Effect of Prior Microstructure and Heating Rate on Austenite Formation Kinetics in Three Steels for Induction Hardened Components (Progress Report - December 1, 2005)

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1. Introduction

This research project was initiated in August 2004 and forms the basis of the Ph.D. thesis project for Kester Clarke. Clarke completed his M.S. thesis at the Colorado School of Mines (CSM) in May of 2002. The anticipated completion date for this project is fall 2007.

The scope of the project is to characterize on-heating transformation kinetics and microstructure development of three steels as a function of heating rate. The materials selected for this project are three induction hardenable steels with varied starting microstructures, including three ferrite/pearlite, two spheroidized, and one tempered martensite microstructure. The goal is to develop improved heat treating cycles, define a processing window for optimal performance, and possibly evaluate resulting impact and fatigue properties.

The present report summarizes an initial literature review of experimental work and modeling efforts and discusses the project plan, which includes characterizing the transformation kinetics in the supplied materials and evaluating the resulting structures.

2. Industrial Relevance

The major advantages of using induction heating for industrial processes (e.g. induction hardening, forge preheating etc.) are shorter processing times (cost reduction) and the ability to predictably heat a specific region of the part in a repeatable manner (improved quality). In addition, induction heating is relatively energy efficient and environmentally friendly when compared with furnaces, baths, and gas surface treating systems. However, the high heating rates associated with induction heating also pose metallurgical challenges relating to the rate of decomposition of the parent microstructure and the homogeneity of the resulting austenite as a function of time. Much of the work on hardening processes has been focused on the decomposition of austenite, and often assumes homogenous austenite of a given grain size prior to quenching. Processing based on such assumptions can produce unexpected residual effects on the final product due to the initial microstructure, resulting in final microstructures that are adequate, but not optimum. If, however the kinetics of the austenite formation can be characterized for a variety of initial microstructures, it may be possible to have a better characterization of the austenite before the final quench. Since induction heat treatments generally are intended to heat treat a specific area on a part, this information may also be used to identify non-ideal microstructures that result from areas surrounding the focus area that are not completely heat treated. Finally, a study of this nature may achieve improvements in the design of induction cycles that can be designed to minimize time and provide optimum, rather than adequate, microstructures.

3. Materials and Initial Microstructures

Three steels have been selected for this project, and were supplied and heat treated by the Timken Company. The nominal chemical compositions for the steels are presented in Table 1. The materials are supplied in tube form, with the outside diameter (OD) and wall thickness (WT) as shown in Table 1.

For this project, two initial conditions are being considered for each alloy, resulting in a total of six initial conditions to characterize the high-heating rate austenitization response.

Table 1 Nominal Chemical Compositions And Dimensions of the As-Received Materials. (wt%)

Element	1045 203 mm (8.0 in) OD; 25 mm (1.0 in) WT	5150 155 mm (6.1 in) OD; 21 mm (0.81 in) WT	52100 71 mm (2.8 in) OD; 16 mm (0.64 in) WT
C	0.46	0.52	1.04
Mn	0.75	0.85	0.34
Cr	0.06	0.80	1.44
P	0.007	0.011	0.016
S	0.020	0.020	0.012
Si	0.25	0.26	0.26
Ni	0.11	0.10	0.11
Mo	0.02	0.03	0.04
Cu	0.25	0.25	0.24
V	0.001	0.002	0.008
Al	0.033	0.028	0.023

The 1045 steel has been supplied in the as-hot rolled condition, and half of the material was heat treated to a normalized condition. The as-hot rolled microstructure is pearlite with grain boundary ferrite, Figure 1. The normalized microstructure is not presented here, but normalizing treatments usually result in finer grained and more homogenous austenite, which will result in a finer grained pearlite and ferrite microstructure, with perhaps a finer pearlite carbide spacing.

The 5150 steel has also been supplied in the as-hot rolled condition, with half of the material oil quenched and tempered. The as-hot rolled microstructure is pearlite with trace amounts of ferrite, Figure 2. The oil quenched and tempered microstructure consists of highly tempered martensite, Figure 3.

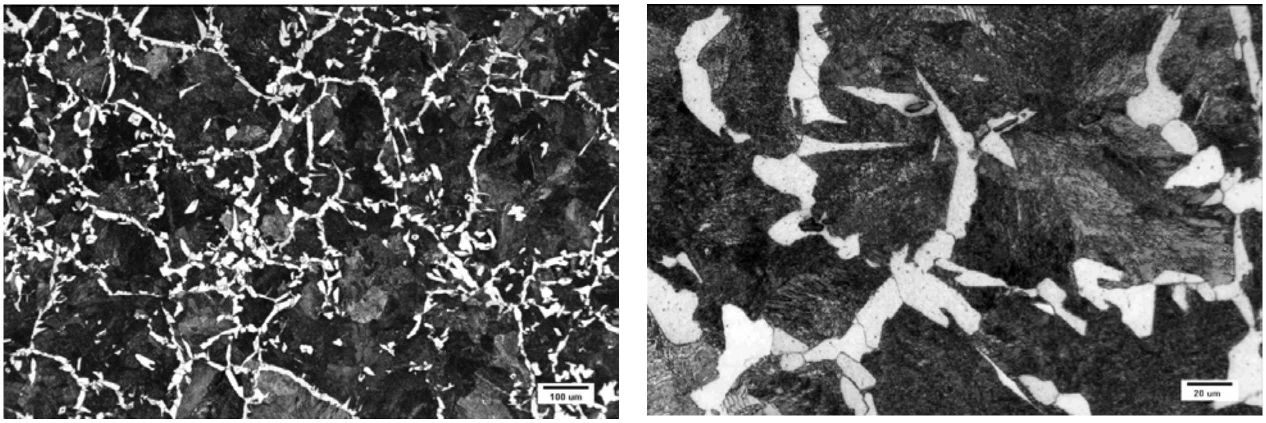

Figure 1 Ferrite and pearlite microstructure of the as-hot rolled 1045 steel. Light micrographs - nital etch.

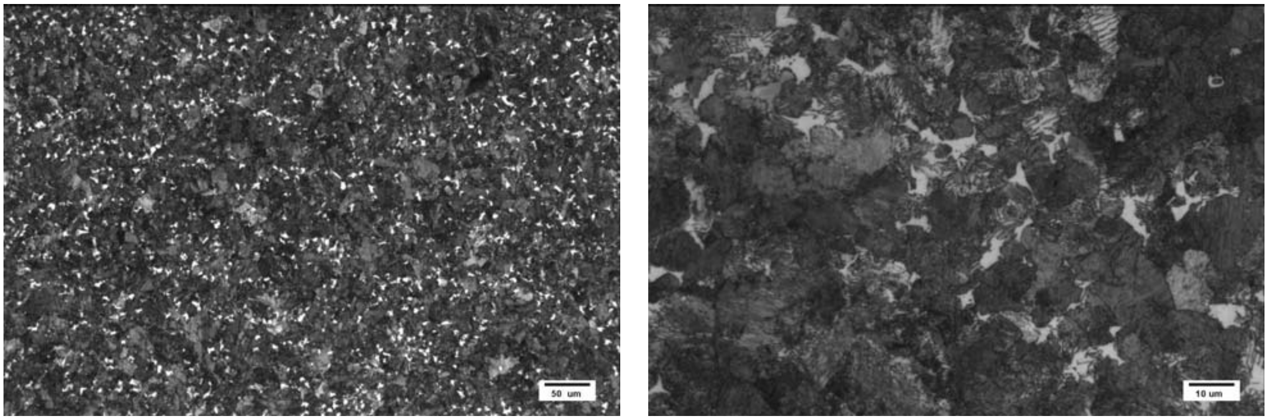

Figure 2 Ferrite and pearlite microstructure of the as-hot rolled 5150 steel. Light micrographs - nital etch.

The 52100 steel has been supplied in the spheroidized condition, with half of the material heat treated to increase the size of the spheroidized carbides. The microstructures were rated according to ASTM standard A892.

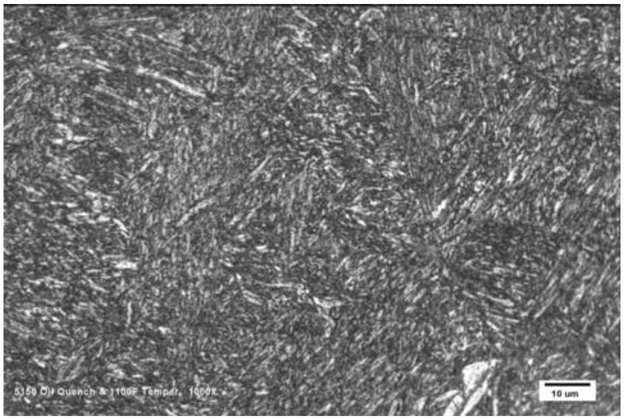

Figure 3 Highly tempered martensitic microstructure of the oil quenched and tempered 5150 steel. Light micrograph - nital etch.

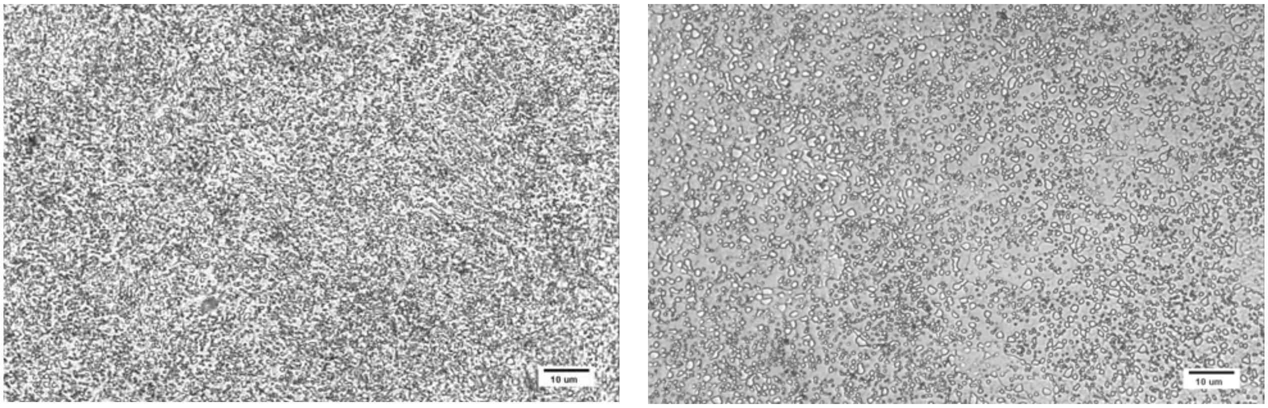

Figure 4 Fine (left) and coarse (right) spheroidized carbide microstructure of the as-received 52100 steel. The fine microstructure is rated per ASTM A892 as CS=2 (419 carbides/400 µm^2) with no retained carbide network or lamellar content. The coarse microstructure is rated as CS=5 (165 carbides/400 µm^2) with no retained carbide network or lamellar content. Light micrograph - nital etch.

The as-received material has a carbide size rating of 2 (~ 419 carbides/400 µm^2), a carbide network rating of 1, and a lamellar content rating of 1. In other words, the microstructure is ferrite and fine spheroidized carbides with no retained carbide network or lamellar content, Figure 4, left. The other half of the material was heat treated to have a carbide size rating of 5 (~

165 carbides/400 μm^2), a carbide network rating of 1, and a lamellar content rating of 1. This translates to a microstructure consisting of coarse spheroidized carbides in a ferrite matrix with no retained carbide network or lamellar content, Figure 4, right.

4. Literature Review-Induction Heat Treatments

The high heating rates and short austenitization times that are realized in induction heating treatments affect the microstructure of the austenite immediately prior to quenching. Several induction hardening studies have been performed at CSM in recent years, indicating several issues to address with respect to the analysis of austenitization kinetics. A short summary of some of the major findings follows.

One thing to consider is the development of austenite grain size during an austenitization treatment. It has been found that induction heating may, in some cases, maintain a very fine austenite grain size, resulting in extremely fine martensite, and higher hardnesses than produced by furnace heating [1]. This is the result of the short time at temperature that is realized during induction treatments. The kinetics of austenite grain growth during induction treatments is therefore of interest.

In addition to maintaining a fine austenite grain size, the importance of retaining a fine carbide distribution in these steels through the austenitization process has also been shown by Krauss [2]. The fine distribution of carbides induces microvoid coalescence, resulting in improved fracture properties [2]. At carbon contents of up to 0.5 wt%, ductile fracture can be found in low tempering temperature (LTT) martensite. Retaining a fine dispersion of carbides can therefore be critical to maintaining fracture properties. In addition, Wong found, in plain carbon steels of up to 0.55 wt% carbon, that as the hardness (or carbon content) of the quenched final microstructure increased to 53 HRC, all failures became brittle [3]. This is indicative of the tradeoff between maximizing the carbon content in the final martensite for high hardness, and allowing the formation of cementite at grain boundaries during tempering treatments because of carbon content in martensite that is too high. It has been shown that carbon contents of 0.50 wt% carbon or less and low tempering temperatures can reduce the formation of cementite at grain boundaries, and therefore reduce quench embrittlement [2].

With respect to the differences found between pearlite/ferrite and tempered martensite initial microstructures, Medlin found that ferrite/pearlite microstructures take longer to completely austenitize than tempered martensite structures [4]. The ferrite/pearlite microstructures retain carbides for longer heating times and higher temperatures, although maximum temperatures were not measured. Remnant carbides remaining after heat treatment can result in lower hardness martensite when ferrite/pearlite steels for a given induction hardening treatment because of lower matrix carbon content. Therefore, steels with ferrite/pearlite microstructures must have higher temperature and longer time austenitizing treatments relative to steels with tempered martensite prior microstructures. As heating rate increases, the need for further extended time and higher temperature austenitizing treatments was demonstrated. Finally, the 5150 alloy had shallower case depths than the 1550 alloy, a characteristic attributed to the alloy carbides (for example, chromium containing carbides) in the 5150, which were found to have slower dissolution kinetics.

Increased temperatures are often required in induction heating treatments to make up for short cycle times. In some cases, where carbides are completely dissolved and austenite grain size is increased, susceptibility to quench embrittlement by phosphorus and cementite formation at the austenite grain boundaries can increase, even in low-phosphorus containing steels with fine carbide dispersions [5]. Cunningham found that the case microstructure is primarily a function of the austenitizing temperature for the very short heating times seen in induction hardening [6]. “Ghost pearlite”, or retained pearlite does not appear to spheroidize in case at these short times.

The kinetics of the above processes will define the working processing window within which optimal properties can be attained. Studying the kinetics of these processes with respect to initial microstructure and composition is therefore of value in the design of induction heat treatments. Results from the present study will also indicate when the process will produce less than ideal microstructures, and indicate heat treatments to be avoided due to poor microstructure in the areas immediately surrounding the induction treated region of a given part.

5. Project Plan

The steel microstructures will be characterized so that the material condition is well documented for baseline evaluations. The metallographic evaluation will include prior austenite grain size (PAGS), ferrite/pearlite grain size, martensite packet size, and spheroidized carbide size and distribution, as applicable. In addition, volume fractions of the various microstructural constituents will also be evaluated. Should there be microstructural gradients through the wall thickness of the supplied material, this will be addressed in such a manner to provide consistent initial material for all transformation characterization studies. Finally, in order to optimize the modeling parameters, an evaluation of the chemical segregation and chemical gradients in the microstructure will be performed.

Initial characterization of the transformations as a function of heating rate for each of the alloys will be performed using CSM's Gleeble 1500 thermomechanical testing apparatus. Cylindrical specimens will be machined with diameters of 6 mm (0.24 in) and lengths of 60 mm (2.4 in). Percussion-welded, type-K (chromel-alumel) thermocouple wire bonded to the outer surface of the samples will provide local temperature readings during heating and cooling. Testing in an argon atmosphere will minimize scale formation and decarburization. Simulations of rapid austenitization processes will be used to simulate industrial induction hardening processes, and radial dilatometry will be used to measure the sample response to rapid austenitization.

The Gleeble dilatometry will be used to run various heating rates in order to identify when the entire structure reverts to austenite. Dilatometry will also be used to investigate isothermal austenite formation when the heating is stopped before the 100% austenite temperature is reached. These data will be used to design thermal cycles where full austenite formation is not realized before the quench. Further Gleeble thermal cycles will also be applied at temperatures well above the 100% austenite temperature in order to evaluate grain coarsening metallographically. These data will be used to design thermal cycles that cause excessive grain coarsening, and, in extreme cases, grain boundary "burning" prior to the quench. Quenching dilatometry will be used to determine sufficient quench rates to avoid non-martensitic transformation products (NMTP) as a function of starting austenite condition (grain size, degree of austenite formation, etc). Further testing and induction cycle development will be performed based on the results of these initial investigations.

Development of a model for the decomposition of various prior microstructures during rapid heating will be investigated. Model development will be based on the previous models that were used for lower heating rates. In addition, the use of DICTRA (DIffusion Controlled TRAnsformations) simulation software will be evaluated.

There are several outside resources available to the CSM for this project. The Timken Company has volunteered the use of their Gleeble and dilatometry facilities for the evaluation of any samples that may not be able to be evaluated at CSM. The possibility of using the Gleeble/dilatometry and material characterization capabilities at Los Alamos National Laboratory and Oak Ridge National Laboratory are currently being explored.

6. Project Status

Materials were delivered to CSM in the as-received and heat treated conditions during February, 2005. The metallographic characterization of the materials has been initiated, with Gleeble familiarization studies also underway.

As part of the initial planning stages of the project, a meeting was held with Dr. C.V. Robino from Sandia National Laboratory in April, 2005, to discuss project goals and specific dilatometry and modeling issues. Specific areas of discussion at this meeting included Gleeble capabilities, fixturing requirements, and ideal sample sizes for detailed dilatometry studies, the significance of various microstructural features, and the repeatability of dilatometric measurements in general. Dr. Robino also agreed to participate in the project as a committee member.

Clarke passed the Ph.D. qualifying-process examinations in the area of Physical and Mechanical Metallurgy in May, 2005. Clarke completed the Ph.D. course work requirements of the Metallurgical and Materials Engineering department in May, 2005. In June, 2005, Clarke attended the Solid-Solid Phase Transformations in Inorganic Materials 2005 Conference.

In addition, Clarke attended the short courses “Computational Thermodynamics using Thermo-Calc”, “Diffusion Modeling and Simulation using DICTRA”, and “Applications of the Thermo-Calc Programming Interfaces” from August 15-19, 2005 at the South Dakota School of Mines and Technology. This instruction will allow the use of Thermo-Calc and DICTRA software for the modeling portion of this project.

7. References

[1] G. Krauss, "Martensitic Microstructures and Performance Produced by Bulk and Induction Hardening", 11th Congress of the International Federation for Heat Treatment and Surface Engineering and the 4th ASM Heat Treatment and Surface Engineering Conference in Europe; Florence; Italy; 19-21 Oct. 1998. pp. 21-32.

[2] G. Krauss, "Deformation and Fracture in Martensitic Carbon Steels Tempered at Low Temperatures", Metallurgical and Materials Transactions A, Vol. 32A, April 2001, pp. 861-877.

[3] J. D. Wong, D. K. Matlock, G. Krauss, "Effects of Induction Tempering on Microstructure, Properties and Fracture of Hardened Carbon Steels", 43rd Mechanical Working and Steel Processing Conference; Charlotte, NC; USA; 28-31 Oct. 2001, pp. 21-36.

[4] D. J. Medlin, G. Krauss, S.W. Thompson, "Induction Hardening Response of 1550 and 5150 Steels with Similar Prior Microstructures", presented at 1st International Conference on Induction Hardening of Gears and Critical Components; Indianapolis, IN; 15 May, 1995.

[5] A. Reguly, T. R. Strohaecker, G. Krauss, D. K. Matlock, "Quench Embrittlement of Hardened 5160 Steel as a Function of Austenitizing Temperature", Metallurgical and Materials Transactions A, Vol. 35A, January 2004, pp. 153-162.

[6] J. L. Cunningham, D. J. Medlin, G. Krauss, "Effects of Induction Hardening and Prior Cold Work on a Microalloyed Medium Carbon Steel", Proceedings of the 17th Conference; 1997 International Induction Heat Treating Symposium; Indianapolis, Indiana; USA; 15-18 Sept. 1997. pp. 575-584.