship Detroit Automotive Applications and Homer Research Laboratory (HRL) had with the Chrysler Tech Center body engineers that were under Paul Belanger. However, Burns Harbor was not so enamored with this product as it required very close control of carbon content. *Automotive Sheet Qualifications* - The 1990s and 2000s was a period in which the automotive industry really began to embrace the use of so-called "advanced high strength steels" (AHSS) in their designs, mainly for weight savings and better crash performance. This period was also a time when the car companies were creating new specifications or revising existing specifications to cover the new AHSS. The LFRP group and Roger Pradhan in particular were actively engaged with the automotive sheet engineers and always on top of the specification developments. Roger had an especially good relationship with the GM Sheet Metal Specialists Team led by Curt Horvath. Roger's connections and metallurgical expertise were very beneficial for ensuring that Bethlehem had a high level of technical awareness of customer sheet requirements and could be competitive and meet these new product requirements. Jim Layland maintained the "Property Reporting System" (PRS), a database of HRL testing results on samples mainly of automotive sheet products. The PRS provided useful and fairly extensive product information for product qualifications, part tryouts and forming simulations. The PRS was used frequently by Hank Darlington and his Automotive Applications engineers for such purposes. Many of the PRS samples came from a Kalamazoo, MI warehouse where a large amount of Bethlehem's automotive sheet was staged. Layland and colleague Harold Held would cut test coupons from the samples and route them to the appropriate HRL lab for testing and analysis. Jim compiled all lab results and issued annual summaries. *Internal Technical Support* – Sheet formability and annealing were among the many training programs developed by the LFRP group. We offered a multi-session, several-day batch annealing class in January 2000 at the then new Cold Mill Complex at Sparrows Point. A big snowstorm hit that week and we had some classes in which only a few hearty students attended. Conrad Diem became our expert on annealing technology. Conrad organized periodic "roundtable" meetings in which Operations folks from the plant annealing facilities would come together and share information and experiences on selected topics. These roundtables received great reviews from the participants. Roger Pradhan was an active member of the Burns Harbor hot rolled and cold rolled grade development teams. Roger's expertise in sheet metallurgy was highly leveraged by these teams. LFRP members were on various teams that came about to address specific quality issues in the plants. Examples include surface carbide and "soot" issues with batch-annealed sheet, EG blistering, white rust, cold mill rust and pit marks, anneal stain, temper mill stain, "smear coat" at Lackawanna, etc. *Customer Technical Support* – Cly-Del Manufacturing Co. was a customer located in Waterbury, CT that used thin-gauge Tin Mill blackplate produced at Sparrows Point for deep-drawn alkaline battery casings. Cly-Del had an unusual (for a tinplate application) requirement that grain elongation be minimal. Their experience was that when grain shape anisotropy was excessive, the deep-drawn casings would develop wrinkles at the casing mouth, which would cause problems with proper sealing of the finished battery and increased potential for acid leakage. Michael Amann, Metallurgical Engineer in the Tin Mill, enlisted the technical assistance of Dipak Shah and Keith Taylor to work with the customer and build confidence that Sparrows Point product would perform satisfactorily in their application. Requirements for a "controlled grain elongation" product were developed. Visits to Cly-Del's production facility were made and trials were followed. We established a good relationship with Cly-Del and our product performed well for them.

The Six Sigma method for process improvement was being widely adopted by companies in the 1990s and 2000s, and Bethlehem was no exception. A number of HRL engineers received Six Sigma Black Belt training, including KS Raghavan and Adel Bastawros. When the "Dot Com" bubble was rapidly expanding in the 1999-2000 timeframe, a number of engineers left HRL for positions at Agere Systems in Allentown. Agere was a Lucent Technologies spinoff that made integrated circuit components and was enjoying booming business. Six Sigma Black Belts seemed to be among the more likely to make the move to Agere, and Adel Bastawros was among them. Of course, the Dot Com bubble burst and Agere fell very quickly on hard times. Most, if not all, of those former HRL engineers had to find new jobs.

The Cold Rolled Sheet Development and Light Flat Rolled Products engineers were active in numerous professional organizations, regularly attending conferences and presenting papers. Roger Pradhan organized or co-organized several major conferences on sheet product metallurgy that drew international participation and resulted in the publication of proceedings books. Keith Taylor was active in ASTM, chairing subcommittee A01.19 on steel sheet and strip. He became the Bethlehem corporate representative to ASTM when Don Mongeon, General Manager of Quality, retired around year 2000.

Cold Rolled Sheet Development & Light Flat Rolled Products
Staff Members 1989-2003

Name	Position	Last Known Employer
Adel Bastawros	Engineer	SABIC Innovative Plastics
Anthony Sfarra	Analyst	?
Bernard Bast	Engineer	Retired from Bethlehem
Conrad Diem	Engineer	Ames Advanced Materials Corp.
Dipak Shah	Fellow	Retired from Bethlehem
Frank Donchez	Analyst	Retired from Bethlehem
Harold Held	Analyst	?
Harold Ambrose	Analyst	Retired from Bethlehem
James Layland	Analyst	?
John Dong	Engineer	SONGWON Industrial Group
John Hlubik	Analyst	Retired from Bethlehem
John Speer	Supervisor	Colorado School of Mines
John Wise	Engineer	U.S. Nuclear Regulatory Commission
Kavesary Raghavan	Engineer	o9 Solutions, Inc.
Keith Taylor	Engineer and Supervisor	SSAB Americas
Paul Bright	Analyst	?
R. Carlton VanKuren	Engineer	Retired from Bethlehem
Roger Pradhan	Fellow	Retired from ArcelorMittal

HOT-ROLLED PRODUCT DEVELOPMENT 1996-2001

By Richard L. Bodnar

This group consisted of 16 people (5 engineers and 11 analysts), excluding the supervisor. The group was responsible for 12 projects and 4 laboratories. The projects were largely associated with the improvement of existing products and the development of new products in the areas of plate, linepipe, hot-rolled sheet, and rail. The four laboratories included: Pilot Plant Hot and Cold Rolling Mills, Electron Microscopes (including SEM, EMPA, TEM, and STEM), Heat Treatment, and Quenching and Deformation Dilatometer. Some of the new plate and hot-rolled sheet products that the group developed included: a multi-purpose, as-rolled structural steel known as T-Star® (ASTM A36/A572-Grades 42 & 50); controlled rolled ASTM A709-Grade HPS 70W; accelerated cooled ASTM A709-Grade HPS 70W, ASTM A572-Grade 65, ASTM A871-65, ASTM A656-Grade 70, and API 5L X65 and X70; a laser cutting friendly steel called LASEReady™; 100 ksi (laboratory only), more castable 80 ksi, and cobble-resistant 50 ksi V steel hot rolled sheet products; and a quenched and tempered API 2Y-60 offshore grade with an excellent balance of strength and toughness. The group was also successful in procuring a new Amray 3200/C ECO SEM.

Two of the group's largest contributions were providing technical support in procuring and successfully producing a 30,000 ton order for the Amerada-Hess offshore platform; and a 47,000 ton API 5L X70 linepipe order for the Cantarell project in Mexico. The Amerada-Hess order was significant in that it was the first time that Bethlehem Steel supplied the API 2Y-60 product. The X70 linepipe order was significant in that it was the first time that Bethlehem Steel supplied plate for sour-gas service pipe, and it was the thickest (0.875") X70 plate product ever supplied by Bethlehem Steel. This X70 order required a special steel composition, known as a "High-Temperature-Processing" (HTP) steel, and it consisted of 0.03% C - 0.09% Nb + Cu-Ni-Cr-Ti. A third major contribution was the technical assistance in the start-up and commissioning of a new accelerated cooling unit (ADCO®) at Burns Harbor.

Some of Rick Bodnar's individual accomplishments in this position were in providing leadership in Bethlehem Steel's gatekeeper efforts in the plate and hot-rolled sheet areas, as well as monitoring and supporting plate projects at the Colorado School of Mines (CSM) Advanced Steel Processing and Products Research Center. As part of the gatekeeper effort, he planned, organized, and executed a three-week trip through Europe visiting 5 plate mills, two hot strip mills, and five industrial research centers. The main objective of the trip was to learn more about accelerated cooled plate products and laser cutting friendly steel products. He also organized a successful one-week trip to Houston to visit oil companies, fabricators, and engineering firms to learn about future needs for high-strength steels for offshore platforms. His interactions with students at the CSM resulted in an improved understanding of ferritic rolling, accelerated cooling, and reheat cracking, and he was successful in attracting three excellent students for employment at Bethlehem Steel. He also provided substantial technical input to help settle a lawsuit against Bethlehem involving steel moment frames (containing heavy column structural sections) which failed in the Northridge Earthquake.

PRODUCT DEVELOPMENT AND CUSTOMER TECHNICAL SUPPORT 2001-2003

By Richard L. Bodnar

This group consisted of 14 people (7 engineers and 7 analysts), excluding the supervisor. The group was responsible for 11 projects and 7 laboratories. The projects were largely associated with the improvement of existing products and the development of new products in the areas of plate, linepipe, and rail, as well as providing customer technical support in the areas of design analysis, fatigue and fracture, thermal cutting, and welding. The seven laboratories included: Pilot Plant Hot and Cold Rolling Mills, Light Microscopy, X-ray, Electron Microscopy (including SEM and EMPA), Heat Treatment, Fatigue and Fracture, and Welding.

HOT- DIP COATED SHEET PRODUCTS 1990-2005

By Theresa C. Simpson

The Hot-Dip Coated Sheet Products team in the 1990's and early 2000's consisted of 10-14 scientists with varied backgrounds in Metallurgy, Chemical Engineering, Electrochemistry and other Physical Sciences. The team had a broad range of focus to support existing products as well as develop new products to meet the demand of the Automotive and Metal Building industries. Facilities within Homer Research Laboratory (HRL) consisted of basic laboratory equipment, but also a Hot-Dip coating pilot line, a Hot-Dip simulator as well as a variety of corrosion and other performance testing equipment. The team provided direct support to new and existing hot-dip coating lines to ensure that production conditions closely matched those that were simulated in the laboratory. The team further worked to convert an existing Electrogalvanized line at Columbus Coatings Company to a new hot-dip coating line aimed at producing exposed quality product for the automotive industry. In addition, a line at the Cleveland coatings facility was converted to produce exposed quality hot-dip galvanized, a novel product for the automotive industry.

During this time new products were also developed by the team including the patented product SLEEK which was a stainless steel look alike that could be used for the appliance industry. In addition to direct support to Bethlehem's production facilities, this team worked with roll-formers, phosphate suppliers, and paint companies to ensure that the processes used downstream would result in optimal conditions for the use of Bethlehem products. Optimizing bend radii and roll forming practice was critical for successful performance of Galvalume on roll formed panels. Phosphate bath chemistry and practices had a significant impact on the painted corrosion performance of Galvanneal coated sheet products. The teams were trained in Six Sigma methodology in the early 2000's and used these practices to mistake-proof the production practices and achieve the most appropriate conditions. This team was responsible for Automotive qualifications of the new products within the Bethlehem facilities and worked with the Society of Automotive Engineers and ASTM to ensure that testing practices would yield meaningful results that would match in-service experiences. During this time the laboratory facilities achieved accreditation by GM to the ISO-Guide 25 and began employing Stage Gate methodology to ensure consistent product development practices and methodologies. Many of the facilities that this team worked on are still operational today and continue to benefit from the research performed by this small team at HRL.

COLD ROLLED & COATED SHEET PROCESS DEVELOPMENT

By Hal A. Long

Introduction

This report highlights research work conducted at Homer Research Laboratories (HRL) by Finishing Instrumentation and Process Group**,** actually a succession of groups that worked in process control, process instrumentation, product measurement, plate rolling, hot rolling, cold rolling, and galvanize coating lines from early 1980s to the end of Bethlehem Steel in 2003.

The work of the group fell into three main areas:

1. Development of advanced instrumentation to measure product or process attributes in real time on the process lines or rolling mills. The measurements were primarily for product quality assurance and control and for real time process control.
2. Development of process models to characterize the real processes for study, for what-if analysis, for studies of alternative capital investments and for development of control systems for process improvement and control.
3. Development of mill set-up tables and algorithms, and computer programs for real time control of rolling mills and process lines.

At any one time, the group consisted of 5 to 15 engineers and 3 to 5 analysts, with backgrounds in electrical and mechanical engineering, physics, control technology, computer systems, electronic circuit design and computer programming. Over time the group established technical expertise in:

1. Instrumentation and measurement technology (such as, temperature measurement, radiation/x-ray technology, vibration measurement, electromagnetic sensing, vision inspection systems, flatness measuring systems)
2. Real time control systems, process controls, and process computers.
3. Mathematical models of hot rolling, plate rolling, and cold rolling processes and models of heating processes and furnaces. And productivity models.

The name and composition of the group evolved over the years as HRL downsized, and correspondingly, the group's mission and focus were frequently realigned/redirected. During the twenty plus years, the group went through six sequential incarnations described below. Hal Long was the Supervisor for all six groups.

<u>1982 - Product Measurement and Identification Group</u> (in the Measurement and Control Systems Division – David Reinbold, Manager)

- Supervisor: Hal Long. Engineers: Jack Baker, Luther Gruver, Carvel Hoffman, Duane Jones, William Locks. Analysts: Allen Buss, Daniel Diehl, David Gombotz, Harry Hunsinger, Dick Morgan.
- The group was in the south part of A-Building of HRL and had a special radiation laboratory on the ground floor in which the tomogage was constructed. The group had projects in the following plants:

    - Johnstown (bar diameter gage),
    - Steelton (the rebar weight per foot (WPF) gage),
    - Bethlehem (the Structural Mill tomography gage and vibration predictive maintenance for rotating machines),
    - Sparrows Point (66” Cold Tandem Mill (CTM) upgrade)

<u>1984 - Measurement and Control Group</u> (in the Finishing Processes Division – David Reinbold, Manager)

- Supervisor: Hal Long. Engineers: Gary Crouse, Carvel Hoffman, John Hoffman, George Wieland, Jack Baker, Carol Berry, Gregory Brown, Duane Jones, Anthony Martocci, John Tiers, Bill Locks, Michael Isenberg. Analysts: Allen Buss, Harry Hunsinger, Dick Morgan, Wolfgang Sawitz.
- This group was a consolidation of several other groups after a major down-sizing at Research. We started out in A-Building, and later moved to C-Building, as A-Building was being sold to Lehigh University. The group had projects in the following plants:
    - Burns Harbor (metal level measurement, mold level sensor, slag detection in the pouring stream, hot mill shape sensor, hot mill robot coil marker, plate mill thickness gage, hot mill reheat furnace control),
    - Bethlehem Plant (tomogage commissioning and patent application),
    - Steelton (rebuild bar diameter control (BDC) system),
    - Sparrows Point (66” CTM modernization, start of tomography gage for hot strip mill),
    - Homer Labs (thin slab caster work on USS-BSC joint project).

<u>1989 - Mill Controls Group</u> (in the Finishing Process Division – David Reinbold, Manager)

- Supervisor: Hal Long. Engineers: Ricky Adebanjo, Frank Arner, Carol Berry, George Mueller, Bruce Grube, Kenneth Kalnitsky, Gregory Brown, Fang Han, KC Chiang. Analysts: Robert Eberhardt, John Hart, Bob McClarin, Dick Morgan, Don Donemus, Mike Wanuga.
- The group was relocated to C-Building, and our focus changed slightly. The measurement projects moved to another group, and we were now more involved in the manufacturing processes i.e., cold and strip rolling and plate mill rolling and associated processes. We had projects in the following plants:
    - Sparrows Point (part of the Sparrows Point P-1 program at the cold mill and tin mill, statistical providing for the plate mill, Hot Strip Mill (HSM) looper control, data loggers for cold mills, tin mill line of business study, offline shape measuring system, slab coating to retard scaling during reheating, 48” tandem mill speed set-ups, microstructural-constitutive modeling at hot mill, instrumented slab trials),
    - Burns Harbor (hot mill reheat furnace control, variable crown roll for skin pass mill, BH 160” plate mill control and modernization efforts, hot charging feasibility study),
    - Lackawanna (75” CTM feed forward control and speed setups),
    - Corporate Engineering (market mill study – reversing mill),

    - Homer Labs (crown and profile joint project with Armco and LTV).

1992 - Cold Rolled and Coated Sheet Process Development Group (in the Cold Rolled and Coated Sheet Division – Dick Willison and later Steve Hansen, and Stavros G. Fountoulakis Managers)

- Supervisor: Hal Long. Engineers: Mitrajyoti Deka, Duane Jones, Kenneth Kalnitsky, Ralph Rudolph, Eugene Deisher, Kaveh Forouraghi, Bruce Grube, Homero Ortiz, Kun-Chuan Chiang. Analysts: Robert Eberhardt, Glenn Hunsicker, Dick Morgan, Donald Ronemus, Michael Wanuga.
- Upon Dave Reinbold's retirement, HRL underwent a major reorganization. As part of this, personnel in the group changed, and the work was refocused again. The hot mill and plate mill projects were shifted to another group, and our group now worked in cold mill processes and hot dip coating line processes and instrumentation. We reported to Dick Willison and later to Steve Hansen when Dick retired. Our projects were at the following plants:
    - Lackawanna on the galvanize line (edge heaters after the pot, edge baffles at the coating knives, instrumentation to measure the flux application before the pot, set-up control of the gas fired galvannealing furnace),
    - Burns Harbor (work to support the new HDCL, trips to NKK Japan for galvanneal process knowledge, help with commissioning the new line, galvanneal temperature measurement and control, percent Fe measurement and control, soak zone operation, surface inspection systems including the AISE-Kodak trials, improve coating weight control, work roll textures at skin pass mill for surface roughness improvement, calibration of the coating weight gages, improvement of shape control at the 80" CTM, multi-group project to reduce microflap/blister problem, hole detection at BH pickler),
    - Sparrows Point (improved surface texture for D&I tin mill products, water on the strip detection at tin mill washer line, continuous annealing line incremental improvements),
    - Sparrows Point for the New Cold Mill Complex (analyses of competing bids, start-up assistance, flatness display systems, shape control improvements).
    - Chicago Cold Rolling (analysis of reversing cold mill options, set-ups for the reversing mill, evaluations of capability and product mix), Homer Labs (BSC/USS Thickness Control Capability Study – Cooperative Technology),
    - Columbus Coating Company hot dip coating line (study the flatness quality of substrate sourced from BH and LTV, galvanneal temperature measurement and control, coating weight and percent Fe measurement),

2000 - Rolling and Finishing Processes Group (in the Process Development Division – Robert Bouman, Manager)

- Supervisor: Hal Long. Consultant: Carvel Hoffman. Engineers: Emin Erman, Bruce Grube, Duane Jones, George Mueller, Homero Ortiz, Ralph Rudolph, Mahesh Vyas, Eugene Deisher, Michael Healy. Analysts: Don Ronemus, Allen Buss, Robert Eberhardt, Jeff Piersza.

- The group was reformed again in 2000 because of another dramatic downsizing of Research. Hot mill and plate mill Researchers came back into the group. A major effort (Corporate effort) was to get as many people as possible trained in Six Sigma methodology (most of the group's engineers went through the Black Belt or the Green Belt training, including myself). As the plants embraced Six Sigma, many of our projects at the plants were incremental Six Sigma projects, run by the newly minted Green or Black belts from HRL or the plants. In addition, we had two major assistance efforts that were major capital projects that needed to be productive and profitable quickly:
    - to support the New Cold Mill Complex at SP
    - to support the new hot dip coating lines at Columbus Coating Company and at Burns Harbor.
- As Carvel Hoffman came back to the group, we worked to finish the interesting and innovative Sparrows Point 68" Hot Strip Mill tomogage project.

2003 - Finishing Processes Group (reporting to Michael Byrne, Director of Research)

- Supervisor: Hal Long. Consultants: Charlie Romberger, Carvel Hoffman. Engineers: Emin Erman, Bruce Grube, Duane Jones, Homero Ortiz, Mahesh Vyas, William Mindler. Analysts: Allen Buss, Robert Eberhardt.
- This was the final incarnation of the group – Bethlehem Steel dissolved into ISG right after this reorganization in January 2003. Research was down to about 70-80 people, organized into six or seven groups, all reporting directly to Director of Research, Michael Byrne

HOT ROLLED PROCESS DEVELOPMENT

By Charles J. Romberger

As mentioned in the Cold Rolled & Coated Sheet Process Development Group supervisor's report, the Hot Rolled Process Development Group came into being in the early 1990's. Research activities focused on rolling process improvement, development and application of advanced tomographic thickness gaging instrumentation, and commissioning and improvement of new water-cooling process technologies in BSC's hot strip, plate, and rail mills. Personnel included; Supervisor: Charlie Romberger, Consultant: Carvel Hoffman, Engineers: Creighton Booth, Bernie Droney, Emin Ermam, George Mueller, Mahesh Vyas, Curt Abel, Jack Baker, Greg Brown, Mike Healy, and Shirong Wang, Analysts: Allen Buss, John Hart, Harry Hunsinger, Alan Kemmerer, Jeff Piersza and Dale Pysher.

Key project work included;

- Application of the hot strip mill x-ray tomographic thickness gage developed by the Instrumentation and Measurement Group in the late 80's and installed on the Sparrows Point hot strip mill in 1991 to characterize both the rolling process and product quality.
- Hot strip mill process improvements on the Burns Harbor and Sparrows Point mills to improve yield, productivity and product quality.
- Development and application of a tomographic isotope thickness gage for the Burns Harbor 160" Plate Mill.
- Improvement of plate mill yield performance.
- Commissioning of the ADCO accelerated cooling system on the 160" Plate Mill.
- Improvement of the rail head hardening cooling system and process in Steelton.
- Characterization of reheat furnace operating performance.

PART 2: DESCRIPTION OF SIGNIFICANT RESEARCH PROJECTS (IN ALPHABETICAL ORDER BY FIRST AUTHOR)

Vanadium Steel (V-Steel) Custom Shapes

By Richard L. Bodnar, Steven S. Hansen, and Bruce L. Bramfitt

Development of V-Steel

The ASTM A572-type Vanadium Steel (V-steel) was developed in the early 1960's by G.F. Melloy and others , and it continues to be used extensively for structural shapes, plates, bar, hot rolled sheet, and piling. The V-steels include products with minimum yield strengths of 45, 50, 55, 60, and 65 ksi, and are generally referred to as V45, V50, V55, V60, and V65, respectively. At the time of their development, these ferrite-pearlite steels were found to be synergistically strengthened by additions of vanadium and nitrogen. Hundreds of thousands of tons of V-steels have been produced by Bethlehem since their introduction.

During the 1980's and 1990's, several researchers at Homer Research Laboratories contributed to a deeper understanding of the physical metallurgy and processing of the V-steels. Their findings include:

- Al/Si killed steels exhibit improved toughness over Si semi-killed and Si killed steels, due to the substitution of smaller aluminate inclusions for larger silicate inclusions.
- As the nitrogen content of the steel increases, the vanadium carbonitrides (V(C,N) become more nitrogen-rich. Nitrogen-rich V(C,N) is more stable than VC and does not coarsen as readily. Hence, alloying with Nitrovan (a ferro-alloy containing both V and N) provides a higher precipitate strengthening increment than alloying with Ferrovanadium (V only). For example, substituting Nitrovan for Ferrovanadium allows the V content of a typical steel to be reduced from 0.070 to 0.055%.
- While finish rolling temperature had little effect on yield strength, the Charpy toughness improves when the finish rolling temperature decreases.
- In addition to using a reduced finishing temperature, toughness can be further improved by reducing the carbon content (less pearlite) and the slab/bloom reheating temperature.
- A coarse austenite grain size and/or high cooling rate can lead to a Widmanstatten microstructure, which decreases toughness. Hence, to the
- importance of refining the austenite grain size and controlling the final product cooling rate to minimize the formation of Widmanstatten structure.

Steel Compositions

Table 1 summarizes the typical chemical compositions for some V-steels, such as ASTM A572-Grade 50, V-Star 50, forklift-mast, joint bar, and truck frame rail.

Table 1. Summary of Typical Compositions for V-Steels, wt. %

Steel	**C**	**Mn**	**Si**	**Al**	**V**	**N**
ASTM A572-Grade 50	≤0.23	≤1.35*	≤0.40**	**	0.01/0.15	-
Typical Si-Semi-killed	0.20	1.15	0.03	0.003	0.06	0.012
Typical Al-Killed	0.20	1.15	0.25	0.03	0.07	0.012
V-Star 50	0.10	1.25	0.25	0.03	0.07	0.012
Forklift Mast (65 ksi YS)	0.28	1.30	0.25	0.03	0.04	0.009
Joint Bar (70 ksi YS)	0.27	1.65	0.32	0.022	0.13	0.017
Truck Frame Rail (85 ksi YS)	0.18	1.60	0.50	0.02	0.20	0.025

*A max. of 1.5% is permissible with an associated reduction of the C max. of 0.03%.

**Bars over 1.5” in thickness shall be made by a killed steel practice.

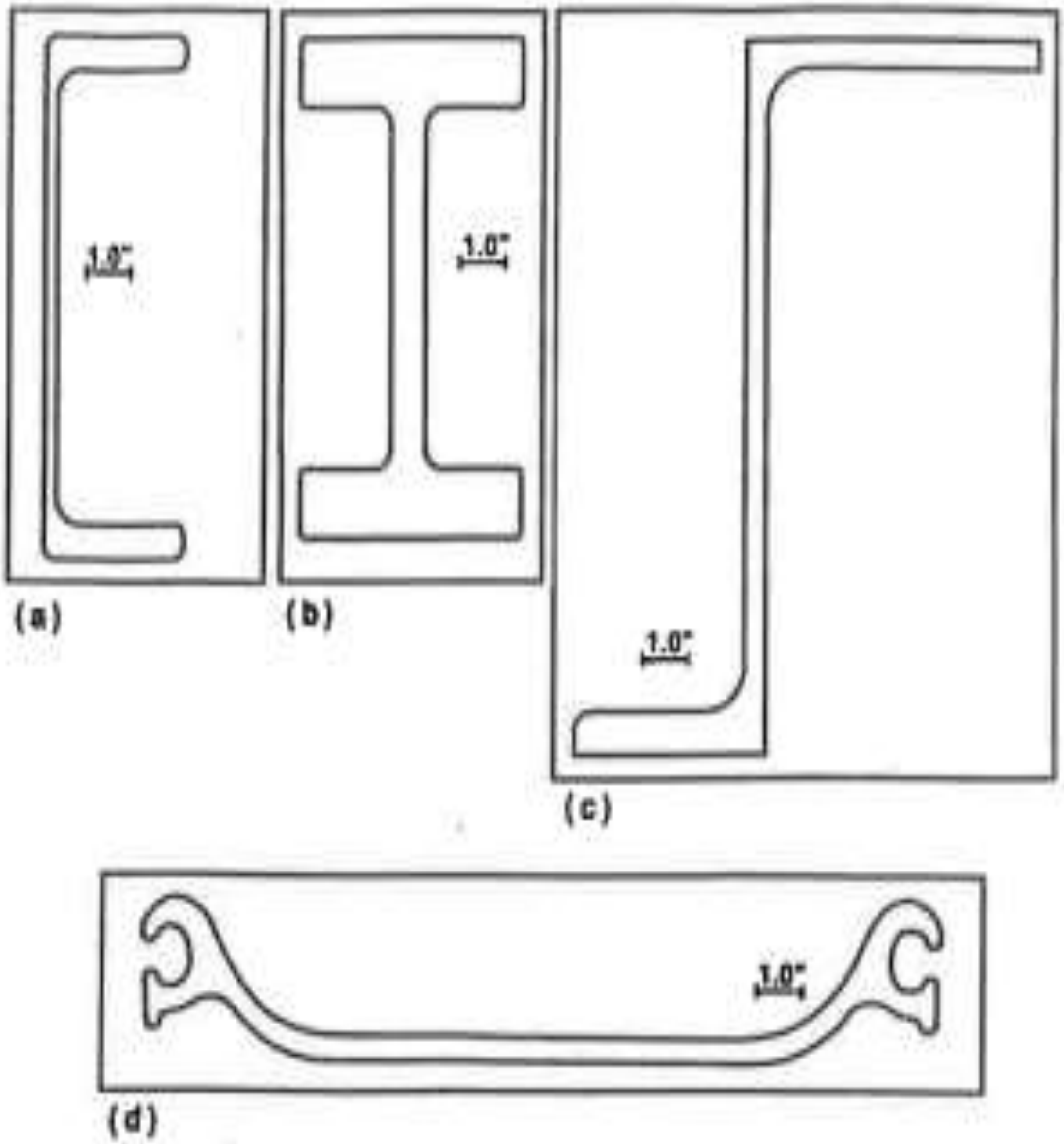
ASTM A572-Grade 50 was supplied as either Si-semikilled or Al/Si-killed, depending on specification or the customer’s requirements; the other steels were all Al/Si-killed. For Bethlehem, the largest application of Al/Si-killed A572-50 steel was for jumbo column sections, classified by ASTM A6 as Groups 4 (W14x219 to 550 lb/ft) and 5 (W14x605 to 808 lb/ft). Hot-rolled jumbo shapes were first used for columns resisting large axial, compressive loads, but were eventually also used in large trusses as tension members.

In 1987, Bethlehem introduced V-Star 50, a hot-rolled structural steel with a minimum yield strength of 50 ksi coupled with good longitudinal toughness (minimum Charpy energy of 15 ft-lbs at -50 °F) and weldability (IIW carbon equivalent between 0.32 and 0.38). This steel has less carbon and more manganese than typical A572-50. Two high tonnage applications for V-Star 50 steel were flatrack channels (FC9x20), utilized to fabricate military pallets to transport supplies, and low-sulfur structural shapes for the truss systems supporting the decks of offshore platforms. The low-sulfur version was needed to prevent lamellar tearing. For example, Bethlehem supplied 350 tons of L6x4x3/4 angles to Belleli for the hull, and 550 tons wide-flange sections to McDermott for the deck, for each of Shell’s Ram-Powell and Mars offshore platforms in the Gulf of Mexico.

Custom Shape Products

During the 1980’s and 1990’s, Bethlehem moved towards market niches by producing custom-rolled sections. The Bethlehem Plant’s 44” Mill or Combination Mill allowed rolling in both the two-high and/or universal modes. Some examples of the custom shapes produced on this mill included the FC9x20 parallel-flange flatrack channel, W9x59 forklift mast section, CZ13x41 railroad tank car center sill, and PSA23 sheet piling sections, as shown in Figure 1 below.

Fig.1. Schematic diagrams of some of the V-Steel custom shapes: (a) FC9x20 parallel-flange flatrack channel, (b) W9x59 forklift mast section, (c) CZ13x41 railroad tank car center sill, and (d) PSA23 sheet piling section.



Forklift Mast: The W9x59 forklift mast section was supplied to Clark Materials Handling Co. The thicknesses of the web and flange for the forklift mast section shown in Figure 1b are nominally 0.75" and 1.25", respectively. For this surface critical application, continuously-cast Steelton blooms were used. Compared to the Al/Si-killed A572-50 steel, the forklift mast steel contains higher carbon and lower vanadium contents. The higher carbon content was necessary to achieve a hardness level in the range of 207 to 255 HBW in the hot-rolled condition. This relatively high hardness level was required to provide resistance to wear from steel rollers, which ride on the inside surface of the flange during forklift operation.

Joint Bar: Historically, Steelton used a C-Mn grade (typically 0.47% C, 0.60% Mn, and Al-killed), which was hot rolled to section and then austenitized and oil quenched to supply this market. Allegheny Rail Products approached Steelton about the possibility of designing a microalloyed grade that would achieve the desired mechanical properties (yield strength ≥ 70 ksi, tensile strength ≥ 100 ksi, total elongation in 2" ≥ 12%, reduction of area ≥ 25%, and 90° easy way bend) in the as-rolled condition at presumably a lower cost (elimination of the heat treatment). After monitoring the rolling of similar sections on the Steelton 20" Mill, three experimental compositions were designed, melted and hot-rolled in the laboratory using a simulation of the commercial rolling practice. Evaluation of the mechanical properties of these experimental steels demonstrated that an as-rolled, lower carbon/higher Mn composition microalloyed with vanadium and nitrogen (see Table 1 on page 19) provided an improved combination of strength/ductility/toughness over the heat treated product. After customer approval, Allegheny purchased a mill trial lot of the new grade. Satisfactory mechanical properties were achieved, and the American Railway Engineering Association modified their joint bar specification to accommodate the new as-rolled grade. Bruce Bramfitt presented the results of this development at Microalloying '88 and a paper was published in the conference proceedings. The development was also protected by an U.S. patent.

Truck Frame Rail: In order to be able to favorably respond to customer requests for high-strength, as-rolled structural shapes, often required for heavy machinery, Rick Bodnar and Steve Hansen developed the V-Star 85 steel (see Table 1 on page 19). This V-N microalloyed steel had a yield strength in excess of 85 ksi in combination with a 15 ft-lb transition temperature well below 32 °F in the hot-rolled condition. When the V-Star 85 steel is hot rolled to a parallel-flange channel (similar to the flatrack channel shown in Figure 1a), this product is suitable for replacing cold-formed and heat-treated truck frame channels made from modified 1027 or 0.21% C – Mn – B steel hot band with a minimum yield strength of 110 ksi. The V-Star 85 steel has comparable fatigue strength to the tempered martensitic 110 ksi alternatives and lower manufacturing cost. There are a number of advantages for a hot-rolled, variable thickness, parallel flange channel for truck-frame siderail. Up until the time when the HRL structural shape product development project was closed out in 1996, Midland Steel and Navistar remained interested in the truck frame siderail development for Class 8 trucks. The truck frame development was captured in two publications, and it is protected by an U.S. patent.

The creative and pioneering solution approaches discussed in this article resulted in the publication of numerous scholarly articles as well as several U.S. patents. For example, this work was discussed in journals such as: *Trans. ASM, Metall. Trans. A, Scripta Metall., Metall. and Mater. Trans. A,* and *Heat Treating*.

Instrumentation for Measuring Coating Weight and Percent Iron (Fe) on Galvanneal Hot Dip Coating Lines

By Mitrajyoti Deka

At the Burns Harbor Hot Dip Coating Lines| (HDCL), the manufacturing of galvanneal required a new type of coating weight gage: one that would not only measure the coating thickness but also measure the amount of iron in the coating (percent Fe). Coating weight gages traditionally measure the fluorescence (back scatter) of an x-ray radiation beam as it struck the strip. The amount of fluorescence received by the sensor is related to the thickness of the zinc coating, and an accurate relationship can be determined between coating weight and fluorescence. The measuring of the percent iron in the coating requires another signal – if the incident radiation beam is angled and the fluorescence is captured at a corresponding angle, the signal contains more information about the amount of iron in the coating. By collecting the signals and processing them, coating weight and percent Fe can be extracted. Radiometrie DMC, a gage manufacturer, had some knowledge of this technology, and was willing to develop a gage for the BH HDCL. Mitra Deka of Research, worked closely with them to improve on their technology and verify it. Several technical issues had to be solved: the first, the very small distance that was required between the strip and x-ray source/sensor meant pass-line variation/vibration had to be minimized - this was solved by installing a set of pass-line stabilizing rolls before and after the gage; the second, the gage was located at top of the galvanneal tower in a very hot location – which required special sensor cooling apparatus; and, the third, the two signals, to be useful had to be calibrated – which required a lengthy process of collecting numerous samples with different coating weights and different percent Fe. In many cases these samples required expensive line trials where the different coating weights and percent Fe where purposefully created. In all, at the end, with diligent work of the plant, Research, and the equipment manufacturer, the resulting gage was a success. A laboratory version of the gage was also developed for quickly measuring the coating weight and percent Fe from end of sheet samples for quality assurance. The gage was replicated for the Columbus Coating HDCL, years later.

Product developers aim for a certain amount of iron (percent Fe) in the zinc coating. A certain value, say 8 or 9 percent Fe, produces a coating with low powdering (a good property, desired by the customer, because the low powdering coated product will not cause problems in stamping dies). So, having a measurement of percent Fe allows for the possibility to control of the process to get the value needed. Mitra Deka used the percent Fe measurement in an outer control loop which automatically adjusted the induction furnace to heat the strip to that temperature which achieved the desired percent Fe. This control loop was programmed into the BH HDCL level II computer. A percent Fe (as desired by the product developer) could be set, measured, and controlled. The percent Fe loop was also included in the US Patent on Galvanneal control.

Plate Mill Projects

By Emin Erman, George Mueller

In the late 1990s, Emin Erman worked on improving the yield of plate product at the Burns Harbor 160” Plate Mill. Through his Six-Sigma project work, he developed rolling rules to improve (decrease) the plate width variability for the class of product that accounted for about 75% of the total product mix. The new practice was incorporated into the 160" Plate Mill's (PM’s) process computer and activated in the early 2000s. After verifying the improvements in width variability, Burns Harbor was able to reduce the plate side scrap allowances by about 0.25", which resulted in a providing yield savings of about $300,000/year.

From 1990s through to the end, George Mueller (and later Emin Erman) supported the Burns Harbor’s long-term effort to produce higher strength plate through thermo-mechanical controlled rolling. The controlled rolling process required processing plate through the mill at a controlled pace where reduction passes were done when the plate reached certain temperatures. The plate during the intermediate passes may have to be held to cool down or cooled by intermediate sprays to the desired temperature before the next reduction pass. The basic objective from a metallurgical perspective was to develop fine ferrite grain size through controlled rolling and cooling, which balanced austenite recrystallization and non-recrystallization for maximum grain refinement (smaller ferrite grain size) with a corresponding increase the plate strength. Knowing the temperature at various stages during controlled rolling was critical for the process and for process control, and this was one of George’s main contributions. He improved the temperature model adaptation schemes by algorithms which compared measured temperature with estimated temperature at certain points and fed back the corrections to the process computer for the next run. Over the time of a rolling campaign, these corrections insured the accuracy of estimated temperature. George successfully tested the strategy at the 110” Plate Mill, and later Emin to the 160” Plate Mill.

Plates are usually manufactured for specific orders, that is, for a specific customer thickness, width, and length. Plates are rolled from slabs which are provided to the plate mill by weight. For a given order, if the slab is too heavy, the resulting plate will be either too wide and/or too long. The excess can be trimmed but that amounts to a yield loss. If, on the other hand, the slab is too light, width or length will be too short and the resulting plate will not meet the customer requirements, and it is scrap. So, the plate mill will tend to order slabs that are slightly heavier than needed to avoid producing an unsalable plate. To help the mill, George Mueller applied statistical thinking to this process of slab providing, which attempted to optimize (minimize) the probability of underproviding, thereby allowing the mill to order a slab closer to the minimum required and produce a plate that will still meet the required dimensions. To do this statistically he had to first determine the variabilities of plate manufacturing process – the probability of producing an out-of-tolerance width or length or thickness. Knowing this, he could calculate a safety factor in the slab providing by ordering just enough extra slab weight to minimize the risk of underproviding, yet not give away too much in yield (trim) loss. The process, which Mueller called “Statistical Providing”, gave the plate mill a rational tool by which to order slabs for the mill. He developed it first at Sparrows Point for the 160” Plate Mill, and then applied it to Burns Harbor. It was a major success.

Electrogalvanize (Zn & Zn-Ni) Sheet for Automotive

by Stavros G. Fountoulakis,

Background - In the early 1980's, the U.S. automotive industry began to focus its attention on improving the corrosion resistance of automobile body panels. Up to that time, exposed panels were manufactured from cold rolled sheet steel, much of which, at that time, was precoated on one side with a zinc-rich paint. The coated side became the interior of the body parts, where it would protect the steel from the accumulating corrosive environments of road salt and moisture. However, zinc-rich paint had limitations. It was only a barrier coating and, as a result, lost all effectiveness wherever and whenever its integrity was breached. As a one-side only treatment, it offered nothing to reduce outer or cosmetic corrosion of the steel automotive panels. It became clear to the automotive companies that, to improve the long-term and cosmetic corrosion resistance of their products, sacrificial, metallic coatings were required that could be applied to one or both sides of sheet steel.

In those early 1980’s hot dip galvanized steel was available in limited supply to the U.S. carmakers for use for structural and extremely corrosion-prone parts. However, it was not suitable for many of the body panel applications because of non-uniform zinc coating thickness, unavailability of one-side coatings and generally unacceptable paintability and visual appearance. For these reasons, the U.S. steel industry responded to the needs of its customers by investing approximately $650 million in five large electrogalvanizing lines between 1984 and 1986, and two additional lines in 1992. All these lines increased the domestic supply of automotive grade electrogalvanized sheet steel from a few hundred thousand tons produced by U.S. Steel in Gary, Indiana, to about 4.0 million tons/year in the peak demand in the mid-1990s.

HRL’s support increases Bethlehem’s automotive share, by making Electrogalvanize available ahead of the competition- A company award early 1988 recognized the dual efforts of Homer Research Laboratories (HRL) and Burns Harbor, collectively known as the electrogalvanized development team. To respond to the rapidly growing market for electrogalvanize for automotive, the team from 1984 to 1988, worked in converting the idle 48-

inch tinplating line at the Burns Harbor plant into electrogalvanizing line; then building a 72-inch EG line at Walbridge, Ohio, through the joint venture with Inland Steel and Pre-Finish Metals, and creating an EG pilot line at Burns Harbor for new coating trials.

The team's efforts did increase Bethlehem's competitiveness in the automotive market by allowing it to supply quality electrogalvanize sheet in advance of most other U.S. steel companies. Homer Research Cold Rolled & Coated Steels Division headed by Bill Jolley, and later by Ed Meyers, and then Dick Willison was instrumental for this strategy and the supporting efforts. Later this same division, until its end of life in 2000, was led by Steven Hansen and then by Stavros Fountoulakis, and introduced both new colds rolled steels as well as other coated product introductions, this time hot dip coated, and supported hot dip coating facility investments.

Zinc-Nickel (Zn-Ni) electroplated sheet steel, Bethlehem Steel's entry ticket into Japanese Automotive Transplants - Production of thick pure zinc electrogalvanize coatings consumes large quantities of electric power and slows down the plating line speeds, resulting in high operating expenses and reduced line capacities. These conditions were reflected in the cost of electrogalvanized steel. In addition, the heavy coating weights caused manufacturing difficulties in automotive manufacturing, in forming and welding.

So, as the United States' steel and automotive companies were moving to implement the use of electrogalvanize steel, development was already under way in Japan and, to a limited extent in Europe, of new electroplated alloy coatings that offered the benefits of heavy zinc coatings at only one-fourth to one-half of the thickness. These new coatings were primarily zinc-iron and zinc-nickel in various forms including dual-layer and composite products with nonmetallic overlays.

Bethlehem Steel believed, even as it was planning a large electrogalvanizing line in partnership with Inland Steel and Pre-Finish Metals, that the alloy coatings would eventually be more cost effective to produce and to use. The conclusion from research studies of both systems was that the zinc-nickel alloy was the most practical coating to produce with the plating technology at Walbridge, and the most suitable product to meet customers' needs.

In 1984, having decided to produce zinc-nickel coated sheet as a second-generation product compared to electro-galvanized steel, a 4-year technical development program was established at Bethlehem Steel. Later, together with Inland Steel and Pre-Finish Metals, Bethlehem specified the generic hardware needed to support a second plating electrolyte for inclusion in the design of the Walbridge Coatings electro-galvanizing line. However, it was also apparent that considerable laboratory work and pilot production trials would be required before a complete zinc-nickel production system could be designed and installed.

The work on Zn-Ni in the lab and later in the pilot and industrial scales was led by Stavros G. Fountoulakis, under the unprecedented mentorship and leadership of Richard N. Steinbicker and David Melcher, Supervisors, and Dick Willison, Division Manager. There were also numerous other individuals, engineers, technicians, and supervisors from all three partners which contributed to the industrial and commercial success of this new ZnNi coating development program. Key HRL individuals with whom the writer was relying on for technical support were Ron G. Herczeg, Sr., Susan Pors Hinnerschietz (current name Susan Wolf), Ed Fodor, Art Helfrich, and Kim Klick.

Laboratory investigations- The Walbridge Coatings electrogalvanizing line includes the Gravitel electroplating technology of Andritz-Ruthner. This process attained high production rates through use of high electrolyte flow rates and use of dimensionally stable inert anodes. The application of the Zn-Ni coating process to the Walbridge equipment posed some problems, however, because alloy plating from a sulfate electrolyte is an anomalous process, i.e., the electrolyte being used to deposit a coating which contains mostly zinc and only a small amount of nickel, is composed primarily of nickel with a much smaller zinc component. Anomalous processes of this type are normally sensitive to many of the operating parameters.

The Gravitel plating process was simulated in the laboratory with a rotating cathode, and a high-velocity flow cell to come up with an optimized electrolyte composition and optimized industrial plating parameters.

Pilot line trials -When Bethlehem Steel, Inland Steel, and Pre-Finish Metals selected the Gravitel plating system for the Walbridge Coatings partnership, the technology of the system had not yet been proven commercially. Only a small, 300-mm wide pilot line in Vienna, Austria, was available to optimize the hardware and to develop processes for new coatings such as Zn-Fe and Zn-Ni. Consequently, the three companies agreed to another partnership: to piggyback an experimental pilot plating section, including two full-sized Gravitel cells, onto the now 48-in. wide electrogalvanizing line at the Burns Harbor plant.

The third tier of the Burns Harbor line was retrofitted with the two Gravitel cells and became the joint venture pilot line. This 2-cell Gravitel pilot facility provided an opportunity to further enhance the knowledge and understanding of the Zn-Ni process and for developing and testing range of plating parameters to test their effect.

A joint venture technical team managed the Zn-Ni pilot trials, and later the industrial trials at Walbridge. Representing Bethlehem Steel in this team were Dick N. Steinbicker & Stavros G. Fountoulakis, whereas William A. Carter and Mark S. Blazer, represented Inland Steel. This team was charged with the following responsibilities:

- Plan and determine how to conduct the Zn-Ni coating trials.
- Equip the pilot and then the Walbridge line with the right instrumentation and process automation.
- Manage the zinc to Zn-Ni and Zn-Ni to zinc switchovers, to avoid contamination of the zinc electrolyte, and to minimize loss of commercial production.

The first trial was conducted on April 20, 1988. Even during this very first trial, Inland and Bethlehem produced about 275 tons of Zn-Ni coated cold rolled steel in various sizes and coating weights, at line speeds up to 525 fpm. Switch-over from zinc to Zn-Ni electrolyte was smooth and was accomplished in less than 8 hr.

The trial demonstrated that: (a) the Walbridge facility can make high-quality automotive Zn-Ni coated steels; and (b) the electrolyte replenishment with zinc and nickel using the available reactor tanks could be done successfully.

Production of initial customer samples - In a second trial on Sept. 13, 1988, after the composition of the electrolyte was optimized, over 350 tons of Zn-Ni coated steel, in various grades, widths, gages and coating weights were produced for Bethlehem alone. During that trial, process automation was used extensively to predict and control the Zn-Ni coating composition. Significant quantities of specific sizes and grades were produced for customer evaluation.

The target customers were Mazda and Nissan. Nissan already had a big manufacturing presence in NA, with their plant in Smyrna, Tennessee, whereas Mazda only then, in the Fall of 1988, the same time we were starting our Walbridge Zn-Ni trials, started up a brand-new joint venture plant with Ford Motor Co., just 40 miles north of Walbridge, in Flat Rock, Michigan. It was and still is today one of the large fully integrated automotive stamping plus assembly vehicle plants.

During the same month when Mazda was starting U.S. manufacturing, HRL management dispatched the writer for his first and yet solo trip to Japan, which lasted two full weeks. First stop was Hiroshima, that's where Mazda's HQ and Technical Center are still located.

When the Japanese interpreter who was to wait to meet at the main Hiroshima Shinkansen station, called to cancel because of illness, the writer was forced to meet without her, except the occasional help from one of Mazda's more English proficient engineers, with a series of Mazda Materials Engineering experts, one after another, over the course of that first week in Japan. However, despite the cultural challenges, the embarrassment for not having an interpreter, the writer did manage to overcome these and become familiar with the most critical of Mazda's manufacturing and in-service Zn-Ni coated steels properties requirements.

The second week was spent in Tokyo, discussing Zn-Ni coated requirements with Nissan Materials engineers, this time together with a representative of Marubeni Trading company.

This trip proved to be of tremendous help when HRL had to carry out one of the most expedited and yet still one of the most rigorous of materials qualification processes. This also would not have been possible of course without the expert help and enthusiasm of many colleagues from HRL, as well as the support from Burns Harbor and Walbridge Coatings people. However, if it is one person that could be singled out, was that person who had the oversight for all the qualification testing; that was Susan Pors-Hinnerschietz (Susan Wolf).

So, in summary, in response to the automotive industry's need for more durable, corrosion-resistant steel products, Bethlehem Steel undertook a 6-year program to develop a zinc-nickel alloy coating as a second-generation alternative product to the thicker electrogalvanized coatings The program evolved from laboratory evaluations of alternative alloy coatings, through bench and pilot line development, to trial production of several hundred tons of material on the commercial electro-galvanizing line at Walbridge.

Followed this, Walbridge Coatings installed equipment that will permit sustained, fully commercial production of zinc-nickel coatings by Oct. 1989. Bethlehem Steel believed that zinc-nickel was an improved coating that enhanced the value and life of automotive customer's products. A family of steels with this Zn-Ni coating were supplied to Mazda’s JV with Ford automotive plant in Flat Rock, Michigan, and to Nissan’s plant in Smyrna, Tennessee.

Development and commercialization of pre-painted Zn-Ni for fuel tanks - In early 90’s, HRL researchers began working with paint companies and automotive producers, in evaluating various types of materials that would meet all of the requirements necessary to produce a gas tank for the future -- a tank that would be compatible with practically any blend of gasoline as well as blends of gas and methanol, compatible with so called “flex fuels”. This R&D project was led by a very knowledgeable and experienced researcher, Dr. Henry N. Hahn, who had just joined HRL, from LTV Steel and their Research Center, in Independence, Ohio.

Test results from the program managed by Henry Hahn, led to the selection of a paint supplier partner, a developer of an aluminum-rich epoxy-type paint, Magni Industries Inc. The Magni paint system, showed great promise when used in combination with Bethlehem’s zinc-nickel (Zn-Ni) coated sheet steel. The pre-painted Zn-Ni was completely resistant to the effects of the methanol fuel blends. The material also was highly corrosion resistant to road salt induced corrosion. So, there was almost immediate interest by Ford and General Motors.

Extensive work on possible production methods for this pre-painted Zn-Ni followed resulted in the eventual development of quick and efficient one-step, continuous production process. Steel sheet will feed into the Walbridge Coatings combination electroplating plus paint-capable line, where the Zn-Ni and aluminum-based epoxy paint were applied, plus at the same time, a dry-film soap-based lubricant was applied directly on the surface of the coated sheet. The lubricant allowed the pre-painted Zn-Ni steel to flow easier through the deep drawing forming dies during the tank manufacturing process. The first commercial coils of this material were made into fuel tanks in August 1993, and for over a decade after that, General Motors and especially Ford continued to use this material for fuel tanks for certain model vehicles, while also using terne, plastics and tin-zinc coated steels for others. Armco and LTV who were by then also producing Zn-Ni coated sheet steels tried to get to supply for that application, but Bethlehem maintain the competitive advantage of the above-described single step process.

Reduction of Defects on Three Piece Can Stock

By Herbert L. Gilles

Background

During the first quarter 2000 Sparrows Point Tin Mill Quality Assurance requested that Research assist in reducing the incidence of lamination and long line surface defects on three- piece can stock. Our major customer, Silgan, was unhappy with the high defect rates in their products caused by our materials. The 3 piece can defect rate had increased significantly in 1999-2000. Silgan was threatening to disengage as a customer. The Tin Mill total rejection costs were about $1,840,000 per year.

Some thinking about the situation went like this:

<u>Mission Statement</u>

To save our Silgan business

To save the tin mill

To save Sparrows Point

To save Bethlehem Steel

The current fire-fighting that was aimed at decreasing defect level was not producing satisfactory results. A more comprehensive approach was needed.

The Sparrows Point Tin Mill produced about 360,000 tons/year of three-piece can stock. The wall thickness ranged from 0.006 to 0.015 in. During inspection at the Tin Mill about 80% of the defective material was identified. The defects appeared on the steel surface as laminations and long lines that ranged in length from several inches to 20 ft. and in width from 1/32 to 3/8 in.

There were two major types of defects. Type One defects, steelmaking, were associated with the process steps from the Basic Oxygen Furnaces to the Continuous Casting Machines. Type Two defects were associated with the Hot Mill. A preliminary study revealed that about half of the defects were of Type One and half of Type Two. At discussions with Sparrows Point it was agreed that the effort was to be directed at Type 1 defects.

Project

A Six Sigma project was initiated with the goal of reducing the steelmaking related surface defects by 50%. Herb Gilles at Research had recently undergone extensive Six Sigma training, a powerful technique for solving difficult industrial problems**,** which was appropriate for the three piece can problem. Herb's contact at Sparrows Point was Mike Amann and he was assisted by Dave Howells and Tom Zimmerman at Research.

The steelmaking defects could be associated with the basic oxygen furnace, ladle, ladle treatment station, tundish or caster mold. Unfortunately, it was not possible to determine the chemistry of a defect visually. Therefore, in order to determine the root cause, chemical analysis of samples was required.

A defect analysis system was set up. A sample from each defective coil was sent to the Sparrows Point Metallurgical Lab. where it was mounted, polished and optically examined to determine whether the defect was of the iron oxide or steelmaking oxide type. The samples were then sent to Research where those samples determined to be of steelmaking oxide type were analyzed with the microprobe. The microprobe identified each of the elements present and allowed for the determination of the source of the defects, e.g., alumina, tundish flux, mold flux, refractory inclusions, etc. Because of the low level of defects, around 1%, the probability of multiple causes occurring simultaneously was small and a single sample for a coil was workable. This was verified by taking multiple measurements on coils.

An analysis of the initial set of coil samples indicated that root causes of steelmaking defects were to be found in the ladle treatment station and caster mold. The necessary in-depth analysis required development of historical operating data. Data bases of operating variables in useful form for process and statistical analysis were established for the ladle treatment stations and casters from Computer Aided Quality Control, Data Warehouse and DB2 tables. A legacy file that connected coil number through hot mill number to heat, slab and cut was developed to ease tracking of material through the process.

Corrective Actions

Extensive analysis of the data indicated that there was no silver bullet that would reduce surface defect incidence. Multiple corrective actions were required at the ladle treatment station and caster.

At the caster, defects were related to speed changes and open pour conditions. Corrective actions for speed were 1) reduce the speed change ramp from 10 ipm / min to 5 ipm / min, and 2) divert the most severe speed changes, such as slabs cast when submerged entry nozzles were replaced. Also, slabs cast with open pour conditions, which allow exposure of the liquid steel to the atmosphere, were to be automatically diverted from Tin Mill applications. In addition to the speed and open pour corrections a computer glitch that was allowing normally diverted first-heat-on-tundish slabs to be sent to the Tin Mill, was identified and corrected.

The majority of the lamination and long line defects contained alumina. Some of this material was related to the open pour condition and speed changes noted above. Statistical analysis also related the alumina defects to conditions at the ladle treatment station. Heats that produced coils with the alumina defects appeared to be associated with ladle reheating, high aluminum fade, low stir time post final addition and high last stir flow rate. Corrective actions included adding artificial slag and reduced aluminum addition. Also additional training of ladle treatment station operators was carried out by Steelmaking Operations and Quality Assurance.

Results

During the last 19 months of the project the number of coils rejected for steelmaking related laminations and long line surface defects was reduced by 46% from the base level. The cost savings amounted to $423,000 per year. We had identified root causes. Additional savings were also anticipated with more controllable operating conditions when the future ladle metallurgy furnace stations were operating.

Increased Bender Service Life at Sparrows Point Casters

By Herbert L. Gilles

Background

The two slab casters at the Sparrows Point Plant were designed by Voest-Alpine. Each had a straight vertical mold, a bender that provided for transition from the vertical mold to a 10 meter radius curved section that brought the strand close to a horizontal position, a straightener, to transition from the curved section to the horizontal, and a horizontal section, Figure 1.

Benders were approximately 120 inches long and comprised of 16 roll pairs on Caster 1 and 15 roll pairs on Caster 2, supported by substantial structural frames. The rolls were nominally 6 inches in diameter and the bearings were lubricated with air-oil on Caster 1 and grease on Caster 2. There was no specific internal or external cooling system for the bender rolls. Cooling of the rolls was effected by metallurgical sprays that were controlling the strand surface temperature. The water that cooled the rolls was partially from direct contact with the metallurgical sprays and partially from the runoff water that collects between the rolls and the strand.

Benders were designed for a 90-day use cycle, after which they were removed from the caster and taken to the repair shop. There the rolls were refurbished and bearings and seals were replaced in preparation for the next 90 day cycle. The in-caster 90-day cycle time basically occurred because of a roll wear limit. At the midpoint of the 90-day cycle, the benders were removed from the caster and checked for damage. Also, the metallurgical cooling water nozzles were checked for plugging. Barring problems the benders were then replaced in the caster for the remainder of the cycle.

Damage to benders can occur due to operational problems. The major causes are breakouts, mold overflows and stuck strands. These do not occur at a high frequency but since the benders are in operation for an extended period of time, a small number of incidents can significantly reduce the useful average cycle time and substantially increase repair costs.

Beginnings

In September 2001 it was determined that the bender repair costs were excessive, more than $1,500,000/year. The costs were associated with in-machine operating lifetimes of about 45 days, 50% of the design capability. Some of the costs were due to operational problems associated with the recently modified Caster 1. There was also a concern that excessive roll wear was occurring. Because of this situation, improving the bender life and reducing costs became the subject of a Six Sigma project. The project team members were Herb Gilles at Research and Tim Lonsbury and Mike Panzeri at Sparrows Point.

In the initial analysis we reviewed historical bender roll wear data, in-caster operating times and reasons for removal from the caster, and determined the following:

1) For Caster 1 the frequency of special operating problems was very high. These problems had to be resolved before we could begin to attempt to improve the operating lifetime. However, each of the special problems was not trivial and would have required its own separate project. This was beyond the scope of our mandate.
2) For Caster 2 there were fewer special operating problems. A frequent cause of bender removal was stuck rolls.
3) Roll wear was high on the first 4 bender roll pairs but significantly less on the remaining 12-13 roll pairs.

Project

Based on this initial analysis we focused our project efforts on improving Caster 2 benders in two ways:

1) Minimize or eliminate the **stuck roll problem**, and
2) Develop a **minimum repair strategy**: when a bender approaches a 90-day cycle time and only a fraction of the rolls are worn, replace only those rolls and put the bender back into service to extend the service life.

Investigation of the stuck rolls revealed several major potential causes related to roll and bearing cooling, bearing lubrication and bearing attachment to the support frame. Modifications were made to the roll cooling and bearing attachment to the support frame, and trials were started in September 2002. The changes made proved to be effective. Stuck roll incidence was greatly reduced. In addition, the minimum repair strategy was implemented in conjunction with the repair shop.

Results

As shown in Table 1, during the last 12 months of the project the average time-in-operation between rebuilds was increased from 53 to 85 days and repair costs were reduced by more than $250,000. In addition, the improvement of the stuck roll condition on Caster 2 avoided the capital expenditure of $500,000 for lubrication system.

NO. 1 CASTER SPARROWS POINT

Figure1. Sparrows Point Caster Component Arrangement

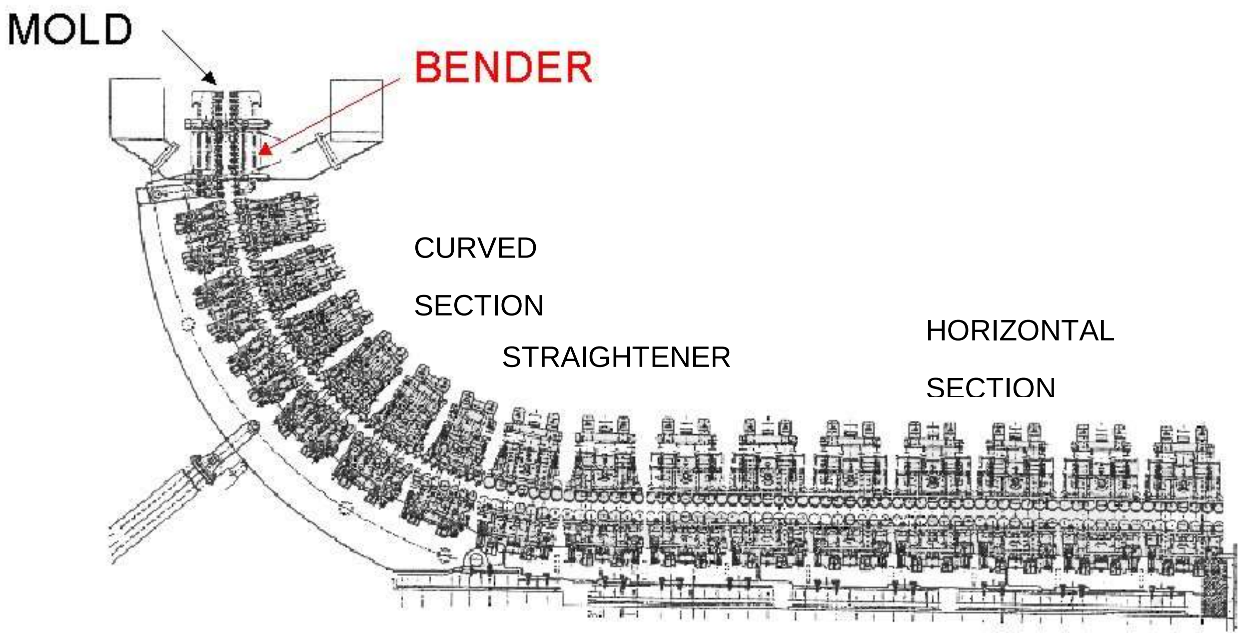


Table 1. next page.

Table 1. Improvement in Strand 2 Repair Costs and Days Between Rebuilds

Year	Time Period	Avg. Monthly Repair Costs, $	Avg. Time-in-Operation Between Rebuilds, Days
1	9/2000 to 8/2001	41,000	43
2	9/2001 to 8/2002	53,000	53
3	9/2002 to 8/2003	24,000	85

Oxygen Reheating of Steel in Pouring Ladles

By Neal Griffing and Philip Stelts

A common problem was that the temperature of a freshly tapped heat of steel was too low. Such heats had to be diverted to ingot pouring instead of being continuously cast. The lower yield and interruption of continuous casting productivity resulted in large cost penalties. The deluxe solution for cold heats is to install an expensive electric arc ladle furnace.

An alternative chemical heating method was attractive and pilot plant at Homer Research Laboratories (HRL) was undertaken in 1987. This entailed adding aluminum and combusting it with oxygen. A series of tests in 500-lb induction furnaces and scale up to 10-ton heats in the Experimental Melt Shop defined the amounts of aluminum and oxygen needed. Argon stirring is important to homogenize the heat. Without stirring, the upper portion of the steel bath becomes superheated. However, stirring with a bottom porous plug eliminated thermal stratification. If concurrent bottom stirring is unavailable, post stirring with an argon lance is used.

In 1988, an inexpensive facility was implemented at Burns Harbor. And at Sparrows Point as well. HRL provided ongoing help in working with the Engineering and Technology departments of the plants to design equipment and operating procedure.

Curiously, unexpected benefits of oxygen reheating were “free opens” as well as excellent steel quality. A free open is one in which the ladle slidegate for pouring is not frozen stuck when activated.

The economic benefits of reheating occasional cold heats were several millions of dollars per year. The creative and innovative solution approach resulted in the publication of several scholarly articles as well as two U.S. patents.

Cold Rolling Mill Set-ups for Chicago Cold Rolling

By Bruce B. Grube

In the late 1990s' Bethlehem Steel built an independent manufacturing facility near Chicago, called Chicago Cold Rolling (CCR), which among other mill equipment had a 68" Reversing Cold Mill. Bruce Grube, Research, had consulted on the type of mill equipment to purchase, including making a trip to Europe to see the latest single and two-stand reversing rolling mills and doing a computer analysis comparison of various alternatives. In the start-up of the line, Bruce continued to provide advice and guidance to mill operations and to the mill's Continuous Improvement team. He had developed a suit of rolling models for analyzing rolling mill set-ups, mill speeds, rolling forces, tension, and winding practices, and, previously, he had provided mill speed set-ups for the SP 66" Cold Tandem Mill (CTM) and for the SP 48" CTM. For the Lackawanna 75" CTM, he developed speed set-ups and gap position models and tension winding practices. Bruce brought all expertise forward and applied it to the CCR Reversing Mill. He evaluated the mill product mix and ran the mix through his set-up calculations and models and compared the CCR actual rolling results with his models. He then suggested setup and practice changes where they were needed, such as, tension policy, coil winding tension profile policy, scheduled pass reduction policy, and attainable pass speeds. Bruce then developed and assisted CCR in implementing a new predictive roll force model / mill gap preset model to allow automatic preset of gap position. The result was greatly improved mill operation, thickness performance, and mill yield. His work contributed to making CCR and particularly the Reversing Mill operation achieve its potential. It was a major success story that was greatly appreciated by the CCR leadership team.

Cold Mill Productivity Models for Capital Investments

By Bruce B. Grube

By the 1990s, as illustrated in some of the project summaries above, our group had developed mathematical computer models of the cold rolling process that were used to provide mill set-ups for tandem mills and provide studies of mill productivity.

One example of how we used these models was the assistance to the Burns Harbor 80" Cold Tandem Mill (CTM). The cold mill was looking for ways to increase productivity for a product mix of thinner gauge material. In general, the tandem mill can run faster (higher rolling speeds) if the product is thinner. But a limit to the speed increase is the gearing of the rolls to the mill drives. The gearing is set during the mill specification and construction stage, with the gearing specified for speeds for the expected product. If the product mix changes over time, according to customer demands, the mill may be no longer geared optimally. For certain products, it may be running slower than it could because of the gearing. Such was the case at Burns Harbor in the mid-1990s. Bruce Grube was asked to use the mathematic models to study the situation and comment on BH's plan for upgrading the mill gearing. Bruce set up his models for the current mill configuration and ran it with the current product mix and ran it with the expected, future product mix. He confirmed what mill the experienced, namely the mill had the capability (horsepower) to run faster on the new mix but could not because of gearing constraints. He again ran the model but with several gearing change scenarios with new expected product mix and provided estimates of the productivity gains that could expected with the different alternatives. BH used the estimates (returns on investment) in the justification in the Capital Request. Bruce also warned that if the product mix did not materialize there was a risk that returns might not be achieved. The Capital Request was approved, and the gearing change installed. However, unfortunately, the product mix did not change as much as was used for the study and justification, and the returns were partially achieved.

Another use of our mill modeling expertise was for the Sparrows Point Plant New Cold Mill Complex decision-making process. Bethlehem Steel and Sparrows Point had been planning to upgrade the cold rolling facilities for many years. The old 66" Cold Tandem Mill (CTM) and even older 54" CTM could not produce the quality and yield required for sustainability. The problem was acute by the time the new (non-automotive) galvanize line was constructed at Sparrows Point in the mid-1990s. The proposed solution was a new cold mill complex consisting of a modern (state of the art) linked pickle line and five stand tandem mill, hydrogen batch anneal furnaces, and a new skin pass line with inline tension leveling. It was a large capital project managed by Bethlehem's Corporate Engineering. Our group was intimately involved in the project, particularly in the startup and commissioning phases, and then, after commissioning, with helping Sparrows Point learning how to run the complex, modern facility. But before it was built, we were asked to advise Corporate Engineering which of three competing bids for the linked pickle - tandem mill would be the best. Bruce Grube and I attended all the vendor presentations and many of the preparatory meetings. To make the best recommendation, Bruce ran his model on all three vendor proposed solutions. He tuned the model to the three mill configurations each with different mill powers, gearing, looper length, speed restrictions, payoff reels, pickling tanks, and take-up reels, etc. Sparrows Point provided the expected product mix in a large matrix form – hot band thickness by cold mill exit thickness by product grade by expected volume (tons per year). Each vendor proposal was evaluated against the product mix and was also compared to what the vendor said their capabilities were. We were asked, basically, could the proposed pickle - tandem mills provide the annual tons in the specified product mix. Bruce's analysis showed that all three proposals were sufficient, but one had more capability – it was the Voest-Alpine proposal – the one that was ultimately selected. Corporate Engineering and Sparrows Point greatly appreciated the rigorous analysis, because the concept of linked pickle-tandem cold mill was new to Bethlehem Steel and new to the United States steel industry (in fact, the mill was one of the first continuous mill for cold rolled product in the US). The New Cold Mill (NCM) complex construction started late 1990s and finished in the early 2000s (just time for the Bethlehem bankruptcy!).

Cold Mill Feed Forward Automatic Gage Control at Lackawanna

By Bruce B. Grube, Gregory Brown, Donald J. Ronemus

In the mid-1990s, Research participated in a several year program to upgrade the 75" Cold Tandem Mill (CTM) at Lackawanna. Because capital was limited for the Lackawanna Plant, the work was done in incremental steps using mainly internal Bethlehem Steel resources, Lackawanna Plant Process Control resources and Research. The main part of this program was to improve the thickness performance capability of the 75" CTM. Bruce Grube, Research lead engineer, developed new mill setups and calculations, which Process Control installed an online computer with help from Don Ronemus, Research. The set-ups allowed the mill to achieve higher mill speeds (and thereby increased productivity) and, by better tuned set-ups, lowered the off-gage footage at the head and tails of coils (thereby improving yield).

Another part of this activity involved improving the in-body thickness performance of the rolling mill by adding a feed-forward gage control module to the existing automatic gage control. Greg Brown was the lead Researcher for this project, which involved the plant Process Control team. Don Ronemus programmed it into the real-time mill control computer. The feed forward control worked by measuring the strip thickness at the x-ray thickness gage between mill stands 1 and 2 and calculating a correction that was fed forward to stand 2 such that the mill stand speed could be adjusted at the precise time to affect a correction. The new automatic control was deemed a great success in improving in-body thickness performance. In recognition, the Research / Lackawanna Tandem Mill Gauge Control team received the Bethlehem Steel Team Excellence Award (from Roger Penny) for the Automatic Gage Control upgrade.

Flatness and Shape Measurement

By Bruce B. Grube, Richard D. Morgan, Donald J. Ronemus

Good flatness (or “shape”) of sheet product is a key requirement at each process step for best manufacturability and for the end automotive customers use in their stamping plants. But for the cold mill and temper mills to control and improve shape, it must be measured. The ability to measure and characterize flatness was developed and refined in the 1980s. Research participated in the early efforts, as various measuring technologies were being investigated by the steel industry. In the late 1970s, Research developed a scanning device that coupled electromagnetically to the strip and sensed a change in magnetic permeability which was related to flatness. Although the device had limited success on the Sparrows Point tension leveling line, it provided the means for improving our knowledge about shape measurement. Through the 1990s, Bruce Grube, Research, helped the 56” Cold Tandem Mill (CTM), the 66” CTM and the 48” CTM at Sparrows Point and the 80” CTM at Burns Harbor in specifying, installing, and verifying commercial shape gages. Several fact-finding visits to European competitors and instrument manufacturers insured good understanding the best technology to install. To verify the accuracy of the online gages, Bruce Grube and Dick Morgan developed an offline gage that consisted of a flat table and translating linear distance transducers to measure the flatness of a cut section of sheet product. At least three of these gages were constructed – for the Cold Mill and the Tin Mill at Sparrow Points and for the Cold Mill at BH. The technology was licensed to a small company (called SPC Engineering) of ex-HRL engineers, who commercialized the instrument. At least one of these commercial devices was sold back to Bethlehem Steel – for the New Cold Mill Complex in the 2000s. Bruce Grube was our lead Research engineer on most of the shape instrumentation.

In the early 2000s, at Sparrows Point, Bruce Grube and Don Ronemus, Research, developed a Smart Flatness Application and Display for the new 68” Continuous Linked Pickler-Cold Tandem Mill. Bruce was the lead Research engineer, and Don was the computer programmer assisting him. The application acquired data from the online shape meter (at the exit of the tandem mill) and processed, reported, and displayed information about the flatness quality of the strip being processed. The system compared strip shape being produced with the customer requirements, and reports/alerts were generated for out-of-tolerance conditions. Real time reports were generated to alert quality managers about flatness problems, and suspect coils were flagged/held for further review before releasing to downstream units. In addition, the flatness application displayed detailed images of the flatness quality on a large TV monitor in the operator pulpit. The display showed the flatness in a color topographic format which improved the operator’s ability to visualize the strip flatness. It included an expert system to recommend operator correction to improve shape, which worked over the top of the automatic shape control system by advising the operator of set point adjustments tailored to the specific shape correction requirements (for instance, perhaps new work rolls are needed, or cooling headers need adjustment, or the bending set-up is too aggressive, etc.) With this real-time Smart Display, the operator was able to anticipate flatness problems and correct the mill conditions causing the problems. Bruce was awarded a US Patent for this application.

The Smart Flatness system was later replicated and installed on the new skin pass mill (the skin pass mill that was part of the New Cold Mill Complex) with the same beneficial results. The systems remained a critical part of the New Cold Mill until the mill was sold, and Sparrows Point closed down in the 2010s.

Accelerated Cooling and Direct Quenching of Steel Plates

By Steven S. Hansen, Richard L Bodnar, Keith A. Taylor

Early Work on AC/DQ

It is metallurgically well-established that increasing the cooling rate through the austenite-to-ferrite transformation regime after hot rolling leads to a more-refined microstructure and an improved combination of mechanical properties. For example, water cooling after rolling has been used on hot-strip mills for decades and Bethlehem was a pioneer in the use of water cooling on the Lackawanna Bar Mill. In the early 1980's, Japanese and European steelmakers started to apply water cooling after hot rolling to reversing plate mills. Each steel producer developed their own type of accelerated cooling (AC) equipment technology. Nippon Steel even installed a Roller Quench unit at the exit end of a Plate Mill for direct quenching (DQ). Most of the reported applications of AC dealt with control-rolled, high strength low alloy (HSLA) plate products for linepipe (up to X120) and shipbuilding applications. Bethlehem researchers were aware of these developments and the Homer Research Laboratory Plate Product Development Team initiated laboratory studies to understand the potential application of this technology to a wide range of products. Initial laboratory work on this topic was conducted by John Paules and Steve Hansen and summarized in a number of internal reports which showed that:

- Accelerated Cooling (AC) can be used to increase the strength level and thickness range of existing plate products.
- AC offered the potential for a reduction in the alloy content of carbon and low-alloy hot-rolled ASTM plate grades, reducing cost and improving weldability.
- Direct Quenching (DQ), in combination with controlled rolling and a small Cb addition, resulted in improved strength/toughness levels compared to conventional quench-and-temper grades.

Subsequent DQ Plate Development

Keith Taylor joined HRL in 1985 and began several years of DQ plate development projects under the guidance of Steve Hansen. Based on a concept suggested by John Paules, Keith developed a method for determining the hardenability of as-rolled steel plate. The method was the subject of a paper presented at the 6th International Conference on Heat Treatment of Materials held in Chicago in 1988. This method was employed in subsequent investigations of the basic metallurgy of DQ plate. Simple C-Mn and C-Mn-Ni lab-melted steels were investigated first for effects of rolling conditions on final mechanical properties, without the potentially complicating effects of alloy carbide/nitride/ carbonitride precipitation. It wasn't clear if a boron addition would deliver a consistent hardenability effect in a DQ process, so that element was also excluded from the initial lab heats. The early DQ work showing the benefits of controlled rolling for good toughness and was presented at the International Symposium on Accelerated Cooling of Rolled Steel held in Winnipeg, Canada in August of 1987.

Subsequent projects evaluated hardenability in more commercially relevant boron steels, with and without microalloy additions. That work demonstrated that boron would provide its beneficial effect on hardenability under most conceivable plate processing scenarios and led to a 1990 paper authored by Taylor and Hansen, which was published in Metallurgical Transactions. A subsequent 1991 Metallurgical Transactions paper focused on effects of processing and vanadium additions in low-carbon 0.5Mo-B steels. That paper won The Institute of Materials' 1991 Vanadium Award.

Taylor was intrigued by work done by other researchers that employed "boron autoradiography" to map the distribution of boron atoms in steels. The technique requires access to a nuclear reactor to expose steel samples to thermal neutrons. Thermal neutron exposure "activates" boron atoms in the steel, which subsequently decay by fission with alpha particle emission. The alpha particle emission creates damage "tracks" in a cellulose nitrate detector film affixed to the sample surface. Keith learned that the Brookhaven National Laboratory (BNL) on Long Island might have a facility suitable for this technique. Dr. David Rorer was the BNL contact who took an interest in the Homer Research Laboratory (HRL) work and arranged for access to the BNL medical research reactor. Metallographic mounts with detector film were carefully prepared by HRL Analyst Kevin Downey and were transported to BNL by Keith for insertion into a reactor beam-line for neutron exposure. After exposure, the detector films were stripped from the mounts and transported back to HRL for etching, gold sputter-coating and microscopic examination. Excellent results were obtained and were published in a 1992 Metallurgical Transactions paper.

Taylor was a member of the TMS Ferrous Metallurgy Committee and ASM Phase Transformations Committee and wanted to organize a symposium on the physical metallurgy of DQ steels. With help from co-organizers Prof. Steven Thompson of the Colorado School of Mines and Dr. Fred Fletcher of the Lukens Steel Company, a *Physical Metallurgy of Direct-Quenched Steels* symposium took place during November 2-4, 1992 as part of ASM "Materials Week '92" in Chicago. Taylor was the principal editor of the symposium proceedings, which was published by TMS and contained 24 manuscripts, including two HRL papers on DQ 0.5Mo-Ti-B steels. One of the Homer Research Laboratory papers featured high-resolution analytical electron microscopy (AEM) results on nanometer-scale Ti-Mo carbide precipitates. The AEM work was conducted by Waldemar Furdanowicz using the HRL Vacuum Generators HB5 instrument.

Concurrent with the research described above, Bethlehem started to evaluate the potential installation of AC/DQ technology on the Burns Harbor 160" plate mill. Also, in the late 1980's the Department of Defense (DoD) became interested in AC/DQ steels for both Navy shipbuilding and Army armor plate applications, anticipating that these more weldable grades would offer a significant reduction in fabrication costs. Homer Research Laboratory researchers initiated discussions with personnel from the David Taylor Naval Research facilities (Annapolis, MD) who took the DoD lead on this effort. Historically, Navy designs had utilized 36 to 50 ksi as-rolled steel grades and high-alloy, quench-and-temper grades (HY-80 and HY-100) for ship/submarine construction. The Navy researchers were specifically interested in looking at higher-strength, as-rolled grades (HSLA-65, HSLA-80 and HSLA-100) to replace the high-Ni HY grades. Eventually the DoD proposed a Title III program (covered in the Defense Production Act) in which purchase commitments would be made to one or more domestic steel plate producers as a vehicle to establish a U.S. production capability for AC/DQ steels.

A three-phase Title III program on AC/DQ steels was proposed. Phase I involved the production and qualification testing of four steel grades in thicknesses up to 3.75" using domestically-melted slabs processed on an existing AC/DQ facility. Assuming successful detailed testing of plates from Phase I, Phase II would involve establishment of a domestic production facility capable of supplying 35,000 tons/year of Navy shipbuilding and Army armor grades. Phase III would involve establishment of a second domestic source for AC/DQ plates. In preparation for Bethlehem's Phase I proposal, joint Research-Operations (John Chilton, Jerry Roe and Van Reiner) visits were made in late 1988 to the five major Japanese plate producers in order to select a partner for the Title III program. Kobe Steel was selected to process slabs - continuously-cast slabs from Armco and Ellwood Uddeholm ingots broken down on the Burns Harbor slab mill (for the thicker plates). Initial testing was to be conducted by Kobe and acceptable plates shipped back to Bethlehem for comprehensive testing. A Phase I contract was awarded to Bethlehem in April 1990 to run for 36 months. During Phase I, over 800 tons of slabs were shipped to Kobe's Kakogawa Works for plate rolling and AC/DQ processing. Regular progress meetings between Bethlehem and Kobe were held during this period and HRL personnel were on hand to witness some of the plate production in Japan.

Detailed testing of plates was conducted at HRL and the results were generally positive and provided the basis for new Navy military specifications for HSLA-65, HSLA-80 and HSLA-100 grades which are in use today. The results for the DQ armor grade were less encouraging and consequently the Army continues to use conventional Q&T processing to the present day. Ultimately, DoD funding for Phase II of the Title III project was not approved and Bethlehem's plans for AC/DQ reverted back to internal justification.

AC on the Burns Harbor 160" Plate Mill

Similar to the 1988 visit to Japanese plate mills, a number of European plate mills with Accelerated Cooling (AC) were visited in 1992. Based on these visits, it was agreed to proceed with an AC unit pending successful trials with the two mill equipment suppliers available at that time. Trips were made to China Steel [Taiwan], who used Mannesmann Demag Sack equipment known as MACOS® (<u>M</u>annesmann <u>A</u>ccelerated <u>Co</u>oling <u>S</u>ystem), and GTS Industries [France], who used Kvaerner Davy/Clecim/Bertin equipment known as ADCO® (<u>Ad</u>justable <u>Co</u>oling), in October 1994 and December 1994, respectively. The MACOS system used laminar water curtain cooling, while the ADCO unit employed air/water spray mist cooling. Both facilities rolled two Burns Harbor slabs to produce 0.75" X70 and 2" grade 50 plates. The ADCO-produced plates exhibited better microstructural uniformity and a superior strength/toughness balance. Also, the ADCO equipment offered a wider range of cooling rates and the ability to process thick plates without the need to oscillate plates in the cooling unit. Therefore, the decision was made to proceed with purchase of an ADCO unit. The Bethlehem Steel Board of Directors approved the capital appropriation request in July 1995, and one year later, an ADCO unit was installed on the Burns Harbor 160" plate mill. Members of the Hot Rolled Product and Process Development groups were active participants in a cross-functional AC team responsible for the trials and successful commissioning of the ADCO unit. These participants included Rick Bodnar, Minfa Lin, Yufeng Shen, Charlie Romberger, Curt Able, and Greg Brown. The 6-cooling module ADCO unit along with a pre-leveler on the Burns Harbor 160" Plate Mill are shown schematically below.

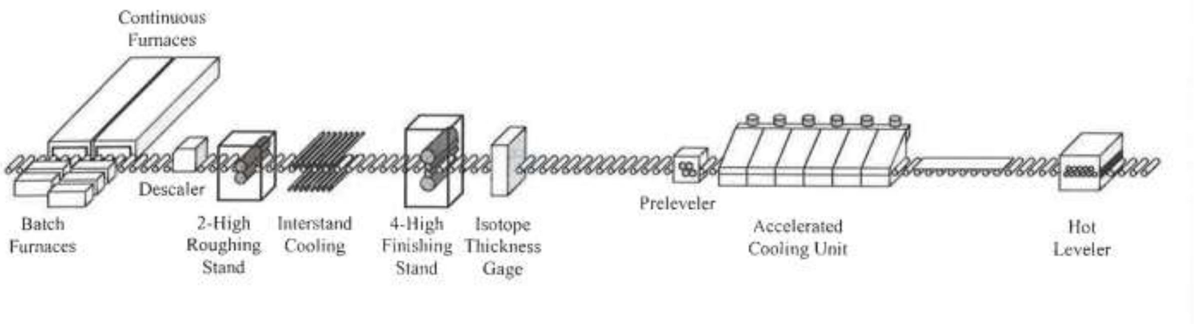


Fig. 1. Schematic diagram showing the layout of the Burns Harbor 160" Plate Mill with preleveler and ADCO unit in place.

During the 1990's, the Plate Product Development Team developed a number of new AC plate products.

Some of the AC plate products developed by this team are summarized below.

X70 Linepipe: X70 composition and processing were optimized in lab rolling trials and then moved into commercial production. For example, compared to conventional severe controlled rolling, the use of AC allowed the finish rolling temperature for 0.75" X70 to be increased by over 200 °F without a degradation in mechanical properties - mill productivity improved by 40% (less for lighter-gauge plates). For sour-gas service, Bethlehem Steel was able to secure a 47,000 ton order for 0.875" X70 plates for the Pemex Cantarell Project in Mexico using a special composition known as "High-Temperature Processing" (HTP) steel. This grade was a 0.03% C-0.09% Cb + Cu-Ni-Cr-Ti steel, and because of a very low-sulfur requirement, the 10" thick slabs were cast by IMEXSA (Mexico) and shipped to Burns Harbor. This X70 order was significant in that it was the first time that Bethlehem supplied plate for sour service pipe, and it was the thickest X70 plate that Bethlehem had ever produced.

T-Star®: T-Star is a multi-purpose structural plate grade. One compositional version of this steel contains 0.09% C, 1.20% Mn, 0.02% V, and 0.01% Ti. By varying processing, plates up to 2"-thick with minimum yield strengths of 36, 42, and 50 ksi in combination with good Charpy V-notch impact toughness were produced. Through standard hot rolling, T-Star can meet a number of customer and ASTM specifications requiring yield strengths of 36 or 42 ksi. By hot rolling and AC, 50 ksi minimum yield strength products can be achieved. The T-Star composition and its processing were protected by three U.S. patents.

V-Star 50®: In 1987, Bethlehem Steel introduced V-Star 50, a hot-rolled steel for structural shape products with a minimum yield strength of 50 ksi coupled with good longitudinal toughness and weldability. The plate version of this low-carbon steel was available up to about 0.875" in thickness. By hot rolling and AC, the maximum thickness for this grade was extended to 2".

Weathering Steels: HPS 70W is a "High Performance Steel" with a minimum yield strength of 70 ksi, coupled with excellent toughness, weldability, and atmospheric corrosion resistance. This weathering steel was designed to replace a 50 ksi grade to allow weight savings in bridge design and was adopted by ASTM as A709-Grade HPS 70W in 1997. As first reported by John Chilton, this product was initially produced by quenching and tempering. In a joint research effort between Bethlehem Steel and Pohang Iron & Steel Co (South Korea), a controlled rolled + AC HPS 70W steel that could meet the requirements of HPS 70W up to 2" was developed and patented. A second patent covered lower-carbon AC 50 ksi plates up to 4", 65 ksi plates up to 1.5", and 70 ksi plates up to 1.25". However, these patents were never employed for HPS 70W production since practices were developed using the standard V-microalloyed grade used in the quenched and tempered condition. In the end, plates up to 1.25" were produced by severely controlled rolling, plates > 1.25" to 2" were produced by controlled rolling + AC, and plates > 2" to 4" were produced by Q&T. In this way, only one melt grade was needed to cover the entire thickness range.

Low-Si A572-Grade 65: This low-carbon/low-silicon – Ti-Nb-V plate product with a minimum yield strength of 65 ksi was developed using AC for transmission towers and light poles intended for hot-dip galvanizing. This product was covered under two U.S. patents.

As part of a gatekeeping effort, Rick Bodnar organized and led an European tour of plate mills in 1998 to learn more about how Bethlehem's competitors were employing Accelerated Cooling (AC). Mild cooling was being used for plate surface conditioning and material handling, i.e., to inhibit secondary scale growth, lower hot leveling temperature, and expedite material flow. The practice of mild cooling to minimize secondary scale growth and improve surface quality was adopted by Burns Harbor and was referred to as the "recipe mode". Another use of AC was the cooling of partially-rolled slabs during the "hold-out" stage of the controlled rolling process to improve mill productivity. Other non-conventional uses of AC were quenching and self-tempering, and cooling to achieve a uniform plate piling temperature for hydrogen diffusion. Lessons learned about AC were summarized in a paper by HRL researchers.

AR 400 HBW DQ Trial at Pohang Iron & Steel Co (POSCO)

As part of a joint project with POSCO, Burns Harbor produced a heat of 0.15% C + Mn-Si-Mo-Ti-Cb-B steel for an abrasion-resistant steel plate trial targeting a nominal surface hardness of 400 HBW. The heat was top poured into 37" x 72" x 128" ingots, slabbed into six 6" x 64" x 100" sections, and shipped to the POSCO-Pohang No. 2 Plate Mill which was equipped with a 7-module ADCO unit capable of Direct Cooling. On November 19, 1997, Rick Bodnar and John Battisti observed the rolling and DQ of two 0.75" and two 1" plates. Two rolling schedules were employed for each plate thickness, viz., hot rolling (HR) and controlled-finishing-temperature (CFT) rolling. In general, the shape and surface condition of plates incoming to and exiting the

DQ unit were rated as poor. Also, the POSCO hot leveler was unable to level the plates. Full width plate sections were shipped back to HRL for metallurgical characterization. The plates were through hardened to martensite and the mechanical properties were acceptable. The CFT/DQ plate exhibited similar hardness and superior toughness compared to the HR/DQ plates. Also, the CFT/DQ plates exhibited similar mechanical properties compared to conventionally reheat quenched plates from the same heat.

Summary

In the early 1980's, Japanese and European reversing-mill platemakers began applying water cooling after hot rolling. Bethlehem researchers were aware of these developments, and the HRL Product Development Team initiated extensive accelerated cooling (AC) and direct quenching (DQ) laboratory studies to understand potential benefits and applications. Concurrent with these laboratory studies, Bethlehem started to evaluate the potential installation of AC/DQ technology in the Burns Harbor 160" Plate Mill. Visits were made to Asian and European plate mills to learn more about AC/DQ production and practices. Navy ship and armor plates produced at Kobe's Kakogawa Works (Japan), and grade 50 and X70 plates produced at GTS Industries (France) and China Steel (Taiwan) using various AC/DQ technologies were evaluated for flatness, microstructure and mechanical properties. Based on the results, AC was determined to be the better investment, and an ADCO accelerated cooling unit was installed at Burns Harbor in 1996. This made Bethlehem the first domestic discrete plate producer with accelerated cooling capability. Using knowledge gained from laboratory studies and trips abroad to competitors with AC/DQ technology, as well as the evaluation of competitor-produced plates, the unit was commissioned on time and a number of new plate products were quickly developed. This new AC capability benefitted both Bethlehem and its customers, viz., improved production throughput, alloy savings, expanded product thickness ranges, higher strength grades, internal chemistry/processing flexibility, yield improvement (longer caster strings of heats through grade consolidation), improved surface quality, and improved weldability.

Tomographic Sheet Profile Gage – Sparrows Point 68" HSM

By Carvel D. Hoffman

Prior to the profile gauge development, sheet profile was typically obtained by comparing the measurements of two single point gauges, one fixed at sheet centerline and the other traversing from sheet edge to edge. The measurements obtained were a series of diagonal profiles that were compromised by any longitudinal sheet thickness variation. The sheet edge measurements were affected by transverse sheet movement and radiation scatter, further degrading profile measurements especially near the sheet edges. Based on market requirements for better control of sheet dimensions and quality, there was a need for more accurate simultaneous transverse profile measurements.

Following the development and implementation of the Tomographic Weight per Foot and Dimensional Gauge for the Bethlehem Combination Mill, the next challenge was adapting the technology to the measurement of hot sheet thickness profile. The idea was to unfold the circular detector array below the sheet, increase the number of detectors and locate two radiation sources above the sheet to obtain stereoscopic views of the sheet. Coincidentally, Scientific Measurement Systems (SMS) in Austin Texas submitted a proposal to American Iron &Steel Institute to develop a sheet profile gauge with similar arrangements of detectors and sources. Ultimately, near the end of 1987 we agreed to jointly develop a gauge with SMS to measure sheet thickness profile. Over the next two plus years, a prototype gauge was designed, constructed and tested in Austin. As the development progressed, a mill test site was prepared, located after the last finishing stand on the Sparrows Point 68" Hot Strip Mill (HSM). Installation of the gauge was started early 1990, followed by operation by mid-year and verification of thickness and width measurement by year-end.

Charlie Romberger was our group Supervisor and handled much of the project administration. Carvel Hoffman was the technical lead throughout along with Richard Savage from SMS. Numerous SMS personnel were involved throughout development. After early successes in the gauge development in Austin, Creighton Booth and Bernie Droney joined the project.

Development experiments in Austin started with a limited array of 64 detectors, 2 fan-beam x-ray sources and a pair of rotating mechanical radiation shutters (choppers), all oriented horizontally due to ceiling height. The detector size and close spacing allowed thickness measurements at 0.2" intervals across the sheet. This orientation also facilitated hanging a sheet sample using ropes and pulleys to manipulate it.

Early success was encouraging but also uncovered problems with detector signal recovery and x-ray source stability. Scaling the array to accommodate a full width 60+" sheet required 512 detectors. The main radiation detection material was changed based on our previous experience and x-ray stability was improved.

Thickness data was available from most of the detectors 200 times per second. With the much larger number of detectors, the gauge computers could not handle the demands of data acquisition and processing. Due to the large quantity of data collected, software development was also needed to enhance the speed and accuracy of dimensional results and to display those results in a useful format. Ultimately detector data processing was limited to half speed. This would give cross sheet measurements every 6" at max mill speed.

As gauge development continued, design and fabrication of mill worthy enclosures for the sources and detectors and mill site alterations and gagehouse construction commenced. Large separate enclosures would allow the sources to operate in a temperature controlled environment on or off line and provide a safe and controlled area offline for the detectors.

Gauge installation in the mill was not without problems. Alignment of the two enclosures, both on and off line, required some rework but the major problem was mill water leakage through several detector maintenance access covers. After rework and then cover replacement the detector enclosure was secure.

Profile gauge measurements were compared with existing centerline thickness and width gauges. After nearly 6 months of online operation and data collection from thousands of coils by the end of 1990, profile gauge centerline thickness and width measurement verification was completed. Meanwhile, work continued to validate the full-width thickness measurements especially near the sheet edges. Software development to improve overall measurement capability and to improve graphical and numerical information display continued. Identifying that the sheet edges were curling was a significant discovery. Without correction the sheet edges appeared to be thicker and the width narrower. We proved that lateral sheet movement resulted in increased edge thickness in the direction of movement, at times causing changes in sheet wedge and other times creating sharp thickness increases (cat ears).

We had tremendous support from Sparrows Point including Dick Hostetter, Mike Homa, Jose DeJesus, Al Westra and Tom Logan. Confidence in the gauge profile measurements and use of the gauge for mill control steadily increased. The measured thickness profile changes over roll campaigns influenced roll grinding practices and product scheduling. The thickness profile variations as a function of sheet temperature profile and rolling speed were observed. Narrow cross sheet thickness variations (ridges or grooves) were detected and could be associated with clogged and blown roll cooling nozzles. Mill roll eccentricities and roll marks could be detected and traced back to the defective roll. The gauge became a very good learning tool and its utility on any mill became apparent.

The gauge was co-patented with SMS and we agreed to seek technology advancement opportunities, Bethlehem in steel and SMS in other metals. Despite our confidence in the gauge technology we were unable to convince prospective partners to commercialize it. SMS made a confidential arrangement with a gauge manufacturer in England. In the absence of any Bethlehem partners, we decided to support the SMS partner. The first commercial gauge was installed in Netherlands in 2000. Working with the partner we installed the first domestic commercial Tomographic Sheet Profile Gauge (TSPG) on the Burns Harbor 80" HSM in 2003. Three additional gauges were installed in Bethlehem successor mills. The commercial gauge measures full speed, rendering profiles every 3" at max mill speed. The gauge also provides high speed measurements of width, sheet contour and flatness. To date, the gauge performance continues to be superior to any competitor's. The gauge manufacturer is now in Germany and has supplied 15 gauges to US mills and a total of 92 globally.

Automatic Surface Inspection

By Duane T. Jones

In the 1980s, as digital camera and vision technology was developing and non-steel industries were beginning the use the vision technology to automatically inspect quality of their manufactured parts, the steel industry realized the potential benefits for steel processes. Bethlehem Steel's early venture into this technology was in partnership with Association of Iron &Steel Engineers and Kodak. Kodak had developed a system for inspecting its film manufacturing process, looking for defects during the film making. AISE provided funding, the Burns Harbor Cold Mill was selected as the test site, and Duane Jones, Research, with his instrumentation experience, was the lead Researcher. Kodak installed a one of its modified Kodak Veritas film vision systems on the BH Cold Mill inspection rewind line. A camera above the strip viewed a section of the strip as it processed through the rewind line. An image of the strip was generated from the camera data, and defects were highlighted. The rewind line offered a flexible platform to evaluate the technology as the line could stop the strip quickly or run the strip at slow speeds (or backwards) so that one could physically verify what the inspection system detected. As a prototype, the system provided an opportunity to learn of its potential. However, it was clear that the technology was at its early stage, and the system was removed after a few years of investigation. But advances in vision systems came rapidly, and from our experience with the Kodak system, Bethlehem continued to pursue the technology.

In 1990's, more advanced commercial vision systems were available. Camera technology with solid state sensors, high powered light systems, powerful minicomputers, and sophisticated image processing algorithms all helped to make the vision systems more capable of detecting and classifying surface defects. Burns Harbor plant continued to embrace the possibilities. Duane Jones helped specify, install and test one of the first Cognex Isys systems at the exit of the BH skin pass mill, where the strip was oily, and the line speed was very high. It was probably the steel industry's first application of the technology on a skin pass mill. The goal was to detect bothersome defects such as dents and slivers. The installation was difficult because of the environmental conditions – vibration and oil mist among others, but Duane was instrumental in designing an enclosure and mounting system that addressed the issues. By the mid-1990's, the system was operating successfully and continued to work for many years until the computer/software became obsolete.

By the late 1990's, the next application of surface inspection systems was at the Burns Harbor new Hot Dip Coating Line (HDCL). Coated sheet destined for use as exposed automotive body panels were required to be free of surface defects. This required quality inspectors to manually observe the sheet from inspection pulpits as it passed by. Surface inspection systems offered the hope that this inspection process could be accomplished by automatic systems. In fact, some automotive customers required that some sort of automatic detection be installed. For this first coating line system, Duane Jones sent defect samples to vendors and worked with them to determine the lighting requirements and the angle of view of the cameras for the optimal detection of all the important defects. He helped determine where to place cameras and lighting for best operation and protection and helped design their system mounting hardware for easier adjustment after installation.

We learned that surface inspection systems were complex devices which required a team of dedicated plant engineers along with Research to install, tune, verify and maintain. With these installations, Research gained experience to assist in the applying the technology to many other process lines, such as, at the new Columbus Coating Company HDCL and the pickler line at the Sparrows Point New Cold Mill. As Bethlehem evolved into ISG into Mittal Steel, automatic surface inspection became a standard component of all high-quality process lines in the steel industry. Duane Jones was the key Researcher involved in helping to direct Bethlehem's successful journey into this technology.

Market Mill – Strategic Study

By Dennis D. Newhart, Kenneth L. Stott, Francis J. Vasko

Background: The process of making corrosion-resistant steel coils for the construction market can be viewed as a continuous line process of consecutive batch operations. The first step of the process is the conversion of raw materials into semi-finished steel in the form of cast slabs. The cast slabs are rolled into hot bands, which are 48" wide and 0.032" gauge and are produced on a hot strip mill. The hot bands may then be inventoried; or they may proceed directly through two facilities in tandem: (1) a pickling operation with an acid bath to clean the surface of the coil; and (2) a cold strip mill to roll and reduce further the gauge of the coil to the final, desired customer specification of width and gauge. After the cold strip mill operation, the coils may again be inventoried; or they may proceed to a coating line where the width of the coil may be trimmed and a corrosion resistant coating of an aluminum-zinc alloy is applied to the coil. The coils are then sold "bare" (unpainted) to the customer for immediate application; or they are painted and delivered to the customer for the construction of metal building panels and roofs.

The construction market for these coated and coated/painted sheets is one that must be supported by consistent and timely delivery of the product to meet customer needs in the construction of metal buildings. Typically, an assortment of bare and painted coils may be ordered by the customer, e.g., MBCI, to be delivered to a building site in three days or less. However the fastest growing markets for these coated and painted coils is located in the southern and south-western United States. Thus the dilemma was how to supply these markets with high-quality products and excellent customer service with minimum inventory investments when the basic steelmaking processes were located in Sparrow Point, Maryland. The management strategy for addressing this problem dealt with locating all or parts of the supply chain near the largest markets.

A corporate study team was assembled to address alternatives which could satisfy the mission of evaluating the return on investment for locating a different part or parts of the steel production supply chain adjacent to the largest product markets. The quantification of which coil sizes to stock, and where to stock these sizes in the supply chain and how much of each size to stock for world-class customer service proved to be a formidable problem for the original study team. Subsequently the study team was enlarged to include members of the Systems Analysis Group of Research to aid in the quantification of alternatives.

The team identified four distinct strategies consisting of different parts of the supply chain being located at or between Sparrows Point and a new Market Mill.

Phase I -The Coil Size Consolidation Phase:

The overall quantitative problem was split into two approaches. The first Phase was dealing with Coil Size Consolidation. This phase was crucial.

A mathematical optimization model was built to select the minimum number of sizes that satisfy all of the customers within acceptable width and gauge tolerances. This model was run for different alternative supply chain designs.

Vasko as part of his PhD dissertation developed a unique and efficient heuristic called OPTSOL which was first developed to model the ingot/ingot mold size selection problem and can be used for other problems to optimize selection problems for thousands of variables.

The results of Phase I determined: 203 customer coil sizes needed for customers, 184 coil sizes needed before painting, 136 coil sizes needed before coating, and 27 coil sizes needed before hot band widths before pickling.

This consolidation had a major effect in reducing the variation in both the lead time and demand which in turn reduces the amount of safety stock required.

This reduction in standard deviation is the same principle used in investment portfolios.

Phase II: The application of Inventory principles

Inventories were estimated according to the distinct functions that they served in the supply chain.

- Pipeline inventories represent the inventory that had left one stage and was in-transit to the next stage. This can be estimated according to Little's formula as the shipment time between stages multiplied by the demand rate per unit.
- Work-in-process-inventories at an operation was dependent upon the rolling cycle with the coffin curve describing the time to roll all widths.
- Interdependence of stages were used to estimate the dependence of one stage on another stage. For example a 99% on time performance would be 99% to the fourth power or 96% overall.

- Safety Stock inventories estimated the interaction between lead time and demand i.e., how often would large demands occur with long lead times, and conversely how often would low demands happened with short lead times. These formulas are part of inventory theory.

After several meetings with Sales and Marketing, it was decided that the standard deviations could be estimated as the difference between best case and worse case scenarios and divide the result by four to get an approximate standard deviation.

An interesting result of this model, which captured both the time and rate of material flowing through the pipeline, was the evaluation of a proposal to ship the coils by barge from Sparrows Point to a new Market Mill near Houston. This method had the lowest cost ($/ton) although the transit time was the longest. The model's results correctly indicated that this was one of the most expensive total cost alternatives since more tons would be in the pipeline for a longer time versus other plans.

Results and Conclusions

The Phase I, OPTSOL, ran on the mainframe with results downloaded to a personal computer. The data file was then converted into a spreadsheet format, and the Phase II inventory model was also loaded onto a spreadsheet that could be taken to team meetings for answering sensitivity what-if questions during team meetings.

The differences in inventory were substantial for the four supply chains. When taking capital, labor, and inventory results into consideration, it was decided to build a coating line and painting line in Jackson, Mississippi. The creative and innovative solution approach used in this study resulted in the publication of a scholarly article in the *Journal of the Operational Research Society.*

Coal Blending Models for Optimum Coke-making and Blast Furnace Operation

By Dennis D. Newhart, Alan D. Strauss, Francis J,. Vasko

BACKGROUND

One of the major objectives for coke producers is to develop coal blends and coke oven battery operating procedures that will produce the lowest cost, highest quality metallurgical grade coke with minimal risk to the longevity of the coke oven battery. Over the years this has become more difficult because of (1) the more stringent coke quality required by high productivity blast furnaces, (2) diminishing reserves of high quality low pressure coals, and (3) aging (and weaker) by-product coke oven batteries.

The wall pressure limitations of high-capacity by-product type coke ovens require coking coal blends which produce lower coking pressures than required in the past. Determining the optimal composition to meet these cokemaking and blast furnace requirements is complicated because the transformation of coal to coke is extremely complex and is still not totally understood today. Determining an optimum coal blend composition is very difficult because of the complexity of both the chemical as well as the thermal properties of the individual coal types. Furthermore, individual coals typically lack all the necessary properties required to make good coke for the blast furnace without being detrimental to by-product coke ovens in terms of acceptable coke oven wall pressure.

MODEL DEVELOMENT

In 2000, a joint project was initiated involving two Research groups: the Ironmaking & Refractories group (Alan Strauss) and the Systems Analysis group (Dennis Newhart and Francis Vasko). The goal of this work was to develop a mathematical model that could be used to ensure the production of high quality coke. This work resulted in a two-step methodology for solving this problem. Step one is a classification step to determine which group of parameter settings lead to “good” blends for operations and which lead to “bad” blends. This statistical regression tree step, for a specific coke-making operation, empirically generates decision trees that contain information about the conditional constraints and information needed as input to a mathematical optimization model.

The mathematical model developed to optimize the blending of coals for coke-making and blast furnace operations accounts for the following constraints:

1. A maximum on the expected coke oven wall pressure
2. A minimum on the expected coke stability
3. A maximum on the percent volatile matter in the coal blend
4. A maximum on the percent sulfur in the coal blend
5. A maximum on the percent of ash content in the coal blend
6. Desired minimum and maximum per cents for each coal in the blend
7. A minimum number of input coals that should be in the blend
8. A maximum number of input coals that should be in the blend.

The optimization model is used to help the decision-making process of narrowing down a candidate list of new coal blends that need to be tested at the pilot oven facility and ultimately used at the blast furnace. This improves the timeliness of the entire pilot oven testing process by avoiding the “change-one-variable-at-a-time” syndrome; and it improves the effectiveness of the decision-making need to arrive at a minimum cost coal blend.

IMPLEMENTATION

The math optimization model was implemented using commercial spreadsheet software (EXCEL©) and embedded mathematical programming software (EXCEL© Solver). Also, a user blend model was implemented that allows the user to input a test blend and then predict the cost and key coal properties of the candidate blend. Coal blends recommended by the user blend model were tested at the pilot oven facility. The results of these pilot oven facility tests demonstrated close agreement between predicted and actual results.

An article describing this methodology was published in the *Journal of the Operational Research Society* and has been widely cited in the coke-making research literature.

Roll Preparation for Improved Sheet Roughness Quality

By Homero Ortiz

Starting in the 1990s, automotive customers increased their demand for better sheet surface (roughness) quality (particularly for coated products used in outer body panels of cars and trucks). Sheet with specific surface roughness quality had improved performance in the stamping and forming process and had better visual appearance after painting. Accordingly, each customer (Ford, GM, Toyota, etc.) specified surface quality attributes. Usually, these attributes were expressed as an acceptable range for average surface roughness (Ra) and peak count (PC) as measured by calibrated surface profilometers. At the new Hot Dip Coating Labs (HDCL), quality assurance personnel measured the sheet roughness from coupons cut from the end of coils to ensure that the product surface quality was within the customer requirements.

It took a while for the plants to develop the mill/line practices capable of meeting those requirements. Research was heavily involved. At Burns Harbor, Homero Ortiz was the lead Research engineer. Homero focused on the two processes that controlled/created the sheet roughness: the cold tandem mill which provides the substrate with a certain roughness to the HDCL and in-line skin pass mill at the end of the HDCL which imparts the final surface roughness characteristics to the coated strip. Homero, working with the BH team, studied a suite of interrelated factors – work roll preparation for each mill (roll grinding, surface texturing methods, roll to strip texture transfer, roll force influence), the effect of the zinc coating and galvanneal coating on the texture transfer (they are different – zinc coating is softer than galvanneal), issues with pick up of zinc particles on the skin pass mill rolls (how to keep the rolls clean), rolling lubrication on the skin pass mill, and finally, roll to sheet roughness transfer relationship. The study also included roll shops who ground the rolls and did the shot (grit) blasting of the cold mill work rolls and the outside vendor who textured the skin pass rolls with special electron discharge texture (EDT) machines. In the end, the EDT processors were asked to texture to lower roughness than they were originally comfortable with. And Homero studied the roll shop grit blaster process and was able to propose a process which produced a lower roughness work roll. The result of the many studies and trials was that BH established processing protocols for each step – the cold mill and the skin pass mill and the roll preparation – that enabled the HDCL to provide the correct surface texture to meet the requirements of the automotive customers. Then, when in the late 1990s, the Columbus Coating Line came on stream, Homero Ortiz again provided the technical support needed to establish good surface quality practices.

Research Efforts in Support of Automotive Steel Products at Bethlehem Steel

By Roger R. Pradhan

Late 70s - Early 80s:

Plain-carbon and high-strength, low alloy (HSLA), or microalloyed steels, annealed via the batch (or box) process, were the work-horse grades being used in the US automotive industry.

Considerable work had been done in the late 60s – 70s to optimize the formability of the plain-carbon grades & the chemistries of the HSLA grades.

The 80s:

Two continuous-annealing lines built in the US, including the Continuous Heat-Treating Line (CHTL) at Burns Harbor. Continuous-annealing has several major advantages over batch-annealing: improved property uniformity in the coil body, improved surface cleanliness, reduced processing time &, in case of HSLA steels, lower alloy levels to achieve a given strength level. On the negative side, formability levels in plain-carbon grades, at equivalent tensile-strength level, were inferior to batch-processed product.

Product development activities included:

- Optimizing the alloy levels in continuously annealed HSLA steels (tensile strength range: 300 – 500 MPa).
- Development of continuously annealed, vacuum-degassed, interstitial-free(IF) grades with high-levels of formability. (Over time, these would replace plain-carbon steels, in majority of applications). Vacuum-degassing capability was installed at Burns Harbor in the early 90s.
- Optimization of the electrogalvanizing process (at Walbridge Coatings), especially for exposed applications.

Process-development activities were primarily in support of the vacuum-degassing & continuous-annealing facilities at Burns Harbor.

The 90s:

New demands from the automotive industry were being driven by the Japanese companies (Nissan, Honda) beginning to set up shop in the US. Hot-dip coated (Zn, ZnFe) steels were gaining popularity in both unexposed & exposed applications. Costlier electrogalvanized coatings were on the decline. New hot-dip coating lines were built at both Burns Harbor & Columbus Coatings (Bethlehem Steel / LTV joint venture).

Interest in dual-phase (ferrite + martensite) steels, in unexposed, structural applications, was growing. Primary reasons were their improved crash-energy-absorption characteristics & ability to achieve high tensile-strength levels (500 – 1000 MPa), which in turn, would allow for reduced part thickness (weight reduction for improved fuel economy).

In exposed (outer body-panel) applications, demand was increasing for enhanced dent-resistance. This led to the introduction of bake-hardenable (characterized by increase in yield strength during the paint-baking process) & high-strength (TS: 300 – 440 MPa) IF (interstitial-free) grades.

Product development activities were focused on the Burns Harbor CHTL & the two hot-dip coating lines:

- Dual-phase grades (TS: 500 – 1000 MPa)
- Bake-hardenable grades (TS: 300 – 500 MPa)
- Higher strength IF grades (TS: 300 – 440 MPa).
- Hot-dip galvannealing (Zn-Fe) of these higher-alloy grades; obtaining exposed-quality surface characteristics.

Late 90s – 2003:

Significant research work had been done, through the late 80s – mid 90s, on ultra-high strength steels (800 – 1000 MPa), with the Burns Harbor CHTL in mind. However, production of some of these grades did not start until the late 90s, as demand for weight savings (via part thickness reduction) accelerated.

Over all these years, the Product Applications Groups (at Bethlehem, Detroit & Nashville) provided invaluable help to the customers in incorporating these new steel grades (with lower formability levels, different welding & surface characteristics) into automotive applications.

Expert Systems Applications

By Douglas J. Renn

Introduction

In the mid 1980's, Bethlehem Steel began applying expert systems technology to applications at the company's facilities. Over the next several years, expert systems were deployed on projects covering a wide range of areas such as:

- Diagnostic Analysis – Infer cause of system malfunctions from observable symptoms. For example, an expert system to assist repair personnel in troubleshooting motor controllers in a rolling mill.
- Process Monitor and Control – Examine process data, identify trends, adaptively govern the behavior of a system. For example, an expert system which combines an operator's knowledge with sensor data to help monitor and control furnace heat in a blast furnace.
- Planning and Scheduling – Plan production sequences or resource allocation. For example, an expert system to assist in the production order picking and allocation in a cold mill.

Members of the Systems Analysis Group of the Homer Research Laboratory (HRL) were actively involved in this effort beginning with an assessment of expert systems technology and its potential use as a tool for group projects. Team members also participated in the investigation and selection of expert system software tools used by the company, as well as developing and deploying several applications.

Overview of Expert Systems Technology

Expert Systems are computer programs which use an expert's knowledge and experience to solve narrowly focused complex problems at a high level of performance. An expert system generally consists of a knowledge base, an inference engine, and a user interface.

The knowledge base contains information such as facts, relationships and heuristics that have been defined by one or more experts. The most common method of representing the knowledge base is with rules. Rules take the form of "IF (condition …) THEN (conclusion …)". Both qualitative and quantitative information can be captured in the rules. Some applications incorporate "hybrid" expert systems which combine the experts' rules with heuristic modeling. This is particularly useful in the area of planning and scheduling. The inference engine controls the order of reasoning by chaining together information in the knowledge base as needed to infer new facts. The user interface provides a dialogue between the inference engine and user to obtain additional information and display results.

Expert Systems differ from conventional computer programs in that the knowledge base is separate from the inference engine, which is built into the expert system development tool. Therefore, information can be added to or changed within a knowledge base as more is learned about a process without having to change the inference engine. Thus, expert systems lend themselves to rapid prototyping, and easier maintenance.

Expert Systems Applications at Bethlehem Steel

Below is a partial list of expert systems that were developed by HRL Systems Analysis Group personnel:

- Westinghouse Motor Controller Troubleshooting (Bethlehem Combination Mill) – An expert system was developed to assist electronics repair personnel in diagnosing mill motor controller problems. The program systematically leads a repairman through a series of diagnostic checks until the cause of the failure is determined and a solution is proposed.

- Coke Oven Desulfurizer System (Bethlehem Coke Works) – A desulfurization plant removes hydrogen sulfide from the coke oven gas stream via a complex system of chemical reactions and equipment settings. An expert system was developed to assist the operator by providing advice for the most likely causes of process malfunctions and the corresponding corrective actions.

- Combination Mill Roll Buildup Scheduling (Bethlehem Combination Mill) – Part of the work required to schedule the flow of material through the combination mill included the preparation of a mill-buildup schedule i.e., scheduling the buildup of rolls which satisfy the mill rolling schedule. Using rules provided by the general foreman of the mill, an expert system was developed to create a mill-buildup schedule for a given rolling sequence.

- Rail Shape Control (Steelton 28’’ Rail Mill) – To improve the dimensional quality of the as-rolled rails, an expert system was developed and installed to provide operators with recommended roll adjustments for both the 28-inch rail mill finishing and roughing stands during rolling of standard tee rails, and to plot rail dimension trend charts and statistical process control charts for control purposes. The experience and knowledge of the mill rollers and theoretical rolling knowledge were used to establish the roll adjustment criteria for the expert system. When the mill operator enters dimensions of rail samples, collected at the hot saw every 15 to 20 minutes, into the system, the expert system compares the new information with stored dimensional guidelines for the rail section being rolled and recommends roll adjustments, if necessary. Routine use of the system helped standardize the mill roll adjustment procedure and improve the operator decisions. The system was also useful in training new operators.

- Diagnostics for the Stamper / Painter Unit (Burns Harbor #2 Caster) – An expert system was developed to improve diagnostic procedures for the stamper/painter unit on the #2 caster. As stamper/painter malfunctions occur, the operator can dialog with the expert system via a set of English-like questions and graphical displays to determine the appropriate repair group to call.

- Tin Products Customer/Order Evaluation (Home Office) – A multi-attribute based expert support system for customer/order evaluation ranks customers and their ordered products based on both objective and subjective marketing criteria.

- Plate Mill Crew Scheduling (Burns Harbor) – To create the weekly manpower schedule for the Plate Mill, schedulers had to account for seniority rules, position requirements, employee qualifications and availability, and additional rules agreed upon with the union. The process was both time consuming and complex. Mistakes in the schedule would lead to grievances filed by the union. An expert system created to automate the process significantly reduced the time required to create the schedule and the number of grievances filed.

- 160'' Plate Mill Jump Scheduling (Sparrows Point) – An expert system was developed to assist schedulers at the 160'' Plate Mill in preparing the daily Jump Sheet (i.e., the scheduled sequence of slabs to be rolled on the mill) using the available slab inventory as input. The system contains logic for several types of rolling (e.g., Burn, Coffin Rolling) and uses the appropriate logic to build the Jump Sheet.

- Hot Dip Coating Line Coil Sequencing (Burns Harbor) – To support the operation of the Hot Dip Coating Line, an expert system was developed that incorporates both expert based rules and a penalty-based coil sequencing heuristic to schedule the sequence of coils thru the mill. Before a coil enters the Coating Line, the end of the previous coil is welded to the entering coil so that a continuous coating operation can be maintained. If the difference in thermal requirements, coil width or coil thickness between coils is too great then a stringer (stock coil) has to inserted in the sequence. The objective of the expert system was to minimize the number of stringer coils used in the schedule, and replace manual scheduling that was time-consuming and tedious and did not always follow the sequencing rules which resulted in an increase in coil rejections. The expert system uses expert supplied rules to assign coils to pre-defined groups based on width range, product type (two main types of coated products), surface requirements (exposed to environment or unexposed to environment), and thermal requirements. The system uses the penalty-based heuristic to create a coil sequence for each pre-defined group. The heuristic first creates a penalty matrix of the "cost" (a function combining all the desired coil sequencing parameters such as, width, gauge and coating weight into a single calculated value) to transition from each coil in the group to every other coil in the group. An algorithm then generates a coil sequence attempting to minimize the "total cost" of the sequence.

In additional to the financial benefits of the above-mentioned projects, their creative and innovative solution approaches resulted in the publication of several scholarly articles. For example publicationsin *The Journal of the Operational Research Society.*

Instrumentation and Control for the Galvanneal Process at the New Hot Dip Coating Lines

By Ralph Rudolph, Mitra Deka

In the late 1990s Bethlehem Steel greatly expanded its capacity in producing hot dip galvanized product. The Burns Harbor Hot Dip Coating Line (HDCL) was built in the early 1990s, and a similar line was built about 10 years later at Columbus Coating (joint venture with LTV). Both

HDCLs were designed to produce sheet for the automotive market, and both were equipped with induction heating furnaces and soak zones above the zinc pot designed to produce galvanneal product, for which there was a rapidly increasing demand. In the galvannealing process, the strip enters the induction furnace immediately after the zinc pot and is rapidly heated. The heat causes some iron from the substrate to diffuse into the zinc coating creating a zinc-iron mixture. The soak zones allow the diffusion process to continue as the coating solidifies. Then the strip is cooled and later quenched to complete the galvannealing process. What could easily be an uncontrolled process, requires precision chemistry in the zinc bath, temperature control of the zinc pot, temperature measurement and control of the induction heating furnace, and soak zones that can hold the correct temperature. Homer Research personnel were a part of a large team of plant and vendor personnel working in all facets of the galvanneal process.

For the Burns Harbor HDCL, two of the areas where my group especially contributed were in the temperature measurement of the strip at the exit of the induction furnace and in the control of the induction furnace to reach targeted temperatures. To measure the strip temperature was difficult because the emissivity of the strip at the exit of the furnace was variable (because the annealing process was not always complete at that point, and therefore the emissivity was not constant). Pyrometers generally require a known or fixed emissivity. Ralph Rudolph, Research, modified a commercial Ircon pyrometer to read multiple wavelengths of thermal radiation to be able compensate for the variable emissivity and provide a reliable temperature reading. He also designed a large thermal shield and water-cooled sight tube for the pyrometer which reduced spray thermal radiation. With an accurate temperature signal available, Mitra Deka, Research, designed a process control loop for the induction furnace. Knowing the temperature of the zinc bath, therefore the temperature of the strip leaving the pot, he developed a model to predict the temperature entering the induction furnace. The model accounted for strip volume, heat transfer, and line speed. Now knowing the temperature in and out (from the new pyrometer) of the induction furnace, he estimated/calculated the heat needed from the induction furnace to bring the strip up to the required temperature. The induction furnace vendor, Ajax, provided the power efficiency tables (tables relating the induction furnace power to actual heat in the strip), and Mitra was able to complete the control loop. Mitra's heating control model was embedded in the process control. Thus enabled, the line operator could set the furnace to the temperature required by the product developers, or it could be automatically set. This was a key development, because for each steel grade or product, the product "recipe," including temperature of the strip at the furnace exit, was different, and these different set points could now be sent down from level II automatically. Mitra applied for and received a US Patent for the galvanneal control process.

In the 2000s, the temperature measurement and control "system" was replicated at the new Columbus Coating HDCL. Mitra Deka helped transfer the technology to the line vendor who implemented it, and Ralph Rudolph again provided the expertise for the temperature measurement of galvanneal on the new line as well.

Production of Exposed Quality Galvanneal

By Theresa C. Simpson, C. Ramadeva Shastry

In the 1990's, the primary product used for exposed quality automotive panels was Electrogalvanized coated steel. This product had a surface that contained the qualities necessary for good paint application and excellent corrosion performance in the field. The primary drawback to this product was the cost of the product. For this reason, the automotive industry was interested in suitable alternatives that would reduce their cost. Bethlehem's Homer Reach Laboratory personnel conducted significant research in pot chemistries, line speed and other critical parameters to determine optimal conditions to produce a hot-dip zinc-coated alternative that would have suitable paintability and corrosion performance to meet the automotive industry needs. Laboratory studies used the HRL hot-dip simulator with a controlled atmosphere to produce initial laboratory panels across a range of chemistries. These materials were tested across a wide variety of conditions to ensure they would meet automotive demands. Other studies targeted the interaction between substrate chemistry and the phosphatability and painted corrosion performance of these materials.

Once optimal chemistries were produced, the teams began work within the Burns Harbor facility to begin to produce this product. This was a new coating line commissioned in late 1992 incorporating the up-to-date coating technologies at the time. Line trials focused on all aspects of the coating process from incoming substrate characteristics, molten zinc chemistry, furnace temperatures and times to yield a suitable product to meet the high demands of this industry. Successful trials enabled product qualifications at customers such as Chrysler (now Sollantis) and GM for both exposed and unexposed automotive body panels. Concurrently, Research personnel embarked on successful development of newer proprietary grades such as titanium-vanadium and titanium-vanadium-phosphorous bake-hardenable steels and high strength dual phase steels based on C-Mn-Mo-Cr chemistry. Trials of one of the newer grades (Ti-V bake hardenable) were conducted at Chrysler's Twinsburg stamping plant for exposed parts 1998 and were successful.

As demand grew for the product, it was clear that additional production facilities would be needed to meet this demand. Efforts were initiated in the summer of 1998 to scope out latest technologies to be implemented in the new line. As this was to be a joint venture line between LTV Steel and Bethlehem, a team of engineers from both companies, including one from Research, visited Japan in 1999 to license furnace roll design and zinc melt de-drossing technologies from Kawasaki Steel. In the early 2000's, the HRL team actively participated in the planning and converting of an Electrogalvanizing line at the Columbus Coatings Facility in Columbus OH to build a new exposed quality Galvanneal line. This facility had the benefits of the learning from the Burns Harbor facility as well as the results of the HRL laboratory studies to ensure that it was designed for optimal production conditions. A six sigma project was conducted in 2002 at the facility to further optimize all aspects to the production conditions for this product. Attention to detail to ensure that pot chemistry, surface roughness, line speed and other operating conditions were appropriate to enable high yield. When this project started the yield was approximately 52%; far from the range needed to make this a profitable product. Through the work of the production and HRL teams, the yield increased to >90% and resulted in the Columbus Coatings facility being a world class producer of exposed quality Galvanneal to meet even the most stringent customer needs. In rapid succession, most automotive grades were quickly qualified at major customers including Japanese "transplants" such as Nissan and Honda that had stricter qualification requirements.

While the Japanese transplants and Chrysler marched forward with galvannealed products, GM and Ford continued with the use of electrogalvanized sheet for exterior autobody panels. The reason for this was their aversion to the appearances of red rust at scratches on painted galvannealed panels as opposed to on painted electrogalvanized. However, a major threat to electrogalvanized emerged in 1998 when Dofasco announced the purchase of hot dip galvanize technology from Europe (Sollac) forming a joint venture galvanizing line dedicated to exposed hot dip galvanized sheet (DoSolGalv). Projects were initiated immediately at Homer Research in collaboration with Burns Harbor in order to develop our own exposed quality hot dip galvanized product to compete with Dofasco. The focus of these efforts were coating weight uniformity, control dross-related surface defects, and achieving uniform matte surface texture on the sheet. Several line trials were conducted in Burns Harbor that achieved excellent surface quality through control of in-line temper rolling practices and lubricants. The culmination of these efforts was a successful stamping trial at GM Saturn in Springfield Tennessee in later years. Additionally, the creative and innovative nature of this work resulted in the publication of several scholarly articles.

An Intelligent Search Strategy for Optimizing Water Spray Settings on a Continuous Caster

By Francis J. Vasko, Herbert L. Gilles, Floyd E. Wolf,
Dennis H. Bright, Bulent Kocatulum

In 1993, Bethlehem Steel's Homer Research Department (Herb Gilles) developed a computer-based thermal solidification model that accurately predicts temperature and solidification profiles throughout the entire length of the continuous casting process. It should be noted that the thermal model requires a complete specification of external cooling conditions, i.e., the water spray settings, throughout the caster before temperatures or solidification conditions can be computed. In many instances, however, it is desirable to specify the thermal and mechanical condition of the continuous caster strand and then to determine how to cool the strand to attain those conditions. Specifying the thermal and mechanical conditions of the strand is not a simple matter due to conflicting operational constraints and requirements. For example, to increase productivity the speed is increased. With increased speed the cooling must be increased to solidify the strand completely before it reaches the end of the caster and is cut into slabs. More cooling means a stronger steel shell and most likely less internal cracks due to inter-roll bulging, but it also means greater potential for longitudinal and transverse surface cracking. This conflict between productivity, surface and internal quality always exists to various degrees depending on the metallurgical grade (steel recipe) and width of the steel being cast. Thus, when searching for the optimum conditions, constraints must also be considered to ensure that all quality and productivity conditions are met.

In 1997, a joint project was initiated involving two Research groups: the Steelmaking and Casting Group (Herb Gilles, Dennis Bright, and Bulent Kocatulum) and the Systems Analysis Group (Francis Vasko and Floyd Wolf). The goal of this work was to develop a procedure to carry out the search for the best or optimal water spray settings to ensure that quality and productivity conditions are met. The objective is to minimize the sum of the cost penalties due to violations of the constraints while allowing the cooling water flow in each zone of the caster to be within its allowable operating range or 0 i.e., the spray is shutoff.

An optimization model, that makes extensive use of domain knowledge of the constraints, was developed to utilize the thermal model and to take into account the following constraints: surface thermal stress, internal, bending, and straightening strains, surface temperature reheat, machine metallurgical length and cooling water capacities. A limiting value is defined for each of the constraints. A "cost" penalty is then linked to the violation of each constraint. The cost penalty can include a weighting factor to reflect the fact that the constraints are not necessarily of equal importance.

The optimization model uses a novel search strategy that has efficiently and effectively determined water flow settings for real-world applications. Specifically, given the caster operating parameters (casting speed, etc.) for a particular metallurgical grade and initial water flow settings, the Optimum Cooling program will determine “optimal” water flow settings without any further user interaction. That is, the program will *automatically* continue to execute the thermal model, evaluate the constraints, and adjust the water flow settings until the intelligent search has determined that no further improvement is possible.

The implementation of the intelligent search strategy (ISS) has resulted in a highly efficient and effective computer model for determining optimum water spray settings on a continuous slab caster. This model allows the user to find the best achievable cooling conditions while avoiding caster problems due to undercooling, longitudinal cracks due to overcooling, and internal cracks due to bulging, straightening, misalignment and reheat, with solidification within the allowable containment length and amount of cooling water available. This model has been designed and used as a tool to assist an engineer knowledgeable in heat transfer and solid mechanics to perform continuous caster cooling studies for process modification and improvement.

In 1999, Francis Vasko, Herb Gilles, Dennis Bright, Bulent Kocatulum, and Floyd Wolf received the Operational Research Society’s prestigious PRESIDENT’S MEDAL for outstanding contribution to the philosophy, theory and practice of Operations Research. Their solution procedure was discussed in the scholarly journal *OR Insight*.

A Hierarchical Approach for the Application of Slabs to Strip Products in the Steel Industry

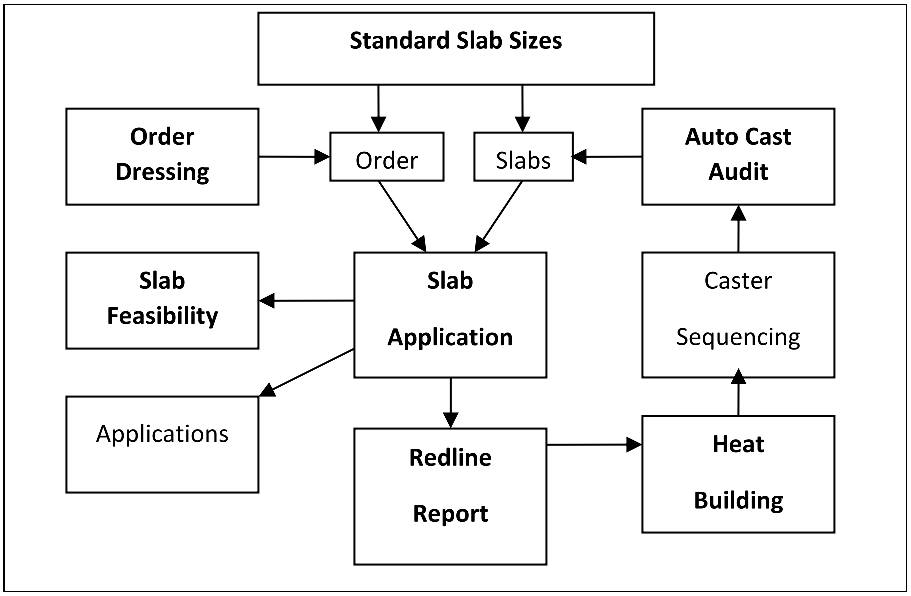
By Francis J. Vasko, Kenneth L Reitmeyer, L. Richard Woodyatt

Introduction

In the mid-1990's, Sparrows Point began an initiative to achieve 100% on time slab (a rectangular semi-finished piece of steel) availability to the hot strip mill. Order dressing or the specification of customer chemical and physical properties requirements, heat building or the grouping of customer orders into batch sizes based on metallurgical grade and slab size requirements, slab application or the assigning of specific slabs (either already produced or yet to be produced) to strip product orders (used to make appliance panels, steel storage sheds, food cans, etc.), and hot strip mill scheduling or the selection and sequencing of slabs to be processed into coils on the hot strip mill were manually intensive. The systems for each were stand alone, each with similar but independent slab application rules. Many efforts to fine-tune the process and systems fell short of the 100% on-time goal.

It was decided to implement an integrated system to do automatic order dressing, heat building, slab application, and mill scheduling (See Figure 1). A client-server based system was designed, with each of these functions accessing the same core slab application rules. This allows for consistent decision making improving customer service, reducing the manual intensity of the process, and providing more efficient use of non-standard inventory. A highly-efficient hierarchical solution methodology was developed and put into daily use from 1999 until the closing of the Sparrows Point Plant.

Figure 1 – System overview



Algorithm Overview

The algorithm starts by building a list of feasible applications for all open orders. These feasible applications can be singles, symmetric doubles, asymmetric doubles, or triples. Each slab usually has more than one feasible application. Also, each order typically has more than one feasible application. When a feasible application is found, it is assigned a score. The score is based on the type of match, the orders used, and how well the slab fits the match with respect to grade and size. The application score has no component based on pile utilization. The application score is treated like a penalty. The lower the score, the more desirable the application is. Two observations based on the list of feasible applications are:

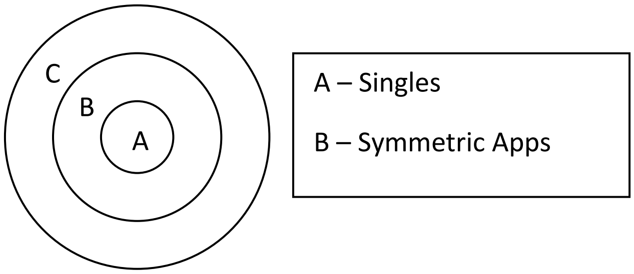
- Orders can be ranked by the number of feasible applications associated with an order. The fewer feasible applications an order has, the more constrained it is.
- Slabs can also be ranked based on feasibility. The more feasible applications a slab has, the more applicable the slab is.

The algorithm processes one order at a time, starting with the most constrained order. For the chosen order, a working list of feasible applications that include this order is built. From this working list of feasible applications, a list of feasible piles is built. A feasible pile is a slab pile with at least one slab included in the working list. The feasible piles are then ranked based on a number of factors: usable slab locations within the pile, number of unusable slabs within the pile, application score, and the number of slabs in the pile applied to a previous order. The working list of feasible applications is sorted by pile score, pile location, position within the pile, and application score. Applications are made from the top of the list down, picking the first feasible application for each slab. This ensures that the slabs are used from the top of the pile down, and the lowest score (penalty) application available for each slab is used. Slabs continue to be applied to the current order until either no more feasible applications are available or the order is complete.

A Hierarchical Approach

There is an inherent hierarchy in applying slabs. Single slabs get applied first, since they are the most constrained inventory. Symmetric doubles and triples come next, since all pieces are usually for the same order, which improves slab-handling logistics. Asymmetric doubles are the least desirable applications, since in most cases both pieces will end up on different hot strip mill schedules. Figure 2 illustrates the decomposition of the algorithm into a hierarchy of passes.

Figure 2 – Decomposing the slab application algorithm into a hierarchy of passes to reduce execution time



O	Number of open orders
S	Number of available slabs

Pass	**Potential feasible applications**	**Approximate problem size**
A	O x S	1.5 million feas apps
B	O x S	1.5 million feas apps
C	**O x O x S**	**1 billion feas apps**

In the first pass, all of the single applications are made. In the next pass, all of the symmetric applications are made. And in the last pass the asymmetric applications are made. In the asymmetric pass, all orders and slabs that have been applied as singles or symmetric applications have been eliminated from consideration. For every slab that does not have to be considered for asymmetric applications, this eliminates the number of feasible applications that have to be considered by the number of orders squared. In a typical problem size, each slab that is eliminated from the asymmetric step will eliminate the generation and processing of 810,000 feasible applications! Every order that is completed in the first two passes also contributes to reducing the number of feasible applications considered in the third pass. This dramatically reduces the time required to generate all feasible asymmetric applications.

Triple applications are limited by having three equal widths applied to the slab. This restriction comes from slab handling logistics and reducing the complexity of the algorithm. At 104 inches wide, a triple application would consist of three 34.5 inch wide pieces. The majority of orders in the typical order book are too wide to be made at this width. A slab must be at least 75 inches wide to be slit into a triple, since the minimum slab width to be rolled on the mill is 25 inches wide. Although it may appear that doing triples would require considering O^3 x S applications, the number is far fewer, since the number of orders that are candidates for triples is small. Restricting triples to be equal widths only also greatly reduces the number of candidates to consider.

Implementation Results and Benefits

This solution approach was implemented in regular production use in the second half of 1999 and used until the closing of the Sparrows Point Plant. After a gradual ramp-up, the system was able to meet its target of 60-70% application rate. During the years the system was in use, the algorithm performed well through a variety of business conditions, operating changes (the addition of the wide caster in 2001 for example), and inventory levels. During inventory rich situations, the slab application algorithm does a good job applying the best slabs to the current orders and pile logic becomes much more important. During inventory lean situations, the system makes good decisions about which orders should be applied given what slabs are available. Pile logic is less of an issue in inventory lean situations since the algorithm typically applies all available slabs.

Customer service was improved by ensuring the right slab is available at the right time to the application system. This was impossible to duplicate in the manual application mode because of the massive reapplication effort that is required. If the correct size slab is not available, the algorithm has the flexibility to find an alternative size that fits with a companion order. Better utilization, increased visibility through intranet reports, and feasibility statistics of the slab inventory has also led to reductions in slab inventory.

The innovativeness of this approach to apply slabs to strip product orders was recognized with its publication in the journal *OR Insight*.

Selecting Optimal Ingot Sizes

By Francis J. Vasko, Kenneth L. Stott, Floyd E. Wolf, James W. Scheirer

The Ingot Mold Stripper Project

In 1980, to remedy the deteriorated condition of its existing ingot mold stripper, the Bethlehem Plant proposed that a new facility be built because the cost of rebuilding the obsolete, existing facility was prohibitive. In 1981, management approved construction of a new facility capable of handling taller ingots; that is, solid rectangular-shaped steel blocks. The new facility was justified on the basis of projected benefits from reduced equipment maintenance costs and improved material flow resulting in fuel savings. The justification for the stripper did not quantify any projected benefits from redesigned ingot molds other than from raising the height of several of the current mold sizes.

Problem Formulation

Bethlehem’s management realized that operations research experts within the corporation’s research department could help design the ingot molds, and they formed an interdisciplinary team to do it. The Systems Analysis Group (an operations research group) within Bethlehem’s Homer Research Department developed a two-phase, computer-based model for selecting optimal ingot dimensions and internal ingot mold dimensions. At the same time, both the plant and the research department were performing steel deformation studies, examining the way the shape and size of the ingot is transformed by sets of horizontal and vertical rolls into a structural shape, for example, an I-beam. The interdisciplinary team of plant and research personnel incorporated into the optimization model (1) the new results from the steel deformation studies, (2) the enhanced capabilities of the new stripper, and (3) all relevant foundry, steelmaking, metallurgical, mill, and shipping yard constraints.

The Two-Phase Optimization Model

Phase 1 of the procedure generated feasible ingot and internal ingot mold dimensions consistent with (1) taking advantage of the enhanced capabilities of the new stripper—it could handle ingots of increased height and weight, (2) avoiding violating any foundry, steelmaking, metallurgical, mill, and shipping yard constraints, and (3) incorporate recent research and plant technology results related to improving yield and quality. Phase 2 then used a set covering approach to select from among the feasible sizes generated the ingot dimensions and the internal ingot mold dimensions that minimize the number of distinct mold sizes required to produce the finished products. Also, phase 2 selects, from among the solutions for the minimum number of mold sizes, the one that achieves the secondary objective of either minimizing product yield loss or maximizing mill productivity for the Bethlehem Plant’s product-mix distribution.

By decomposing the formulation into two phases, many math programming constraints were implicitly handled in phase 1. This reduced the size and complexity of phase 2 without sacrificing the accuracy of the overall problem formulation. This resulted in a very robust procedure that could easily handle changes in both constraint parameters and logic associated with generating feasible ingot sizes.

In phase 2 the first priority was to minimize the number of mold sizes because the inventory investment, material-handling, and logistical considerations associated with an additional mold size outweigh the potential yield or productivity benefits from increasing the number of mold sizes.

Analyses and Results

From June 1983 through February 1984, members of the Systems Analysis Group (K. L. Stott, F. J. Vasko, and F. E. Wolf) conducted extensive computer analyses using their two-phase math model for selecting optimal ingot and internal ingot mold dimensions. During this time period, studies performed at the Bethlehem Plant (J. I. Kinsey, W. S. Hutchinson, T. W. Sojda, R. J. Leonard, J. W. Scheirer, and R. A. Apple) and at Research (D. W. Reinbold, D. C. Ronemus, and M. M. Vyas) provided more refined input information for phase 1 of the optimization model. As they became available, these results were incorporated into the optimization model and analyses were performed to determine trade-offs among ingot taper, maximum section length, pour height range, minimum and maximum ingot dimensions for each final structural product, predicted yield loss and ingot-to-bloom reduction logic.

The analyses progressed through five major stages, with the total number of scenarios analyzed exceeding 50. The differences among the stages were the availability of new, more refined input information for phase 1 of the optimization model. After the systems analysis team analyzed each set of scenarios using the two-phase optimization model, the team met with representatives of the appropriate plant departments and with steel deformation specialists from the research department to discuss the results.

Based on results generated by the two-phase optimization model, a trial mold size was selected and mill trials were begun in November 1983. The ingots produced from these molds consistently resulted in improved mill yield, surface, and internal and mill rejection rates.

In March 1984, after completing these analyses, six new rectangular mold sizes (which included the trial mold size) were recommended to replace the existing mold sizes. At that time, the plant decided to phase in the new mold sizes as the existing molds wear out and were scrapped. When all six new mold sizes were implemented, the *anticipated* net annual cost savings due to yield improvement, increased mill productivity, and reduced mold inventory costs was $1.8 million.

Benefits Actually Realized

With all production coming from the new mold sizes, the actual benefits were considerably better than the $1.8 million estimate:

- The annualized reduction in mold investment due to fewer mold sizes was $0.42 million per year.
- The mill yield improvement was $2.0 million per year.
- The energy savings from the new taper was $1.8 million per year.
- The reduction in product reworking saved $0.2 million per year.
- Better mold life was $1.75 million per year.
- Reduced handling costs were $0.75 million per year.
- Productivity improvement was $0.7 million per year.
- More business due to heavier and longer product length was $0.5 million per year.
- Total: $8.12 million per year.

This project also provided the following qualitative benefits to the plant:

- It improved communication among plant departments and between the plant and the research department.
- A multitude of ideas went into the mold designs, and everybody shared in the success.
- It improved “customer-supplier” relationships within the plant.
- The project demonstrated that substantial savings could be achieved by changing the process.
- The two-phase optimization model accurately traded off a multitude of design considerations and constraints and gave Bethlehem the confidence to implement a reduced set of optimally designed mold sizes.
- The project was an example of how to manage a major plant effort involving diverse expertise and many departments.

The creative and innovative solution approach used in this project resulted in the publication of several scholarly articles. For example, publications in the journals *Operations Research, Interfaces, European Journal of Operational Research, and Fuzzy Sets and Systems*. Additionally, this work was a finalist in the 1988 International Edelman Competition which recognizes the best implementations of ingenious applications of mathematics to solve real-world problems.

Surplus Plate Application Module (SPAM)

By Francis J. Vasko, Kenneth L. Stott, Floyd E. Wolf

Introduction

From 1983 through 1985, Bethlehem Steel was in the process of installing, at a total cost of about half a billion dollars, a continuous slab-casting machine at the Sparrows Point Plant and a second continuous casting machine at its Burns Harbor Plant. In order to be able to utilize this equipment efficiently, Bethlehem concurrently developed Production Planning and Control (PPC) systems to coordinate its use. Since continuous casters link steelmaking directly with finishing mill operations, the PPC systems necessarily encompassed the majority of the plant functions.

The Systems Analysis Group (SAG) of Bethlehem's Homer Research Laboratory (K.L. Stott, F. J. Vasko, and F. E. Wolf) was asked to develop several critical PPC modules. One of these modules was the Surplus Plate Application Module referred to as SPAM. SPAM performed the key function of generating optimal cutting patterns for surplus plates produced by the batch steelmaking process.

Problem Description

In the steel industry, as a by-product of the batch steelmaking process, surplus rectangular plates (flat pieces of steel used in production of railroad cars, ships, pipes, boilers, etc.) of non-standard dimensions (length and width) are generated. Before new steelmaking is scheduled, an attempt is made to apply customer plate orders directly to existing surplus plates. Specifically, SPAM is designed to optimally map customer orders for steel plates into larger surplus plates.

When trying to determine the "best" mapping of orders into a surplus plate, several criteria are used. The primary objective is to maximize surplus plate yield; however, it is also important from a productivity and quality standpoint to cut few orders from each plate. Also, it is preferable in terms of customer service to map mostly high priority orders into a plate.

Because of practical cutting considerations, only two-stage cutting patterns were considered. The two patterns used are called the H and I patterns. In the H pattern, rows are formed by making cuts parallel to the length of the surplus plate S, that is, each row has its length equal to the length of the surplus plate. In the I pattern, rows are formed by making cuts parallel to the width of S, that is, each row has its length equal to the width of S.

Solution Procedure

A) General comments

Conceptually, plant personnel would manually first try to find an acceptable (reasonably good yield) cutting pattern with few cuts, mostly high priority orders, and few customers. If such a pattern was not found, then the constraints would be "loosened", i.e., more cuts allowed and/or lower priority orders allowed and/or more customers allowed, in order to attain a pattern with an acceptable yield. Because of the combinatorial nature (many possible cutting patterns) of this problem, it was very difficult to manually generate even modestly acceptable cutting patterns in a timely fashion.

The goal of the SAG was to develop a procedure that, without having to interact with the decision-maker during the solution generation process, captured the essence of this human reasoning and generated the "best" pattern without "violating" the constraints.

B) SPAM's solution strategy

Associated with each order were three attributes which indicated the priority or urgency of that order. Also, each order consisted of one or more plates, all of which have the same dimensions and physical and metallurgical specifications. For each set of plate orders that is associated with a surplus plate several "runs" are made. Each run is a cutting stock problem in which the goal is to find a high yield pattern that requires few orders. Runs differ based on which order plates are input, what the maximum number of rows and columns are in a pattern, and whether the program is generating either an H or an I pattern. More specifically, the SPAM strategy is to allow only high priority orders and very few rows and columns on the first run and to progressively loosen these constraints on subsequent runs. If a "stop yield", which is defined for each run, is achieved by the best pattern found for that run, then no further runs are made. In other words, we are trying to apply the highest priority orders first and only if the yield is not acceptable do we either include orders of lesser priority or allow more rows and columns in the pattern. The solution procedure, SPAM, uses a highly efficient customized branch-and-bound procedure to generate patterns. SPAM is set up to handle up to ten runs per problem (per surplus plate) and the nature of each run is defined on input.

SPAM Implementation

SPAM was coded in FORTRAN as a subroutine to be called from within a COBOL program. The Systems Analysis Group generated the FORTRAN code and a user's manual detailing the information required by SPAM and the results it generates. The COBOL program (developed by plant information services) accesses the appropriate data bases in order to match surplus plates with customer orders. After SPAM is called to apply orders to a surplus plate, the SPAM results are used to update the surplus plate inventory data base, the customer order data base, and other related data bases.

SPAM was executed as one of the first components of a nightly run of a production planning and control system. Since a large number of production planning and scheduling functions have to be executed nightly, it is important that SPAM executes quickly. Logic in SPAM is so efficient that more than 100 surplus plates could be applied to customer orders in only a few minutes on a 1986 computer (IBM3081).

SPAM was put into nightly use in March 1986. Due to the speed with which SPAM was able to determine high yield cutting patterns that require few orders, a substantial number of customer orders were applied directly to surplus plates on a daily basis. This resulted in:

- A minimum 10% surplus plate yield improvement (plant estimated improvement),
- Reduced inventory levels,
- Servicing orders quicker,
- Reduced new steelmaking.

The creative and innovative solution approach used in developing this computer-based module resulted in the publication of a scholarly article in *Fuzzy Sets and Systems.*

Physical Modeling Studies

By Mahesh M. Vyas

The steel industry faces some particular difficulties to study and improve its rolling and forging processes since many of them are carried out at elevated temperatures, and the effect of subtle changes in process parameters become difficult to monitor and /or measure. The study and improvement of these processes have historically been based on empirical data from full-scale operations. This is expensive and interferes with normal production.

A simple and more inexpensive means of studying these high temperature deformation processes is physical modeling using plasticine, wax and soft metals to simulate the hot working of steel products. When simulations are carried out under appropriate conditions, these materials can provide detailed information about high temperature metal flow at room temperature. Since these model materials also have low deformation resistance, the deformation equipment need not be high powered. As a result, scaled-down processes can be reproduced in the laboratory at room temperature to replicate the deformation of steel in hot rolling and forging processes.

For the above reasons, a physical modeling laboratory was set up at Homer Research Laboratories (HRL) in 1981 to investigate problems encountered in some of the Bethlehem Steel's high temperature rolling and forging operations. Initial efforts were directed to characterizing modeling material properties and to develop modeling techniques and procedures. As experience was gained, the capability of this facility was expanded by continually adding new equipment. These developments were mainly application driven on an as-needed basis in direct response to the plant requests and needs. Plasticine was the basic modeling material in the early years. Later lead was also used because it provided better workpiece dimensional stability and accuracy.

Modeling technology and procedures evolved over several years. Although the procedures varied depending upon the requirements of a particular experiment being conducted, the following is a general description of the plasticine and lead modeling procedures.

Modeling Materials: The mechanical and dynamic properties of plasticine may vary significantly between different suppliers and its colors/grades. To minimize these variations, only white plasticine was purchased and only from one vendor. This purchase was usually made in large quantities manufactured in one batch. Lead containing 1% to 2% antimony was found to be more suitable as a modeling material for some forging simulations.

Specimen Preparation: The specimen preparation procedures varied widely depending upon the process being studied and the material. Plasticine was usually extruded under vacuum in a kneading extruder prior to any shaping. Specimens requiring large irregular cross sections were prepared by compression molding plasticine in molds. After preparation, plasticine specimens were kept in the controlled laboratory environment for 2 to 4 days for temperature equalization. The as cast lead material, purchased from suppliers, was either machined into smaller specimens or extruded into the desired shape.

Deformation Experiment Procedures: All plasticine modeling simulations were conducted in a laboratory where the ambient temperature was maintained at 68F. The rolls and dies for deforming plasticine were either made of plaster, steel or aluminum. Talcum powder was used as lubricant between dies and the workpiece. Lead modeling experiments were conducted in the high-bay areas on two existing Stanat mills.

Specimen Analysis Techniques: Specimens were measured and examined before deformation, at intermediate stages and after deformation. Samples were collected at as many stages as practical. Surface and internal ink grid markings were measured to analyze strain levels and characterize metal flow within different segments of the workpiece during deformation.

The correct selection of model material and simulation techniques and equipment was important to ensure that the information on processing characteristics can be directly applied to the actual process under study. Few examples of successful applications of modeling to solve steel plant processes are shown below.

One early study was to evaluate the mill hardware and rolling practice proposed by the Steelton Plant operations for rolling a new track shoe section on their 28” Section Mill. The breakdown, roughing and intermediate stand roll passes were modeled using plaster rolls and plasticine blooms at 1/3 scale to evaluate the proposed rolling practices, such as roll pass (groove) designs, bloom sizes, reduction schedules and workpiece behavior during mill entry and exit. The results helped identify some potential problems and modifications were made to the originally proposed rolling practices. Studying different options in the laboratory prior to manufacturing the mill hardware and then conducting multiple mill trials resulted in production of saleable product during the very first mill trial.

Extensive modeling carried out using lead was quite successful in developing universal rolling practices for the new roughing stand for Saucon 48” Gray Mill. At the request of the Bethlehem Plant, a new Stanat rolling mill with two horizontal rolls and two tapered vertical rolls was acquired to support these efforts. Many section rolling practices were modeled using plasticine and/or lead for the sections, which were rolled on the Bethlehem Combination Mill.

In 1978, the Lackawanna structural mill was shut down and some complex sections that had been rolled at Lackawana were transferred to the Bethlehem to be rolled on the Combination Mill. This included sheet piling sections, channels and track shoe sections. The rolling of Z-piling sections proved to be a particular problem and the Bethlehem Plant requested our assistance in designing mill hardware and developing rolling practices. We were successful helping the plant in developing rolling practices to produce Z-piling sections and other complex sections transfered from Lackawanna.

<u>Bloom Rolling</u>: Experiments were conducted using plasticine at 1/5 scale to study rolling of Steelton continuous cast blooms into semi-finished round cornered square (RCS) blooms. Solidification cavities, typical of casting process, must be properly closed during rolling to produce semi-finished products with little or no voids. To measure three dimensional strain distributions at the core of the bloom, checkerboard type specimens using layers of two color plasticine were utilized. The consolidation of internal cavities was simulated by drilling holes in all three directions of specimens. Temperature gradient, existent in the bloom during rolling,

was simulated by using plasticine with different consistencies to make bloom specimen with softer core. The revised rolling practices were implemented at Steelton Plant, which included heavier reductions in later passes, a temperature gradient in the bloom and slower rolling speeds.

Open Die Press Forging: The solidification process of large ingots for heavy forgings after casting result in centerline (core) in homogeneities, such as porosity and segregation. To achieve the desired mechanical properties, the original ingot structure must be changed during forging to redistribute segregations and close up porosities. The forging process was simulated by carrying out physical modeling experiments using plasticine and lead as modeling materials. New forging practices were developed based on the understanding of stress states most favorable for internal consolidation, effects of several blocking parameters (workpiece aspect ratio, die width and shape, die overlapping, die staggering, temperature gradient and draft design) and upsetting parameters (aspect ratio, ingot chuck and die configuration and percent reduction) were investigated and new forging practices were developed.

SUMMARY

Physical modeling laboratory at Research Department was in operation for more than two decades. By continually adding new equipment and improving modeling techniques, the facility had evolved into one of the best in the industry. Modeling using plasticine and/or lead encompassed most of the processes and products in corporate operations. Successful implementation of modeling results resulted in improving yield and product quality and in minimizing new product development time and costs. Most of the laboratory activities were in support of joint plant and Research projects. The laboratory facility also became an excellent forum for training mill operators.

PHYSICAL MODELING - RESEARCH INDIVIDUALS

Over a period of more than two decades, several Research individuals, who are listed below, contributed to the physical modeling efforts. In addition, many individuals from several plants actively participated in conducting experiments.
Research individuals are listed here in alphabetical order:
J. Albert, R. Bodnar, B. Bramfitt, E. Erman, R. Lichty, H. Long, H. Ortiz, G. Padjen, D. L. Pysher, C. J. Romberger, D. C. Ronemus, D. C. Shah, A. K. Sinha, S. A. Tusan, M. M. Vyas and R. A. Zukawski

Automated Order Dressing

By L. Richard Woodyatt

In the steel vernacular, *order dressing* is the interpretation of a customer's order specification into metallurgical requirements and any other applicable mill production requirements. Traditionally this was a manual process conducted by experienced metallurgical department employees. As computers became more available, formatted screens were developed for inputting the instructions and linking them to the process control systems. However, the actual order interpretation and determination of the mill instructions remained a predominately manual process.

This automated grade dressing process system development was initiated by researchers at Homer Research Laboratories (HRL) in the early 80s. The concept was to input the customer order requirements in their terms and output the corresponding mill instructions in terms that are understood by the process control systems. This was to be accomplished by having an expert computer system that contained the customer specifications, a database of the available grade chemistries and statistical study of the expected properties as functions of the chemistry, processing and plate thickness.

The process was first applied to hot rolled plate products at the Sparrows Point plant. Most of their product specifications were based on trade association standards such as those defined by ASTM, ABS and various military specifications. In addition, many customer specifications added some chemistry restrictions or added testing requirements that supplemented the basic specification. Also, the steel service centers wanted multi-certified products so that their inventory would be as versatile as possible. These multi-certifications and other specification modifications were often difficult to handle manually but easily handled by the expert system.

It was quickly recognized that there were often more than one steel melting grade that would meet all the requirements and, more importantly, those valid options could be ranked by their desirability. As a simplified example where a customer ordered 1" hot-rolled plate that needed to be multi-certified as ASTM-A36, ABS-A and adds an additional restriction of 0.19 %C max we can see that there is an overlap area where all three criteria can be met.

Specification	C	Mn
ASTM A-36	0.25 max	0.80 -1.20
ABS A	0.21 max	2.5*C min
Modification	0.19 max	-
Overlap Area	0.19 max	0.80-1.20

Grade	C	Mn
X1	0.05-0.19	0.55 -0.85
X2	0.05-0.15	0.80-1.10
X3	0.10-0.15	0.90-1.15
X4	0.10-0.21	0.85-1.15

When we look at the available grades we see that two of them (X2 and X3) will meet all three criteria with X3 being a bit more desirable because it hits the middle of the desired manganese range. Grade X1 would have been acceptable if the steel was only ordered to the ABS-A specification and Grade X4 failed because of the added carbon restriction. In actual practice we had to deal with over a hundred melting grades and specifications that involved many other elements, complex equations relating combinations of elements for constraints such as weldability as well as a variety of mechanical property specifications.

This concept that having more than one applicable melting grade would result in fewer heats of steel being required to fill the order book was initially looked at skeptically but was soon embraced by the metallurgical and operations departments. It became of particular importance as the plant worked toward 100% on time deliveries coupled with a minimum slab inventory.

The general concept of applying more than one melting grade soon expanded to other products and plants. However, unlike hot rolled plate where chemistry variations was the most important criteria, and internal and external slab quality were of lesser importance, in hot rolled strip, the slab's internal and external qualities were more important. Thus it was important to have strip orders dressed with the minimum acceptable quality levels in addition to the chemistry restrictions.

In summary, an automated order dressing system was developed to interpret the customer's order specifications into mill process control instructions. The system ability to provide options for melting grades was instrumental in helping the plant reduce slab inventories and improve on-time deliveries. [More = Less]

Enhanced Slab Application

In a continuous casting shop, a continuous series of 300 ton heats of steel are bought from the melting furnaces to the caser in ladles. The liquid steel is then poured from a ladle into a refractory-lined holding vessel called a tundish to moderate the flow of liquid steel into the continuous caster. As the ladles are changed to bring in the next heat of steel, there is mixing of the material from the two heats and a small variation in the flow rate into the caster. This will result in both a chemistry transition zone and a zone of slightly reduced surface & internal slab quality. Although much work has been done in designing the tundish to minimize the turbulence and the extent of the chemistry mixing zone, they do exist, they are predictable and they must be considered in the slab application process.

The availability of alternative grades is of particular importance in the slab application process. They allow us to utilize the mixing zones on prime orders rather than on secondary orders. As an example, when we change from grade A to grade B, the mixing zone will transition from 100% A to 100% B over a few slabs. There is also a slight reduction in slab surface quality in that same zone.   As mentioned above, the caster control systems can accurately predict the chemistry and the surface & internal qualities along the cast slab. Given that data, there is a higher probability of applying these transition slabs to prime orders when we have orders dressed with alternative grades. For example, if a plate order can accept both grades A and B, it can accept the transition slabs between those two heats. Similarly, if a hot strip mill order has less restrictive surface quality requirements, it can utilize the transition slabs between two heats.

Epilog

The use of alternate grades and the enhanced slab application system played a major part in the improvement in steel making's on-time delivery of slabs. By 4Q96, Sparrows Point achieved 100% on time delivery of slabs to both the plate mill and the hot strip mill.