

# STEEL GRIPS

JOURNAL OF STEEL AND RELATED MATERIALS

[www.steel-grips.com](http://www.steel-grips.com)

Products  
& Quality



GRIPS media GmbH

ISSN 1611-4442



2010

**Mohammad R. Allazadeh:**

## Brief history of controlling cooling rate in cast steel

Steel history and its chronological progress have been reviewed from different aspects on many published papers, and books and it can be found on many websites. However, one historical aspect of this topic, which has received limited attention, is the gradual progress in knowledge of controlling cooling rate to get the desirable thermal and mechanical properties for the steel products. This paper presents some evidence of understanding the effect of cooling rate on the material properties from Iron Age era. It also discusses briefly the importance of determining optimum cooling rate in enhancing the production rate.

The huge current steel industry has been built as a result of enormous amount of research in different stages and procedures of steel manufacturing over centuries. In nature, iron is always in compounds or more precisely in iron carbide and some other type of alloys. Therefore, Iron Age is associated with steel production and one may state the interest on steel products has started since Iron Age when man learned how to produce cutting tools and weapons out of steel. It is hard to specify the time and location in which human has started to apply the knowledge of controlled cooling rate in optimizing the final steel products' properties. But a review of the steel history brings forth the idea of gradual progress of human understanding about the importance of the influence of cooling rate in the manufacturing of the various products of steel. Some believe the invention of iron technology was in the Mediterranean area about 1500 B.C.. However, lack of ability to reach high temperatures delayed the production of cast iron until a much later time when the Chinese developed the method of heating the steel up to a melting point around 800 - 700 B.C. [1; 2]. Nevertheless, the trace of discovery of steel can be found all over the world, **fig. 1**.

### Archaeological discovery of controlling cooling rate from Iron Age

From the beginning, black smiths were aware of basic factors in changing properties of many metals including steel. They had skill to manipulate the steel's strength and ductility properties via alloying containment, hot and cold working of the steel products, exposing the hot metal to different cooling rate during casting or heat treatment, etc. Although work hardening and alloy elements play important roles in modifying the properties of the steel, the configuration of the solid phases in steel can be optimized the properties of the cast steel for a particular application. Cooling steel from the austenite temperature may result in different transformation sequences and the allotriomorphic phase proportions such as ferrite, pearlite, Widmanstätten ferrite, bainite and martensite [4]. Many phenomena which control the density and arrangement of phases presented in the steel microstructure are a function of time and temperature. These phenomena determine the material properties of steel. The phase configuration is assembled during

heat treatment process and it depends on the number of factors such as steel chemical composition, cooling process parameters and some other key parameters in building phase configuration. Effective cooling process parameters on final microstructure configuration are the number of cooling cycles during heat treatment, number of isothermal steps, holding temperature at isothermal step, holding time interval at isothermal step and more importantly cooling rate. Factors affecting the cooling rate include: quenchant type and temperature, agitation velocity, viscosity, agitation type, aging, grade of steel, geometry, part area, part volume, density, specific heat, surface oxide layer, surface roughness, carbon content, grain nature, grain size, and a number of other issues [5].

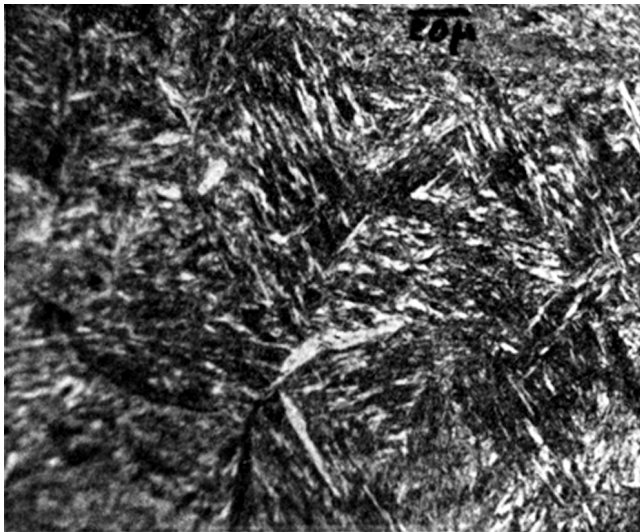
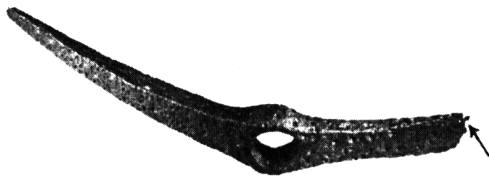
Black smiths centuries ago had used different coolant agents, such as natural and forced air cooling or quenching in water, to produce steel products of handcraft which needed good formability, or weapons that required steel to be very tough [6]. A study of the ancient history of steel reveals that the effect of heat treatment was known in ancient industry. **Fig. 2** is an engraved heating picture belonging to 4500 years old in *Sakkara* in Egypt. This may give evidence that heat treatment techniques were known to our ancestors. The stretched out hand blowing into the fire with hollow reeds image in **fig. 2** reveals the monitoring of the temperature by forced air-cooling.



**Fig. 1:** The Eskimos in Greenland made their iron tools for hundreds of years from a large (30 t) meteorite. It was moved later to the Natural History Museum in New York in the 1890s (courtesy of [3])



**Fig. 2:** Engraved picture from a mastaba in Sakkara, the necropolis of the early (and later) pharaohs (courtesy of [3])

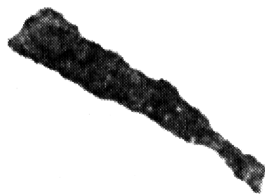


**Fig. 3:** An axe found in an excavation in 1976 manufactured in the 13<sup>th</sup> to 12<sup>th</sup> century B.C.

Fig. 3 is the picture of a “lightly tempered martensitic structure” from a flake from the pick of an axe found in an excavation in 1976 and manufactured in the 13<sup>th</sup> to 12<sup>th</sup> century B.C. [7]. There are many forms of evidence that show the research and study on cooling technology has been started even before man can melt the iron. Metallurgists verified signs of *carburizing and quenching* in the microstructure of knives found in Cyprus manufactured in 11<sup>th</sup> century B.C., **fig. 4**, in a dig in 1971 [8].

**Fig. 5** is the picture of an Iron Age Merovingian artifact [9]. Metallurgists were able to recognize pure ferrite in a Merovingian spearhead (fig. 5a) using etching techniques.

It is believed that it was normalized after forging at a temperature not less than 900 °C that is above austenite temperature (A<sub>3</sub> line in the Fe-Fe<sub>3</sub>C phase diagram). The bainite grain structure in the

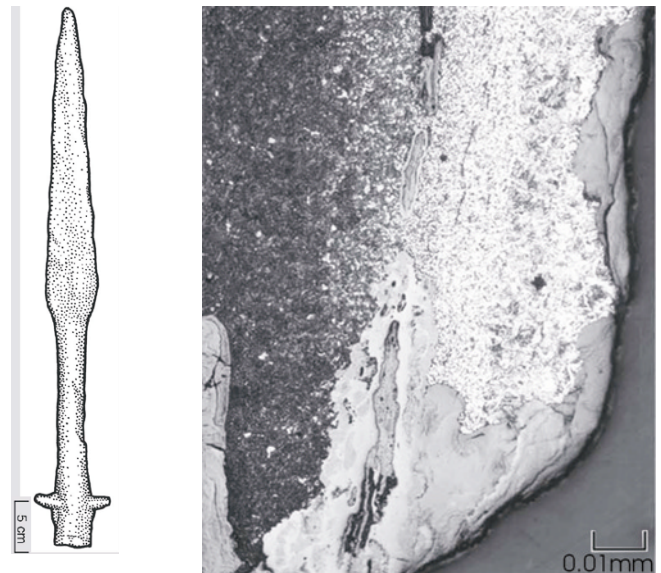


**Fig. 4:** Knives found in Cyprus in a dig in 1971 manufactured in 11<sup>th</sup> century B.C.

battle-axe (fig. 5b) reveals the quench hardening. It seems that the Merovingians were aware of the importance of controlling cooling rate to change mechanical properties of the steel. Published papers on Persian Shamshir and Damascus technique suggest the application of the monitoring cooling rate to obtain steel microstructure with proper strength and hardness, e.g. [10].

**Classical research on controlled cooling rate**

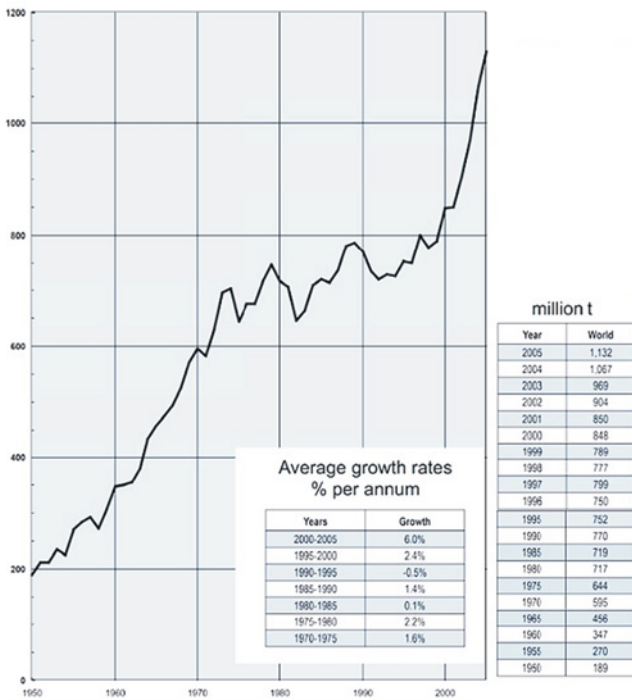
The knowledge of heat treatment in ancient time was base on trial and error and scientific research about the effect of heat treatment started at much later time. One of the earliest reports of classical research in heat treatment is in the book *De La Pirotechnia* from Biringuccio who quoted: “Every work of gold and silver as well as copper may be worked either hot or cold, only you must be careful to anneal the thing at every hammering or when it needs it” [11]. This is a proof for the attention of early classical researchers to understand the connection between time-temperature treatment and behaviour of steel during machining.



**Fig. 5:** Merovingian artifacts: a large spearhead (left) and a battle axe (right)

Revolutionary progress in physics of optical instrumentation and discovery of X-ray and etching techniques in the 19<sup>th</sup> and 20<sup>th</sup> centuries allowed metallurgists to investigate the microstructure of steel. These investigations helped to enhance the quality of the steel product along with its quantity. Supercomputers allowed researchers to develop theoretical models on the basis of experimental results and a number of papers has been published presenting the results of simulations of these theoretical models. Computer simulations have been deployed in the last decades to lower the cost of microstructural experiments. Work on modeling of thermo-mechanical treatments of steel has provided the possibility to predict the final microstructure during and after cooling process with different rates or heat treatment with different sequences [12...15].

Nevertheless, mass production of steel occurred only after the invention of the steam engine. The continuing in-



**Fig. 6:** Production of crude steel in 1950 - 2005 (source: International Iron & Steel Institute)

crease in the demand for steel around the world has been establishing the competition between countries and companies in producing steel. **Fig. 6** presents the fast growth of steel production since 1950 until 2005 around the world [16]. This annual increase in demand for steel and competition to dominate the market encouraged worldwide investment on research in increasing the production rate and lowering the cost of the final steel without sacrificing the quality of the steel. In the last decades, there has been an enormous body of research on heat treatment and the effect of temperature and heating or cooling rate on different metals and especially steel due to its wide consumption in different products in modern life.

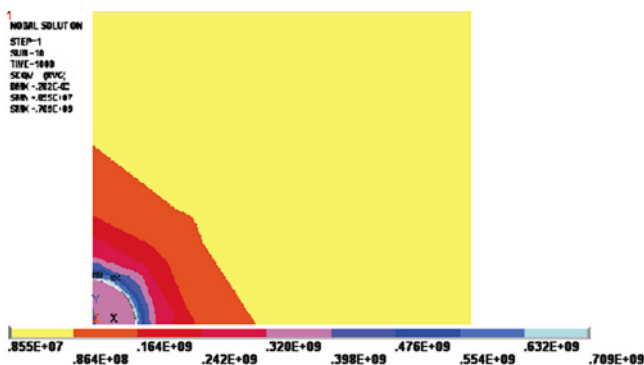
The previous experimental results and theoretical analyses led to higher profit in the steel industries and fast investment return by reducing the cost of the steel casting process and shortening the inventory time of the steel in the production line. An attractive method in mass metal casting is continuous casting method which is producing semi-finished metal shapes (slabs, blooms, and billets) from molten metal. In comparison to ingot casting, the continuous casting method has many advantages such as increase

in yield, better surface condition and internal quality of production, more uniform product, higher manpower productivity, easier integration into metal production systems and reducing metal production cost by saving time, energy, and capital investment. This is due to eliminating extra steps, such as ingot teeming, stripping, transferring, soaking pits; and primary rolling [17; 18]. George Sellaer received a patent on continuous casting of metal for producing pipes in 1840 [19]. Henry Bessemer patented a process for the manufacturing of continuous sheets of iron and steel in 1946 [20]. Thereafter, many inventions and modifications helped continuous casting process technology to grow to become the primary technique in producing ferrous and non-ferrous metals. The first vertical-type large slab machine with bending of the strand to horizontal discharge was launched in 1961 [20]. Detailed historical aspects of continuous casting can be found in many papers [21; 22]. Today, annually 750 million t of steel in the steelmaking operation, 20 million t of aluminum and many tonnes of other alloys are directly cast from molten metal by continuously casting method.

The last step in any method of metal casting is to cool the hot solidified cast product to obtain the desired microstructure. Imposing a high cooling rate on the hot slab increases the productivity rate, however, it might have disadvantages because of lowering soundness of the steel product due to formation of cracks and flaws because of thermal gradients and residual stresses mainly generated by phase transformation which results in the yield loss. Kobasko's [23] experimental results showed that the tendency for crack formation is higher with a range of cooling rates and it decreases for the cooling rate higher or lower than this critical cooling rate range as a function of quenching rate. Therefore, an optimum cooling rate must provide to increase the production rate without sacrificing the quality of the steel.

An FEM algorithm suggested by the author simulates the accumulated residual stresses in cooling as-cast slab with different cooling rates for three temperature regions in the Fe-Fe<sub>3</sub>C phase diagram based on the temperature of the as-cast steel prior to quenching [24]. These temperature regions are super-critical (austenite  $\gamma$ ), intercritical (austenite and ferrite,  $\gamma + \alpha$ ) and sub-critical ( $\alpha$ ) regions. Application of high cooling rate in steel manufacturing is done to obtain the desired mechanical properties such as, hardness, yield strength, improvement of wear resistance and toughness, ductility etc. [25; 26]. But quenching may result in flaw formation and accumulating the residual stresses within the microstructure. **Fig. 7** shows the effect of inclusions on increasing residual stresses within the microstructure during quenching of the as-cast steel slab [27]. The high stress region at the interface is the potential region for void nucleation and expansion.

Degradation of quality is a term that corresponds to any deviation from desirable composition; microstructure, application, commercial requirement specifications or chemical composition and mechanical properties as well as corrosion or heat resistance and formability. Efficient cooling rates obtained for a specific grade of steel provide an increase in productivity of steel and a decrease in the inventory time of production of steel slabs, blooms, and billet without degrading the quality of the steel. **Fig. 8** is the



**Fig. 7:** Equivalent von-Mises stress distribution in Pa in the model of Al<sub>2</sub>O<sub>3</sub> inclusion and steel matrix

schematic presentation of this fact which its detail can be found in [24].

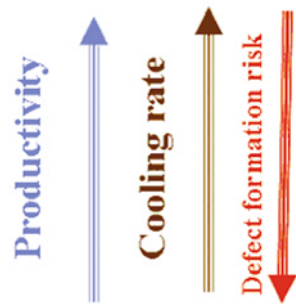
## Conclusion

There are many developments with the sole purpose of maintaining and/or increasing high production rate. Most of these developments, supported by extensive research, have been aimed at increasing the sophistication of the caster machine design and casting process in order to decrease the casting time and cost. Results from experimental tests, analytical computation and numerical simulation utilized the promotion of steel manufactured techniques around the world and lowered the cost of the steel making process. However, the research works will continue towards increasing the efficiency and productivity of the steel making process by enhancing both quality and quantity of steel casting process.

Many questions in regard to optimum cooling rate of casting steel may be raised from different points of view. For example, what is the effect of accelerated cooling on the overall soundness of the slab when cooled from the supercritical, intercritical and/or subcritical temperatures at different cooling rates? How does the composition of the steel dictate the industrial optimum cooling rate? How can the formation and propagation of the flaw and micro-cracks be predicted and prevented at high cooling rates? Although, the residual stress distribution during quenching has been addressed in previous research works [24; 28], to perceive comprehensively what factors determine the optimum cooling rate, more extensive research work needs to be accomplished. Elaborating the influences of these factors on the optimum cooling rate of the as-cast steel keeps this research field open for many new ideas and researchers. Customer defined properties for steel products call upon the metallurgists and engineers for new challenges to improve the steel products quality and higher casting production rates.

## Reference

- [1] <http://www.vikingsword.com>
- [2] B. L.Simpson: History of the Metal Casting Industry
- [3] <http://www.tf.uni-kiel.de>
- [4] T. Thewlis: Mater. Sci. Technol. 20 (2004), p. 143/59.
- [5] A. S. Varde, M. Maniruzzaman, E. A. Rundensteiner, and R. D. Sisson: The QuenchMiner™ Expert System for Quenching and Distortion Control, Heat Treating and Surface Engineering-Chemistry of Quenching, Indiana, USA, 2003, p. 174/83.
- [6] R. Maddin: A History of Martensite: Some Thoughts on the Early Hardening of Iron, Martensite, G. B. Olson and W. S. Owen, [eds.]: ASM Intern., 1992, p. 11/19.



**Fig. 8:** Optimum cooling rate of the as-cast slab based on the criteria of the objective of this dissertation

- [7] P. Astrom, R. Maddin, J. D. Muhly, and T. Stech: [in:] *Opuscula Atheniensia XVI* (1986), p. 27/41.
- [8] D. Davis, R. Maddin, J. D. Muhly, and T. Stech: *JNES* 44 (1985), p. 41/51.
- [9] C. S. Smith: Early Ideas on the Structure of Steel, G. B. Olson and W. S. Owen, [eds.]: ASM Intern., Metals Park, Ohio, 1992, p. 21/39.
- [10] Ehrenreich R. M., Hamilton E., Nash S. K.: *Archaeotechnology: Feature 57* (2005) No. 8, p. 51/55.
- [11] P. R. Riosa, F. Siciliano Jr, H. R. Zschommler Sandimc, R. L. Plautd, A. F. Padilhad: *Mater. Res.* 8 (2005) No. 3, p. 225/38.
- [12] B. Donnay, J. C. Jeraman, V. Leroy, U. Lotter, R. Grossterlinden, H. Pircher: *Proc. Int. Conf. Modeling of metal rolling processes*, London, UK, 1996, The Institute of Materials.
- [13] Lee J. K., Han H. N.: *Thermomechanical processing of steels*, Vol. 1, p. 245/54, 2000, London, The Institute of Materials.
- [14] Trowsdale, J., Randerson, k., Morris P. F., Husain Z., Crowther D. N.: *ibid*, p. 332/41.
- [15] Parker K. V.: *Modeling of phase transformations in hot rolled steels*, Cambridge, UK, 1997 (PhD thesis).
- [16] Bramfitt B. L., Speer J. G.: *Metal. Trans.* 21A (1990), p. 817/29.
- [17] Hogan, W.T.: *Steel in the 21st Century*, Lexington Books, New York, 1994.
- [18] B.G. Thomas: *Continuous Casting: Modeling*, The Encyclopedia of Advanced Materials, J. Dantzig, A. Greenwell, J. Michalczyk, [eds.]: Pergamon Elsevier Science Ltd., Oxford, UK, Vol. 2, 2001, 8 p.
- [19] U.S. Patent 1908: *Continuous casting of metal for producing pipe*, 1840.
- [20] Bessemer H.: *J. Met.* 17 (1965), p. 1189/191.
- [21] *Continental Iron and Steel Trade Report*, The Hague, Aug. 1970.
- [22] Pehlke R. D.: *JOM* 40 (1988) No. 11, p. 72.
- [23] Kobasko N. I.: *Met. Term. Ob. Metallov.* 2 (1964), p. 53/54.
- [24] Allazadeh M. R.: *The Effect of Cooling Rate on the Microstructural Configuration of Continuously Cast Steel Slabs*, Pittsburg, 2009, (PhD dissertation).
- [25] Gür C. H., Tekkaya A. E.: *steel res.* 67 (1996) No. 7, p. 298/306.
- [26] Totten G. E., Tensi G. M., Canale F.: *Fundamental Thermophysical Processes Involved in Quenching, Heat Treating and Surface Engineering-Chemistry of Quenching*, Indiana, USA, Sep. 2003, p. 148/55.
- [27] M. R. Allazadeh, C. I. Garcia, A.J. DeArdo and M. R. Lovell: *J. ASTM Intern.* 6 (2009) No. 5, paper No. 016905JAI.
- [28] Allazadeh M. R.: *Simulation of solid-solid phase transformation during cooling process*, symp. Domain Microstructures and Mechanisms for Advanced Properties in Phase Transforming Materials, session modeling of rolling and cooling, MST09 conf., October 2009.



Mohammad R Allazadeh, PhD

Mechanical Engineering and Material Science Department  
University of Pittsburgh  
Pittsburgh, Pennsylvania