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Improving Quench Hardening of Low Carbon Steel

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Abstract

The carbon content in steel determines whether it can be directly hardened. If the carbon content is low (less than 0.25wt%) then an alternate means exists to increase the carbon content of the surface. In this study, the mixed quenchant consisting of brine and surfactants known as Superquench was applied in the quench-hardening process on AISI 1015 low carbon steel. The quench results were compared with quenching in heavy brine solution, water and oil which are recognized as the basic quenchants and cannot cause bulk-hardening low-carbon steels. The hardness tests on different points along the radius of cut round bar specimens were performed, and the results exhibited a greater hardness compared to brine quench. The hardness obtained from water quench was below 20 HRC while quenching in heavy brine solution and Superquench gave a hardness of above 40 HRC.

Key words: Quenching, Hardening, Superquench, Low-carbon steel

Introduction

Only steels in which the carbon content exceeds 0.3wt% are heat treatable to improve mechanical properties by formation of martensitic structures. The lower carbon steels can be strengthened by refining ferrite grain from heat treatment [5] using a sufficient cooling rate during quenching from the austenite region. Steels containing below 0.3wt%C can be hardened only by aggressive quenching that can result in distortion of steel parts. In practice, production lines of hot-coiled low carbon steel are subject to rapid cooling after the steel leaves the last section of the rolling mill. In this example, quenching after hot rolling according to Jeong [6] and Berbenni et al. [1] makes it possible to utilize the effect of hardening by deformation which is an alternative technique for hardening low carbon steels such as strain hardening and dynamic recrystallisation [8] by deformation-induced ferrite transformation. In this way mechanical properties of low-carbon steels can be improved by controlling grain-recrystallisation under appropriate quenching conditions.

The quenchant to be used depends on the type of steel. In general quenching in a more severe quenchant than necessary can cause distortion and quench cracking in the steel. Overheating according to Lee et al. [10] prior to the quench can have similar effects. Oils according to Totten et al. [14] are excellent quenchants and are valued for their ability to offer rapid cooling over a wide range of temperatures [12]. They can be used on a variety of steels, as well as on parts with complex geometries and of varying thicknesses. Oils are classified in three distinct groups: conventional, fast, and martempering (or hot quenching). They are classified with respect to their quenching effect, temperature of use, and overall composition. Emulsions of soluble oils that are more commonly used as cooling liquids during the grinding, cutting and forming processes are also used as quenchants. Water remains the most common quenchant since it is inexpensive, easy to use and has minimal safe handling or disposal considerations. Water, however, does have a number of limitations that makes it a less desirable choice in certain applications, particularly with steels of high hardenability.

Brine [14], which offers faster quench rates than plain water, can also be used as a quenchant. Brine solutions are typically made by adding a small concentration (usually five to seven percent) of sodium chloride or calcium chloride to distilled water. Brine and water quenches are used for steels with low hardenability.

When steel is quenched in brine, a layer of salt is precipitated onto the metal surface. The salt layer disrupts the vapor jacket that forms around the quenched part, which helps to reduce and eliminate non-uniform heat transfer during

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quenching. In addition, brine permits a reduced level of agitation compared to water. Temperature is less critical for a brine system, thus reducing its importance as a variable. Brines are most commonly used with high carbon steels or parts requiring high hardness. The main disadvantage of brine as a quenchant is its corrosive nature. This is an issue not only for the quenched work, but also for the quenching equipment used, which will be prone to more frequent equipment shutdowns and higher maintenance costs.

Brine solutions can be mixed with suitable surfactants based on soap or detergents to increase the ability of brine to disrupt vapor jacket formation, thus increasing both the rate and uniformity of cooling. As in normal brine the salt causes the vapor phase to break up faster and initiates boiling at a higher temperature while the surfactants encourage improved wetting of the quenchant on the steel. Suitably modified brine quenchants may be suitable for treatment of very low hardenability steels.

One such modification is Superquench according to Dempsey [(4)] which was developed by Rob Gunter of Los Alamos National Laboratory after the use of sodium hydroxide based quenchants was banned. Sodium hydroxide offered faster cooling rates than water, was slower than brine, but gave less corrosion than brine. The Superquench mixture was based on 20.46 liters (4.5 gallons) of water, 2.27 kg. (5 lb.) salt, 0.9 kg. (32 oz.) dish soap and 0.23 kg. (8 oz) anti-bubbler (or 0.96% anti-bubbler, 3.77% dish soap, 9.51% salt and 85.75% water in weight percent). Basically, the quenchant is a heavy brine solution, mixed with a surfactant and an anti-bubbling agent. There are claims that Superquench has substantial hardening effect on steels containing 0.15-0.25 wt% C.

Hardenability depends on the carbon and alloy content of steel [(9)], but maximum hardness depends only on %C content. The higher the carbon content is the greater is the hardness of martensite. Figure 1 showing martensite start and finish temperatures of carbon steels suggests that low-carbon steels can be hardened by formation of martensite. Figure 2 is TTT diagram representing low-carbon steel. The diagram shows that martensite can be produced by controlling cooling time from austenitising temperature to martensite start temperature within 2 seconds.

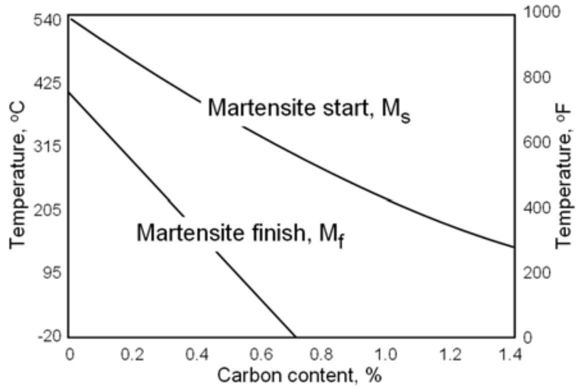


Figure 1. M_s and M_f plot relate to the wide range of carbon content in plain-carbon steels including low-carbon steels [(2)].

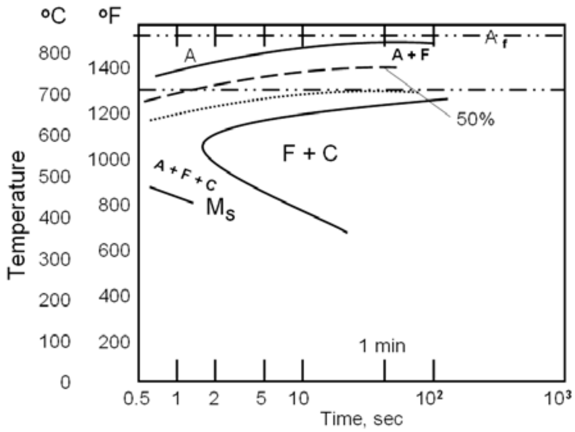


Figure 2. TTT diagram of AISI 1020 (0.15-0.25%C) according to Blair and Stevens [(2)].

Theoretically, low carbon steels can be heat treated by quenching at the critical cooling rate (Starodubov, 1965) of around 4500°C/sec for steel with 0.04wt% C and 1925°C/ sec for steel with 0.19wt% C while a cooling rate of around 600°C/sec is sufficient for a medium-carbon steel with 0.4wt%C.

Materials and Experimental Procedures

The maximum attainable hardness of quenched steel is controlled almost exclusively by carbon content and is obtained by cooling at a rate equal to, or greater than, the critical cooling rate for a particular steel. To determine the effect of quench hardening on carbon content in both unalloyed low-carbon steel (AISI 1015) and alloyed low-carbon steel (AISI 4115) round bars with 25 mm. diameter, in the rolled condition, were sectioned as 10 samples with identical dimensions for quench hardening tests in 5 quenchants, i.e., oil, water (tap water), brine, heavy brine and heavy brine mixed with dishwasher detergent as surfactant as a mixture similar to Rob Gunter's Superquench [(4)]. Compositions of the selected steel grades in round bar products are shown in Table 1.

Selected steels for the study are normally specified as non-hardenable grades; only case hardening is widely applied. Material property data sheets [(11)] present maximum hardness values reached are 126 HB or 71 HRB for AISI 1015 and 192 HB or 11 HRC for AISI 4115, while the hardness values of 163 HB or 84 HRB are presented as hardening results for AISI 1020 in the data sheet.

The samples, prepared as 25 mm. diameter round bar with 25 mm. length, were austentised at 930°C and soaked for 1 hour before quenching into the 5 quenchants which were prepared for each experiment at 27°C. In this work, each quenchant was prepared in a 4.5 gallon bucket equipped with an air purge for circulating and cooling the quenchant as well as minimizing the effect of bubbling boiling steam film on heat transfer [(7)], and hence the flow velocity of 0.01 m/s was set for the simulation. The furnace used was a front-loading digital muffle furnace; a controlled atmosphere was not used. The appearance of the cut steel sample for the study is shown in Figure 3; all samples are prepared with 25mm. length and the sectioned surfaces were set at the half-length cut after quenching while microstructure examinations were performed at 1 millimeter depth ensuring microstructures presented without decarburization.

To avoid any effect of decarburization [(15)] on the measured surface hardness, Brinell hardness testing was performed to obtain hardness results at deeper indentation depths. The relative cooling rates of the different quenchants are listed in Table 2.

In selecting sample positions for hardness tests it was assumed that the edge position represented the fastest cooling area and the core position the slowest cooling area. SolidWork COSMOSFlowork® flow analysis software was applied at this stage to affirm the selected positions in comparing hardness levels in relation to quenching media.

Figure 3. Geometry of AISI 1015 and AISI 4115 samples for the study, i.e. quenching, hardness test and microstructural examination.

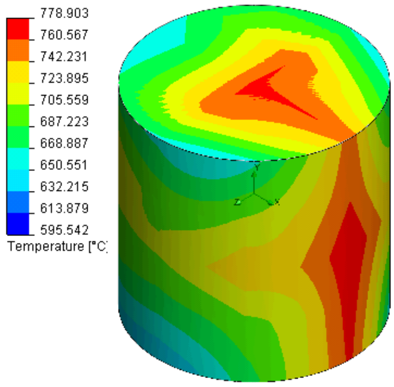


Figure 4. Illustration from simulation assisting to select tested positions for determining quenched effects and obtained microstructures.

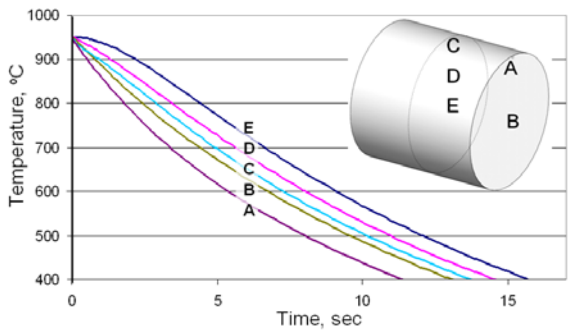


Figure 5. Plots of simulated cooling curves of quenching plain-carbon steel in the water referring for hardness test positions, i.e., (A) the near-edge of face area, (B) center of face area, (C) 2 mm. depth under the rim of cross section, (D) mid-radius of cross section and (E) center of cross section.

Table 1. Chemical composition in wt% checked from 2 steel bars identified as low-carbon steel grades (alloyed and unalloyed).

Elements	AISI 4115 sample	AISI 1015 sample
C	0.1683	0.1351
Si	0.2933	0.1239
Mn	0.8135	0.3311
P	0.0224	0.0159
S	0.0042	0.0130
Cr	1.0951	0.0093
Mo	0.2115	0.0107
Ni	0.0194	0.0554
V	0.0061	0.0013
Al	0.0187	0.0127
Cu	0.0138	0.0852
Ti	0.0127	0.0010
Nb	0.0020	0.0008
W	0.0011	0.0007
As	0.0033	0.0083
Co	0.0062	0.0094
Fe	balance	balance
Max. hardness	192 HB (as tempered)	126 HB (as quenched)
M_s	426.38	469.40

Remark: M_s temperatures are determined approximately by a formula developed by Atkins:
Maximum hardness according to www.matweb.com
M_s = 539 – 432 %C – 30.4 %Mn – 17.7 %Ni – 12.1 %Cr – 7.5 %Mo (Blair and Stevens, 1995)

Table 2. Selected quenchants in the study compared with some other quenchants in terms of cooling efficiency.

Quenching mediums	Cooling rate compared to water
Heavy brine +Surfactant	> 1.96 (approx.)
Heavy brine (15% Salt)	> 1.96 (approx.)
Sodium hydroxide (10%)	2.06 (Chandler, 1996)
Brine (10% Salt)	1.96 (Chandler, 1996)
Brine (7% Salt)	1.00-1.96 (approx.)
Water (Tap water)	1.00
Lube oil	0.20 (approx.)

Salt levels of 7% and 15% were selected to represent normal and heavy brine, respectively. Sodium hydroxide solution is recognized as a quenchant with fastest cooling rate, but has been banned for safety reasons.

Results and Discussion

Use of COSMOSFlowork® simulated the different cooling areas in the sample as shown in Figures 4 and 5. The fastest cooling rate of the plots in Figure 5 is below $50^{o}C$/sec and this is much lower than the critical cooling rate for formation of martensite in low-carbon steels (0.19wt%C). The simulated quenching temperature was started at $930^{o}C$ and the quenched time was set for 20 seconds ensuring that the temperature of the samples decreased below the austenitic region. Although rapid cooling by quenching may not be fast enough to yield fully martensitic structures in such steels, it can result in the formation of bainite and/or very fine ferrite structures [(6)] which also provide increased hardness.

The results of hardness tests at the different test positions (A-E) for each quenchant are given in Figure 6. Selected microstructures before and after quenching are given in Figure 7.

To compare the effects of the different quenchants, hardness tests were performed at different surface positions and different positions on the cut areas. In general, different quenchants have greater effects on the hardness of AISI 4115 compared to AISI 1015 due to alloying elements present in AISI 4115. Hardness values for different quenchants at different test positions are given in Figure 6.

Quenching in the mixture of heavy brine and dish washer liquid had a significant effect on the surface hardness of the AISI 1015 sample, increasing its hardness to a level very close to that of the AISI 4115 sample. Oil and water quenches did not significantly affect the hardness of AISI 1015 samples at both surface and core positions (Figures 6 (a) and 6 (b)). For AISI 1015, quenching in brine solutions clearly improved surface hardness (Figures 6 (a) to 6 (d)) while quenching in the mixture of heavy brine and dish washer liquid increased both surface and core hardness levels (Figure 6 (e)). Quenching in oil, water, brine and heavy brine solutions resulted in hardness levels of AISI 4115 in a range between 300 to 420 HB as shown in Figures 6 (a) to 6 (d). For AISI 4115 the highest recorded hardness, above 440 HB, was achieved by quenching in the mixture of heavy brine and dish washer liquid as shown in Figure 6 (e).

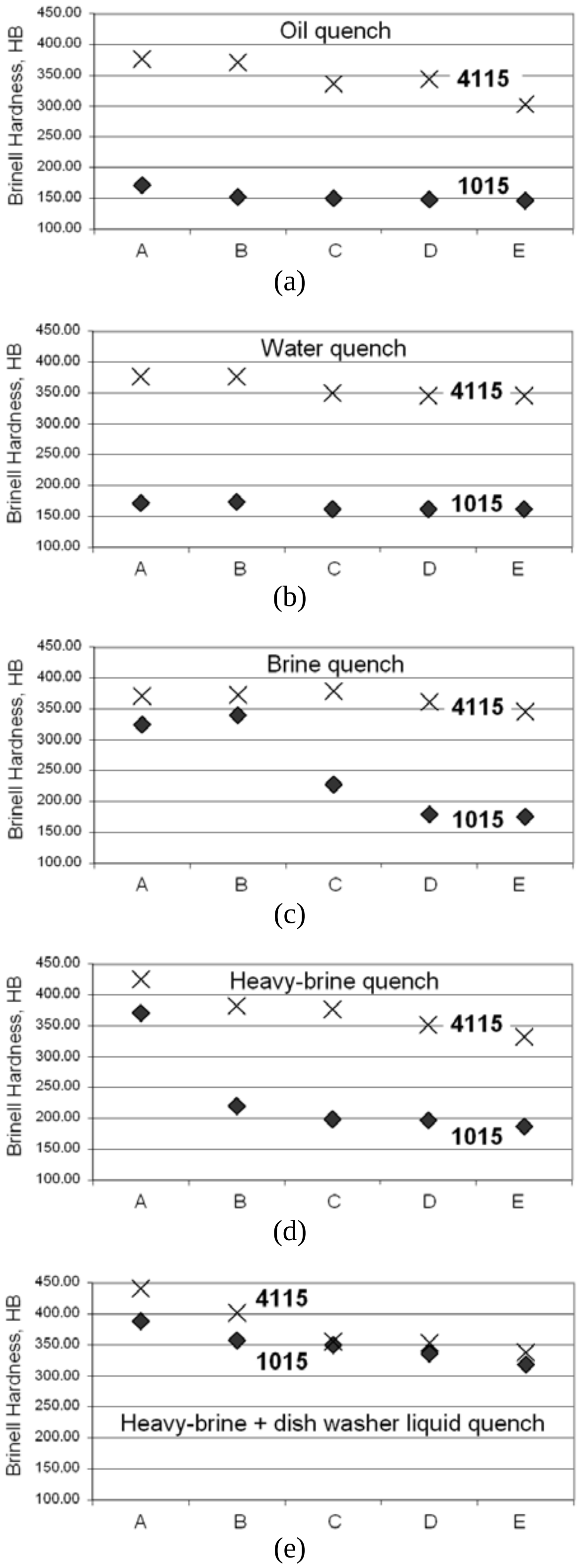
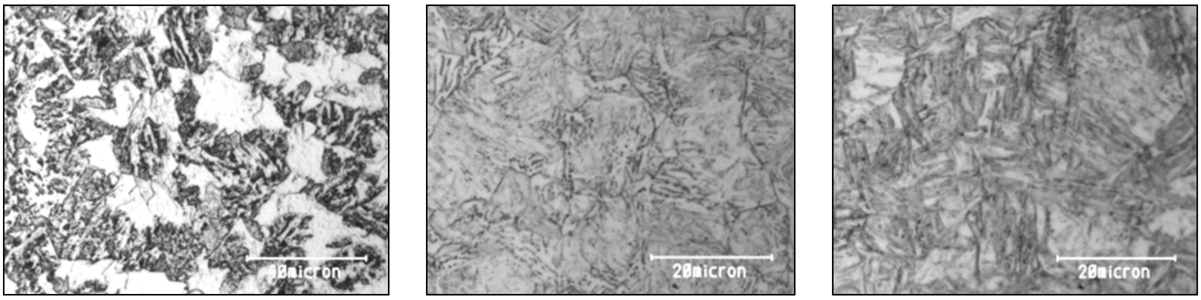


Figure 6. Hardness results of samples quenched from $930^{o}C$ to near ambient temperature in different quenchants such as (a) oil, (b) water, (c) brine, (d) heavy-brine and (e) heavy-brine mixed with dish washer liquid. Squares represent AISI 1015 samples and crosses represent AISI 4115 samples.

Surface hardness values of above 320 HB in AISI 1015 samples were obtained from quenching in brine and heavy brine solutions (Figures 6 (c) and 6 (d)). The highest hardness for AISI 1015 samples was 389 HB obtained from quenching in the mixture of heavy brine and dish washer liquid. Using this quench core hardness could also be improved to above 310 HB (Figure 6-e) which approaches the average core hardness of 330 HB for the equivalent AISI 4115 sample.

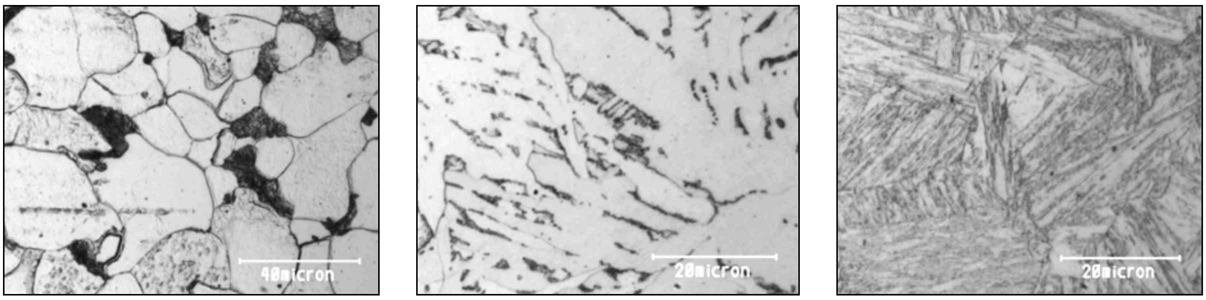
The microstructures of samples quenched in different quenchants can be related to the hardness test results. Before austenitising and quenching the microstructure of AISI 1015 consisted of ferrite grains with a small amount of pearlite while AISI 4115 contained a greater proportion of pearlite due to its alloy content. Figures 7 and 8 present selected micrographs from the 12 samples to compare the microstructures in the original condition and after quenching in oil, water, brine (7%), heavy brine (15%) and the mixture of heavy brine and dish washer liquid.

The microstructure of AISI 4115 obtained from the most aggressive quenching consists of martensite while that obtained from quenching in oil with a slower cooling rate is a mixture microstructure of bainite and martensite. Although AISI 1015 is unalloyed low-carbon steel, quenching in suitable quenchants can result in bainite and fine ferrite structures. The highest hardness level of AISI 1015 presented in Figure 6-e of 388 HB (42 HRC) was obtained from such acicular structures.



(a) (b) (c)

Figure 7. Microstructure at the edge position of AISI 4115 samples comparing (a) as-annealed, (b) quenching from 930°C to near ambient temperature in oil and (c) quenching from 930°C to near ambient temperature in a mixture of heavy brine and dish washer liquid.



(a) (b) (c)

Figure 8. Microstructure at the edge position of AISI 1015 samples comparing (a) as-annealed, (b) quenching from 930°C to near ambient temperature in oil and (c) quenching from 930°C to near ambient temperature in a mixture of heavy brine and dish washer liquid.

Conclusions

The quenchant based on a mixture of heavy brine (15% brine solution) and dish washer liquid gave fastest cooling in quenching low-carbon steels. For AISI 4115, representing low alloy-low carbon steel, quenching in brine (7% brine solution), heavy brine and a mixture of heavy brine and dish washer liquid did not show any significant differences in quenched hardness since the steel had sufficiently high hardenability. Although the steel contains less than 0.2 wt% C quenching gave improved hardness levels at both surface and core positions.

AISI 1015 is classified as a non-hardenable steel grade. Quenching in oil, water, brine and heavy brine gave no increase in core hardness level. Only quenching in the mixture of heavy brine and dish washer liquid could improve core hardness, from around 170 HB to 310 HB, while a greater corresponding increase in hardness was obtained at the surface. The highest hardness for AISI 1015 steel in the study is 388 HB (42 HRC) similar to the published hardness levels of just over 40 HRC obtained from quenching low-carbon steel in Rod Gunter's Superquench.

It must be remembered that such aggressive quenching conditions are not suitable to all steel grades or all kinds of application. High quenching rates can lead to severe distortion and even cracking, and these effects were not included in this study.

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