

# **The Samurai Sword Design Project and Opportunities for Metallurgical Programs**

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## **Abstract**

During the 2008-2009 academic year the faculty and all upper-division students (B.S. degree Metallurgical Engineering) at the South Dakota School of Mines and Technology (SDSM&T) were involved with an ambitious, integrated design project. Specifically, the project focused upon the modern-day reproduction of the Samurai Sword. The design project was inspired by the recent NOVA feature on “*Secrets of the Samurai Sword.*” The project involved all steps toward creation of a Samurai sword including identification and concentration of a local iron ore, steelmaking and final metal working. The results from this project are discussed as well as the implications for future training of Metallurgical Engineers. Finally, the project will be put in context with other pedagogical initiatives within the SDSM&T B.S. Metallurgical Engineering program.

## **Introduction**

The universally revered Samurai Sword embodies steel’s remarkable and valued properties emanating from steelmaking and metal working expertise. The correct fusion of these skills results in the legendary sword recently featured in the NOVA special “*Secrets of the Samurai Sword*”[1]. The NOVA episode detailed the identification of the ‘black sand’, furnace construction, ore reduction (production of the *tatara*), steelmaking (production of low-carbon and high-carbon *tamahagane*), forging/swordsmithing (making the *katana*), heat treatment, surface preparation, and finally measurement of sword performance[2].

The NOVA production highlighted the technical and geo-social aspects of this renowned sword. In particular the NOVA episode resonated with the B.S. Metallurgical Engineering students. The students raved about the NOVA episode for weeks after it aired.

The program faculty then logically wondered if a modern-day recreation of the Samurai sword might form the basis of a year-long design project. Subsequent faculty discussions led to an outline for an experiential design project that included extensive teamwork, industrial interaction, integration with the core Metallurgical Engineering curriculum, safety training, modern technical communications and fostering of an appreciation and understanding of the historical and artistic aspects behind the Samurai sword.

The resulting design effort involved all Junior and Senior level B.S. degree students as well as five program faculty, and encompassed the entire 2008-2009 academic year. During this

time the students were all enrolled for a total of three semester credits (first semester two credits and second semester one credit). Initial meetings involved team formation and overall project introduction. Four teams were formed: 1) Agglomeration Group, 2) Furnace Group, 3) Drawing and Hammering Group, and 4) Forge Welding and Quenching Group. What follows is a brief overview of the activities and results from each of these groups.

The B.S. Metallurgical Engineering Degree program involves a junior-senior cohort consisting of 36 semester credit hours of which 23 are required metallurgical engineering courses and six are directed metallurgical engineering electives. The incoming seniors in this project had completed during the previous academic year 14 credit hours of physical and mechanical metallurgy, composites materials and four credit hours of mineral processing-related instruction. During the term of this project, both the incoming juniors and the seniors working on the project were enrolled in four credits of transport phenomena (momentum, heat, and mass) during the fall semester and four credits of high-temperature extractive metallurgy in the spring semester. Not part of the cohort is a four credit course in Metallurgical Thermodynamics all students complete in the fall semester of their junior year. During the spring semester of the project, four students completed a three credit hour elective course in steelmaking.

### **Agglomeration Group**

The Agglomeration Group was tasked with the design of the processes for making the iron ore feed material for the Furnace Group.

#### ***Industrially Produced Pellets***

The Samurai used as starting material so-called “black sand” of local origin. Ideally, the Agglomeration Group preferred to follow this path rather than to simply use industrially-supplied iron ore pellets. However, the group decided that the most prudent path was a two-pronged approach. Namely, to pursue the identification of a local iron ore source, while simultaneously working with an industrial pellet producer to secure a well characterized source of iron ore pellets for use by the Furnace Group. Toward the latter path, Cleveland Cliffs donated iron ore pellets for the project. This interaction caused the Agglomeration Group to carefully weigh the many physico/chemical options associated with commercially available iron ore pellets. These interactions proved valuable for the team, both in terms of learning about the industrial pelletization process and industrial standards and protocols.

#### ***‘Black Sand’ of Local Origin***

Identification of a local iron ore source proved challenging. The Agglomeration Group began this process by conducting an analysis of the local mineralogy of the Black Hills region, which has a rich history of mineral/metal development (most notably the Homestake Gold Mine). The students determined that magnetite ( $\text{Fe}_3\text{O}_4$ ), associated with schist deposits, occurred in the Southern Black Hills. The Agglomeration Group students had earlier toured a Southern Black Hills mica ( $\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{F},\text{OH})_2$ ) mill as part of the MET 220: Mineral Processing and Resource Recovery course, and recalled that Pacer Corporation had recently installed an Eriez Magnetic Separator into the mill. The magnetic separator was installed to remove the ‘tramp’ magnetic content. The students subsequently contacted Pacer Corporation to determine if they

could secure a donation of the magnetic materials. Pacer Corporation graciously agreed to the request and donated a 55-gallon drum of material.

The Agglomeration Group performed a sieve analysis on the material donated by Pacer Corporation, as well as a visual inspection by optical microscopy. The color of the majority of the sample, its magnetic character, and finally x-ray diffraction (XRD) analysis indicated that a significant fraction of the sample was comprised of magnetite. However, the optical microscopy revealed that significant “locked” flake mica was present. Since mica is detrimental to the eventual steelmaking process the students determined that the sample had to be comminuted to allow the magnetite to be further concentrated before pelletization. The sample was subsequently comminuted by roll crushing followed by ball milling. The ball mill product (30 wt% -100 mesh) was once again viewed by optical microscopy, revealing that the magnetite was essentially liberated.

Next, the students used a shaking table to concentrate the magnetite. XRD analysis of the shaker table concentrate is shown in Table 1. Although the concentrate contained more than desired non-iron bearing minerals the Agglomeration Group determined that the shaking table product was of adequate quality for pelletization and use by the Furnace Group.

**Table 1. XRD analysis of shaking table concentrate**

<b>Mineral</b>	<b>Chemical Formula</b>	<b>Weight Percent</b>
magnetite	$\text{Fe}_3\text{O}_4$	75.5
albite	$(\text{Na}_{.98}\text{Ca}_{.02})(\text{Al}_{1.02}\text{Si}_{2.98}\text{O}_8)$	8.2
silica	$\text{SiO}_2$	10.6
hematite	$\text{Fe}_2\text{O}_3$	1.6
muscovite	$\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{F},\text{OH})_2$	4.1

### ***Pelletization***

Throughout the design process the Furnace Group communicated with the Agglomeration Group the status of their furnace design and their pellet requirements: size, shape and flux. These requirements caused the Agglomeration Group to draw heavily on their prior coursework (MET 321: High Temperature Extraction, Concentration and Refining and MET 426: Steelmaking), and the relevant technical literature on iron ore pelletization. The group determined that a basic flux was required, which necessitated the addition of 2.5 wt% sodium bentonite and 2.5 wt% calcium oxide to the shaker table concentrate. In addition both green strength (10 wt%  $\text{H}_2\text{O}$ ), fired strength and firing temperature and time (1300°C for 45 minutes) for pelletization was determined to be satisfactory.

Time constraints prevented the Agglomeration Group to completely supply the Furnace Group pellet needs, but the foundation for future pelletization efforts are in place. Consequently, the Furnace Group relied primarily upon the iron ore pellets donated by Cleveland Cliffs.

### **Furnace Group**

The Furnace Group was tasked with the design and construction of a furnace to reduce iron oxide to useable iron and refine it to useable steel. The primary completed coursework the students relied on was from the course MET 320: Metallurgical Thermodynamics, which offered neither kinetics nor heat transfer and only modest heat balance guidance. Packed bed flow computations for blower sizing were based on concurrent instruction in MET 422: Transport

Phenomena as were heat transfer computations. However, the instruction needed for a complete thermal analysis occurred after the design needed to be settled. The same was true for kinetic considerations.

The theoretical foundation for kinetic analysis occurred in the last few weeks of transport phenomena (MET 422) in the fall, and extractive metallurgy (MET 321) and the elective steelmaking (MET 426) course offered in the spring semester. The students' furnace experience made clear to them the critical importance of kinetics and heat balances. A retrospective analysis based on kinetic data from their steelmaking and extractive metallurgy coursework resulted in considerably improved design suggestions for the coming year. Additionally, a student graduating December 2009 who completed the steelmaking course is engaged in a Research Experiences for Undergraduates project to complete a design based on published kinetic data and his newly-acquired transport phenomena knowledge[3].

### ***Furnace Design***

The first semester effort was largely devoted to the design of the furnace. This process included several sub-tasks including: calculation of the expected pressure drop within the furnace (needed to size the furnace), determination of the optimal pellet size, determine of steel production method, calculation of the heat balance within the furnace and selection of materials and equipment. These tasks relied heavily upon prior content from the courses MET 232: Properties of Materials, MET 321: High Temperature Extraction, Concentration and Refining, MET 422: Transport Phenomena, and MET: 426 Steelmaking. In addition, one of the faculty mentors gave this group several lectures on these topics to assist them with calculating the chemical reactions for furnace design.

### ***Furnace Construction***

During the first semester of the design sequence the Furnace Team worked with the campus facility personnel to identify a safe and secure location for locating the furnace.

The furnace shown in Figure 1 was constructed from two commercially available water tanks. The inner tank shell was lined with a castable acidic refractory donated by GCC Dakota Cement. The outer tank formed a plenum for the blast (combustion air) while simultaneously regenerating the small amount of conductive heat loss through the furnace wall. Steel pipe pivots 2½ -in diameter were welded to both shells to allow easy cleaning, inspection, and repair of the furnace. Four tuyeres symmetrically placed through the inner shell could be accessed via ports in the outer shell. This made possible the punching of plugged tuyeres and radiation pyrometric temperature measurement. A 1½ -in. diameter hole was designed in the bottom of the furnace for removal of molten product. The furnace stand was designed to allow a secondarily heated crucible under the tap so that molten hot metal product could be collected and refined.

### ***Furnace Operation***

The furnace was charged with charcoal and fired for initial bakeout. Coke, donated by Nucor Steel (Nebraska), was then added slowly. The fire was allowed to burn for one hour to heat the furnace uniformly to approximately 1400°C. A small blower was used for bakeout.

In the first trial of the furnace, tuyeres were fed with air. The charge and pellets from Cleveland Cliffs were layered in the furnace to allow for reduction. After three hours, oxygen was fed into the air jacket along with the constant air supply. This was done to achieve a higher temperature. The furnace ran for two hours before cleanout of the furnace shaft. Reduced iron product, unreduced pellets, and coke came out of the furnace. A magnet was used to separate the reduced iron product from gangue material. This separated the magnetite/wustite mixture (54% magnetite, 44% wustite, and 2% hematite as determined by XRD) from the hematite. The separation was not perfect; however most of the reduced iron product was collected for further analysis. The total reduced iron product recovered was approximately six pounds.



**Figure 1. Furnace constructed by the Furnace Group.**

There were two distinct changes between furnace trial one and trial two. First, an oxygen tank was attached to the air jacket for continuous use, in addition to the air flow supplied from the blower. The oxygen tank was maintained at 30 psi. Temperature estimation was accomplished through the tuyere holes. With continuous oxygen, the temperature was approximately 1550°C. This was 100 °C higher than the previous trial. Furthermore, liquid iron was seen continuously throughout the process. Secondly, a sand plug was inserted into the bottom of the shaft to achieve a layer of liquid iron, close to the oxygen source. This caused liquid iron to clog and solidify in the tuyeres resulting in a premature cleanout of the furnace shaft. As a result, no reduced iron product was recovered.

### **Drawing and Hammering Group**

The Drawing and Hammering Group was tasked with developing the metalworking processes for homogenizing steel. Inclusive in this design was the characterization of the blade microstructure and selection and installation of any required equipment.

#### ***Metalworking***

The Drawing and Hammering Group developed the techniques for homogenization of steel including the design of a heat treatment schedule. This process involved interpretation of

isothermal transformation diagrams, alloy specification and heat treatment practices, followed by metallographic analysis to help validate the metalworking and heat treatment schedule.

The overall goal of the Drawing and Hammering Group was to homogenize steel produced by the Furnace Group by drawing it out and folding it over on itself multiple times. As per the discussion above, the Furnace Group did not successfully produce cast steel. Consequently, the Drawing and Hammering Group focused their design on commercially available steel product.

Successful homogenization of the steel requires it to be drawn out, folded on itself, forge welded, and repeated numerous times. Thus, the Drawing and Hammering Group was initially faced with the task of determining the adequate number of folds to homogenize steel. The group conducted a literature search (primarily drawing upon sources on knife and sword making), and determined the number of folds that would adequately homogenize steel. The group worked with a professional blacksmith (Mr. Jack Parks) to develop the skills necessary for homogenization of steel. First, the steel was heated and when it had become hot enough to bend easily, which can even be a dull red, it was wired brushed clean and then was folded over on itself. Next, the steel was put back into the forge, allowed to heat, fluxed with borax, and put back in the forge again. The flux was used to help keep the mating surfaces between the fold clean and free of impurities, including scale. As the steel was hammered, the flux was squeezed out and removed the interface impurities.

Once the steel had reached forge welding temperature the piece was removed from the forge, excess flux removed and metalworking began at the hinge end of the weld while working toward the open end. This process was needed to minimize trapping the flux in the weld. The steel, which was welded but approximately two layers thick, was reheated and drawn out using a hammer that dimpled the steel in such a way that it expanded in only the longitudinal direction. Ideally, the piece was drawn out to the thickness of the initial layer. The whole process was then repeated for each fold until the desired number of layers was reached.

All of the metalworking was performed on samples using a forge, hammer and anvil. Initially the homogenization was completed using a coal forge. In an attempt to expedite the sample heating, the group decided to use a natural gas fired forge. Despite many attempts, a successful forge weld was never accomplished in the natural gas forge. The group concluded that the steel needed to be heated to roughly 1500°C to be forge welded, while the gas forge could only attain temperatures between 1300-1400°C. The group also found pieces that were homogenized with forge welding techniques lost a great deal of scale during heating and working, and therefore, the group decided to purchase and implement a pneumatic trip hammer for the homogenization process. To conduct the homogenization portion of the design the Hammering and Forging Group drew upon their knowledge from a number of courses including: MET 232: Properties of Materials, MET 330/330L: Physics of Metals, MET 332: Thermomechanical Treatment, MET 430: Welding Engineering and Design of Welded Structures, and MET 440/440L: Mechanical Metallurgy.

### ***Trip Hammer Procurement and Installation***

As per the discussion above, the homogenization process via traditional blacksmithing techniques proved very time consuming, and consequently, the Drawing and Hammering Group decided to procure a trip hammer to facilitate the process. Toward this end, the Group: 1. developed performance specifications for the trip hammer, 2. obtained quotes, 3. worked with

the university purchasing system to order the trip hammer, 4. modified an existing lab to install the trip hammer, and 5) determined what safety equipment was needed in the renovated laboratory. The final installed trip hammer was supplied by Big Blu Manufacturing Company. In addition to installation of the Big Blu trip hammer an adjacent coal forge for adequate metal heating was required. The installation of the indoor coal forge necessitated significant attention to safety, specifically ensuring that there was adequate ventilation to avoid build up of carbon monoxide. The Drawing and Hammering Group tackled this design problem by applying course content from MET 422: Transport Phenomena and working with university facilities personnel.

## **Forge Welding and Quench Group**

The Forge Welding and Quench Group was tasked with developing the design processes to forge weld a hot rolled 1018 low carbon core and a hot rolled 1095 high carbon sleeve into a single component. In addition, the Group was to develop a subsequent heat treatment schedule to achieve the final desired sword properties and shape.

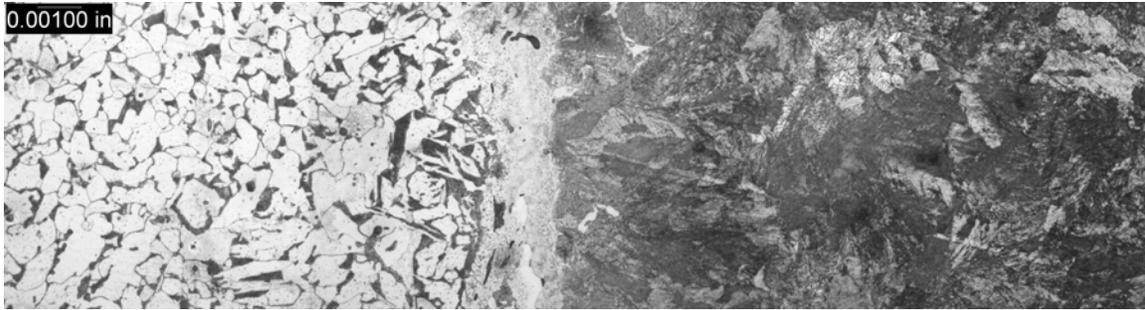
### ***Heat Treatment Background***

The Samurai Sword contains a low carbon core that acts as the spine to the blade for improved toughness. Consequently, during the quench process, the back edge of the sword was insulated to give a slower quench. This slow quench caused the back of the sword to transform into a non-martensitic microstructure such as pearlite. Pearlite has high ductility and fracture toughness. Due to these properties, the core keeps the sword from shattering upon impact. The front edge of the sword was not insulated and it formed primarily martensitic microstructures which are very hard but brittle.

During the quench process, a clay insulating mixture was used to slow the quenching process. The difference between the cooling rates of the front and back edges of the sword and between the low carbon and high carbon steel causes a volume difference in the martensitic transformation resulting in the signature curve of the sword. The outside high carbon sleeve keeps an extremely sharp edge very well. During the quench process, the sleeve is un-insulated and undergoes a relatively rapid quench. This transforms the high carbon sleeve into martensite. Martensite has high strength but low ductility and fracture toughness. Without the core, the softer and tougher sword would crack or shatter upon impact.

### ***Microstructural Development***

A forge was used for heating and the low carbon steel was then forge welded into the high carbon steel sleeve. The use of borax during the forging process, aided in the bonding of the steel by lowering the melting point of the oxides[4]. During the heating process, the flux reached its melting point and carried the oxides out of the welding regions. The task of forge welding was accomplished by heating the low and high carbon components until both reached approximately a lemon yellow color or 1000°C. The composite piece was quickly removed from the forge and welded by light hammer blows starting in the center of the material and moving outward to remove any flux that remained. Figure 2 shows the resulting forge welded microstructure.



**Figure 2. Optical micrograph showing the forge welded microstructure. Low carbon steel on left and high carbon steel on the right. The forge welded interface is in the center of the image.**

To achieve the desired metallurgical qualities, the back edge of the sword needed to be coated in an insulating material. The mixture chosen consisted of 35% soda ash, 7% carbon in the form of charcoal, and the balance northern light stoneware clay. Water was added until the mixture reached a consistency approximating that of pudding. The mixture was applied to the sides and spine of the sword, while the front edge of the blade remained uncoated. After the application, the mixture was allowed to air dry overnight. When the soda ash reached its melting temperature, it formed a glaze, helping the mixture adhere to the sword. The carbon helped prevent decarburization during heat treating, whereas, the clay acts as an insulating material. The Forge Welding and Quench Group spent several sessions experimentally determining the optimum mixture for insulating material.

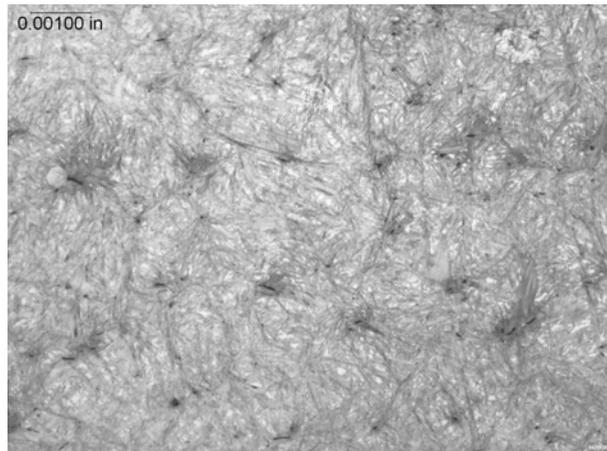
The sword was placed in the forge and allowed to fully austentize. A magnet was used to determine if full austentization had occurred. Water was utilized as a quench media for its ability to quickly quench steel. The fully austentized sword needed to be completely submerged in the quench medium in less than one second and remained submerged until the heat transfer of the sword to the water medium was halted. The angle of quench was also critical for ideal sword curvature. Upon the quenching of the sword, the blade formed a combination of lathe and plate martensite, as shown in Figure 3.

The low carbon core formed a pearlitic grain structure with proeutectoid ferrite at the boundaries, as shown in Figure 4. The characteristic curve of the Samurai Sword is produced from the difference in transformation volumes of martensite and pearlite. Figure 5 shows an example of the resulting curve after the above described heat treatment. The Forge Welding and Quench Group performed hardness tests on the martensitic blade edge and pearlitic core, and average hardness values of 68 and 21 HRC, respectively, were found. The Forge Welding and Quenching Group drew upon their knowledge from a number of courses including: MET 232: Properties of Materials, MET 330/330L: Physics of Metals, MET 332: Thermomechanical Treatment, MET 440/440L: Mechanical Metallurgy and MET 422: Transport Phenomena.

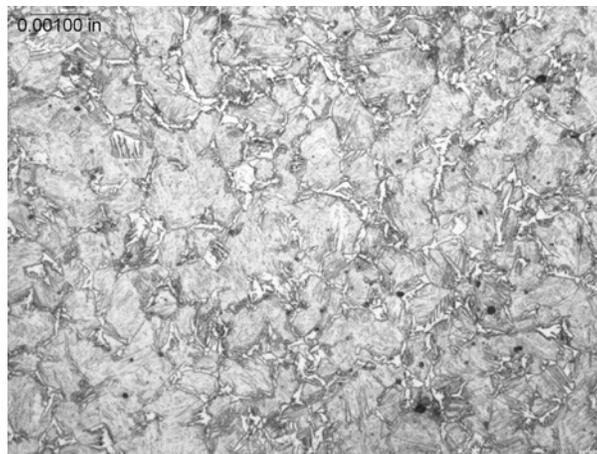
## **Technical Communications**

Throughout the design project the student groups relied upon traditional technical communication methods such as oral presentations and weekly memoranda and full-length technical reports. Additionally, the student groups utilized more non-traditional methods to document their design efforts. These methods included poster presentations and instructional videos associated with the design. Toward this latter aspect, the local Public Broadcasting

affiliate will use the student videos to augment their own in a subsequent documentary of the student design experience.



**Figure 3. Optical micrograph showing the desired martensitic microstructure of the quenched high carbon sleeve.**



**Figure 4. Optical micrograph of pearlitic microstructure with proeutectoid ferrite at the grain boundaries in the low carbon core.**



**Figure 5. Sample flat bar that was quenched with insulation and achieved the signature Samurai Sword.**

## **Curricular and Co-Curricular Activities**

The above described Samurai Sword design project is a component to a program-wide effort that involves substantial curriculum reform to include kinesthetic laboratory activities augmented by outreach and recruiting efforts. In addition, a focused undergraduate research component is included within the program. These efforts and their assessment are fully described in other publications. [3,5,6]

## **Lessons Learned**

One of the goals of the project was to determine the efficacy of the design project for use as a multi-institutional design competition. In this regard, the faculty concluded that indeed the project would be amenable, albeit it with appropriate modifications, to such a national competition.

Toward this end, we can summarize other “lessons learned” by the four groups as follows:

### ***Agglomeration Group:***

- Identify several iron ores during the first two weeks of the first semester and perform a critical design review to select the best candidate ore
- Provide for continuous mineral processing rather than batch processing
- Provide for scale-up of the pelletization process

### ***Furnace Group:***

- Provide for either faster reduction rate or allow longer reaction time
- Measure the oxygen potential of the blast furnace atmosphere using an oxygen probe to assure adequate reducing gas potential
- Design a means of reaching hearth temperature sufficient to maintain a molten iron product

### ***Drawing and Hammering Group:***

- Anticipate the need to devote time to develop the hands-on skills to forge welding a continuous weld
- Communicate early in the project the need to work with the university facilities on potential laboratory modifications
- Identify metal forging temperatures and forge temperature limits

### ***Forge Welding and Quench Group:***

- Identify type of forge to be used
- Practice forge welding technique early in the semester
- Perform initial heat treatment tests on commercially available steel

## Conclusions

An ambitious integrated design project was undertaken to develop the complete design for fabrication of a Samurai Sword. The design project included four sub-groups, each with specific tasks. Throughout the design process core metallurgical concepts were reinforced by drawing upon prior student coursework.

The cohort curriculum, which favored the project with physical metallurgy and mineral processing preparation this year, will be reversed during the coming year. With high-temperature extractive metallurgy and transport coursework behind them, the incoming seniors working on the furnace group during the coming year are expected to perform at a more advanced level. Conversely, students on the agglomeration, forging, and heat treating teams will, at least initially, discover the need for more knowledge before they encounter it in their coursework. However, they will have the advantage of project history.

## Acknowledgments

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