FERROUS METALLURGY: PAST, PRESENT, AND FUTURE DEVELOPMENTS

Significant advancements in metallurgy were highlighted at a special symposium presented at the Materials Science & Technology 2016 conference recently held in Salt Lake City.

Kester D. Clarke, Colorado School of Mines, Golden

The historical and technological developments that have driven metallurgy as a science provide a fundamental understanding of metals processing. This enables manufacturers to produce advanced materials and components that allow designers to push technical and scientific innovation across industries. Knowledge of the past ensures that both current and future metallurgists understand the significance of technologies developed to reach the capabilities we have today, and reveals the areas of need for fundamental understanding and technology development moving into the future. Armed with this knowledge, the next generation of metallurgists and materials scientists can once again revolutionize metals manufacturing and improve the quality of life for people around the world.

Bessemer converter, Kelham Island Museum, Sheffield, England.

To highlight some perspectives from significant advancements in metallurgy, an invitation-only symposium was organized at the Materials Science & Technology 2016 conference in Salt Lake City on October 24. Entitled "Ferrous Metallurgy: Past to Present," it was the second time this symposium has been organized, with the first taking place at MS&T14 in Pittsburgh. The goal of each symposium is to showcase important developments in metallurgy and the effects they have had on manufacturing and society.

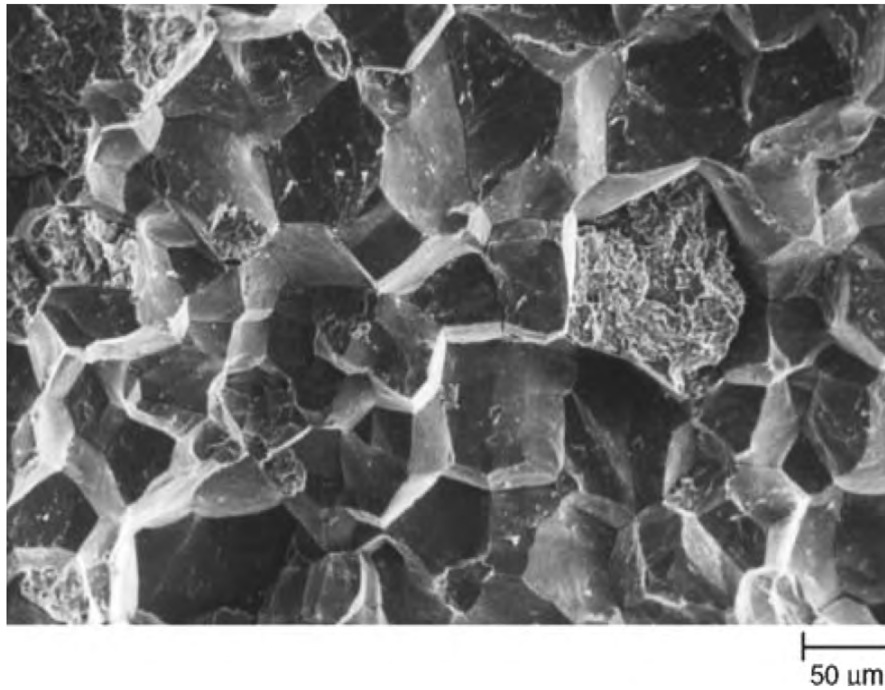
The first symposium brought together discussions on noteworthy historical aspects of ferrous metallurgy to remind us of the excellent work that has been done in the past and highlight the technological challenges to be overcome. Presentations focused on metallurgical eras ranging from cast iron smelting in the 8th century BC to the present day, and topics ranging from better understanding of microstructure-property relationships as characterization techniques improve to the development of science-based understanding of materials. In addition, significant industrial challenges such as understanding embrittlement in large ingot production, manufacture of plate armor at the end of the 19th century, and North American industrial development were addressed. Each speaker provided a valuable perspective on where we are today, how we got here, and where we need to go in the future.

Here, we highlight the subjects and topics presented in this symposium's second edition at MS&T16, which again covered a broad range of related topics to provide perspective on the drivers behind historical metallurgy development. Six invited speakers presented on topics ranging from the Bessemer process development to the history of very large forging presses, the latest developments in high temperature microscopy to the implementation of fine-grain practice in steel manufacturing, and from the fundamental understanding of near-equilibrium phase transformations to the mechanisms behind embrittlement in quenched and tempered steels. Recommended reading on each topic is listed in the references section.

SYMPOSIUM HIGHLIGHTS

In "The Age of Bessemer Steel," *AM&P* editor-in-chief Frances Richards presented the story behind the development of the revolutionary processing pathway that simultaneously reduced the cost and increased the quality of steel, fueling the Industrial Revolution and enabling reliable rail transport across continents. Based on the articles, "Metallurgy Lane: The Age of Steel" (Parts I and II) published by ASM life member Charles Simcoe in this magazine, the talk highlighted that both Henry Bessemer (of Sheffield, England) and William Kelly (of Kentucky) simultaneously and separately (around 1850) discovered that bubbling air through molten blast furnace cast iron removes carbon, thus enabling efficient steel production.

Along with Robert Mushet's discovery that the addition of manganese reduces "hot-shortness" by manganese sulfide formation, these developments allowed William Kelly to open a small plant using his process in Wyandotte, Mich., in 1863. At the same time, Alexander Lyman Holley was able to navigate the patent space in the U.S. and build the first Bessemer steel plant in Troy, N.Y., in 1865. By the end of the century, Andrew Carnegie became the leading producer of steel and the industrial and technological revolution was at full steam.



Brittle intergranular fracture along prior austenite grain boundaries in carbon steels quenched and tempered to martensite, known as quench embrittlement.

Jon Tirpak, FASM, immediate past president of ASM, then spoke about the technology development that enabled the move from hammer forging of steels in the years prior to World War II to hydraulic press use to control strain rates. This development allowed light metal forging and enabled the burgeoning aerospace industry. After the war, technologies originally developed in Germany were transferred to the U.S. and U.S.S.R., and a race to produce the largest presses to enable the production of large aluminum, magnesium, titanium, and steel components ensued. ASM International recognized the historical significance of six of these heavy hydraulic presses worldwide in 2013 by naming them ASM Historical Landmarks.

Press size correlates directly to the size of components that can be produced, which determines the largest aircraft size possible. In a world where new technologies for manufacturing components are being developed, including additive manufacturing, this talk highlighted the critical need to teach and develop expertise in processes such as forging. Unlike many other techniques, materials produced by forging feature refined grain structures and substantial mechanical work, and allow designers flexibility and opportunities to reduce weight in large structural components where properties and repeatability are critical to performance.

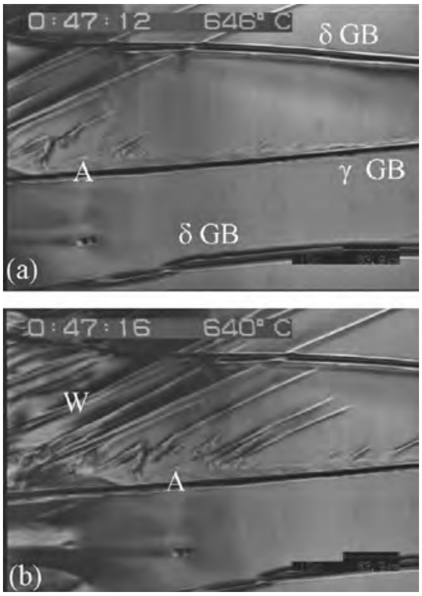
The third speaker, Prof. Rian Dippenaar from the University of Wollongong, discussed development of high-quality lenses that enabled optical metallography use, which in turn allowed for identification of phases and constituents in microstructures, transforming metallurgy. Initial observations using optical

Alcoa's 50,000 ton press, Cleveland, refurbished in 2012.

metallography were open to interpretation and each successive improvement in lens quality increased available magnifications, which further clarified microstructural details.

Dippenaar related these developments to current work using laser-scanning confocal microscopy to observe high-temperature microstructure development in-situ. Using this technique, important changes in microstructure such as solidification, and diffusional and displacive solid-solid phase transformations in real time, may be observed. Laser-scanning confocal microscope development now allows unprecedented observation of these phenomena as they happen, and interpretation of these results requires many years of study moving forward. The ability to characterize materials at higher resolutions and in real processing environments is a critical area where technological developments promise to unveil previously misunderstood fundamentals of metallurgy.

An area where improved characterization will continue to enhance understanding and result in vastly improved performance is steel processing. Prof. Emeritus George Krauss, FASM, Colorado School of Mines, gave an example by discussing the phenomena of



Observation of formation of Widmanstätten ferrite (W), from ferrite allotriomorphs (A) during cooling from austenite (γ) in an Fe-C alloy.

Cross-section of meteorite shows 3D microstructure formed over millions of years.

steel embrittlement. Several conditions exist where low ductility is observed in steels, including quench cracking, temper embrittlement, tempered martensite embrittlement, hydrogen embrittlement, and quench embrittlement. There was a focus on quench embrittlement, which results in intergranular fracture on prior austenite grain boundaries.

Krauss summarized the efforts over the past 40 years to understand low toughness that occurs in quenched and tempered steels with carbon levels of approximately 0.5 wt% and above. Through high quality characterization by various methods, it has been shown that cementite formation on prior austenite grain boundaries is associated with this reduction in ductility, and that alloying elements such as phosphorous further aggravate the problem. Over time, a map of tempering temperature vs. carbon content has been developed, showing that quench embrittlement occurs only in high carbon steels tempered at low temperatures. Understanding the mechanisms behind phenomena such as quench embrittlement allow the use of high strength steels with microstructures designed to avoid conditions where brittle failure would occur.

The fifth speaker, Robert Glodowski of RJG Metallurgical LLC, highlighted the importance of understanding microstructural development as a function of processing in his presentation, "The Evolution of Ferrous Grain Size Control: Standards and Practice." In the late 1950s, it was often necessary to specify use of alloying for austenite grain size control to ensure that hot rolled steels were heat treatable, and that the quality of the resulting products was satisfactory. However, as steelmaking and rolling processes steadily improved, the need for grain size control via alloying and prescribed processing procedures for as-rolled steels disappeared.

Improved processing technologies enabled controlled thermal and mechanical rolling techniques, which eliminated the need to separately roll for shape and heat-treat for properties. Because the fine-grained austenite quality requirement is often still cited in standards, the perception that they are still needed remains, even though they do not benefit modern as-rolled steels. Grain-refining alloy additions and associated testing increases the steelmaking process cost, and may in fact cause other quality problems and an unwarranted sense of security to the user. This is another example where a fundamental understanding of microstructural development as a function of processing is imperative to enable manufacturing with the highest possible quality at the lowest possible cost.

Finally, Prof. John Jonas from McGill University discussed how the study of meteorite microstructures could be used to better understand microstructure formation fundamentals. Because meteorites cool extremely slowly (around 1°-100° C per million years), the microstructures that form do so in near-equilibrium conditions, allowing observation of phase transformations that occur over time periods not practical in laboratory tests. This understanding can then be compared and contrasted to phase transformations that occur during manufacturing processes such as rolling.

In meteorites, phase growth occurs slowly and in the absence of stress; in rolling, transformations are rapid and occur under stress. The use of electron backscatter diffraction (EBSD) shows that the applied stress during rolling allows rapid ferrite formation at temperatures above those for equilibrium conditions, and also produces preferential crystal orientation selection with respect to rolling directions. In addition, ferrite formation during rolling results in softening and load drops as well as physical volume increases. This understanding allows metallurgists to better understand the phase transformations that occur during processing, design tailored processes to manipulate microstructure development, and improve the materials produced by rolling processes.

SUMMARY

All six speakers in this special symposium shared examples of the importance of understanding how the specific manufacturing process affects microstructure development in metals. The fundamental understanding of microstructure allows metallurgists to select manufacturing processes and schedules to tailor the microstructure, and therefore mechanical properties and performance, for a particular component.

Moving toward the future, continued improvements in the control of manufacturing processes and the ability to test and characterize materials will enable substantial further improvements in manufacturing capabilities. Metallurgists who understand this relationship will be better able to exploit technological advances and provide great benefits to manufacturing and society. It is critically important for industry to promote the education and training of metallurgists to ensure advanced understanding and capabilities.

Further reading related to each topic is referenced below. These symposia were organized through the AIST Metallurgy: Processing Products and Applications Technology Committee (MPPATC) and will be organized for a third time at MS&T18. Contact Kester Clarke (kclarke@mines.edu) if you would like to participate in the future or have topic ideas of interest. **~AM&P**

For more information: Kester Clarke is assistant professor, Colorado School of Mines, 1500 Illinois St., Golden, CO 80401, 303.384.2301, kclarke@mines.edu, www.mines.edu.

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