Low Distortion Intensive Quench of Low-Alloy High Hardenability Steel

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Abstract

This work aims to compare methods of quenchant delivery between an intensive quench (IQ) system and forced convection bath (FCB) systems. 4340 billets were machined, austenized, quenched, and examined for distortion. The parts were then sectioned for hardness and the microstructure was characterized by light optical microscopy (LOM). The results show that spray pattern arrangement is critical for effectively quenching the part without distortion or cracking and that the IQ process can be used with more versatility to quench highly hardenable castings without cracking.

Keywords: Quench-hardening, water quenching, intensive quench, forced convection, low-distortion, low alloy steels, spray quench.

Introduction

In 2020, an intensive spray quench tank was constructed for use in Missouri S&T's Heat Treatment Lab. An intensive quench system produces first a martensitic shell and austenitic core. Then the core can be hardened or air cooled, depending on purpose. C-Rings machined from 4340 were chosen as quench subjects. The high hardenability of 4340 and the variable section sizes and design of C-rings make it the ideal candidate to maximize any distortion or stresses caused by the different quenches. By varying the quench orientation in the IQ system, these C-rings should show any cracking, in ways that easily indicate where stresses are present. {1}{2}{3}

Methodology

The 4340 steel in this trial was machined from billets. The chemistry was tested using Leco Carbon-Sulfur and optical emission spectroscopy (OES). Each quench method was allocated 10 rings to test. The rings for the IQ system were notated 51-60, and those quenched in the FCB system were notated 61-70. This was a small part of a large study with several industry partners, which is why the rings were given these numbers.

In preparation for austenitizing and quenching, the rings were welded to rebar at the base to support fitting into the quench systems and the rings were wrapped in stainless steel foil to prevent scaling during the heating process. Regardless of quenching method, each ring was individually heated to 920°C for an hour, then quenched in 22-25°C water for 2.5 minutes. The IQ system was set to deliver water at 180 psi, while the FCB, which is controlled by velocity, was set to deliver at a velocity of 6 ft/s.

In the FCB system, all 10 rings were quenched with the forks down. In the IQ system, 3 rings were tested with a 45° offset to the nozzles, while the rest were quenched in-plane with the nozzles. This orientation is shown in Figure 1. Transfer time between furnace and quench was also tracked for each quench method.

The measurement of distortion and crack failure was done using the gap between the forks of the C-Rings, which, if measured in multiple places, can give an indication to the direction of change in shape of the C-Ring. This is shown in more detail in Figure 2. The gap was measured in 6 places, before and after quenching, and the percent change for each ring was established.

After distortion measurement, samples were sectioned for hardness testing using Rockwell C scale and light optical microscopy (LOM). The sectioning procedure is shown in Figure 3. Hardness testing was measured as an average for each sample, with maps produced for individual hardness measurements in relation to location in the sample. An average can be computed because through-hardening should be produced in both methods. The LOM samples were etched with 2% Nitric acid to produce an optically visible microstructure.

Results and Discussion

Chemistry

The chemistry results, shown in Table 1, show slightly high levels of manganese and chrome when compared to 4340 standards. Because this study is comparative between quenchant delivery methods, this will not negatively affect other testing data. Also, as the goal is to minimize distortion in high hardenability steels, the Mn and Cr levels contribute to a higher DI and further validate any testing results.

Hardness and Transfer Time

The FCB system produced a transfer time between 7-12 seconds for all 10 samples. While this is slightly higher than desired, the samples were insulated with kaowool sheets during transfer to reduce cooling before quench. The samples tested for hardness produced an average hardness of 56.9±1.13 HRC.

In comparison, the IQ system produced a shorter transfer time of <7 seconds for all 10 samples, simply due to space allocation in each testing room. Hardness testing showed a more consistent through-hardness of 58.3±0.17 HRC. Maps of the hardness based on orientation for one FCB and one IQ sample is shown in Figures 4 and 5.

Distortion and Stress-Induced Cracking

Only one sample quenched in FCB failed as a result of quench stress. However, this one cracked sample was caused by improper placement in the FCB tank. For the other 9 samples, the distortion was minimal with every fork gap measurement falling below 3% change due to quenching. This will be the control used for comparison in the IQ system.

All 7 IQ samples quenched in-plane with the nozzles produced visible distortion, with 4 cracking in various ways. The fork gap measurements all fell between 3-5% distortion. The placement of the cracking on the sample seemed to change with even minute changes of quench orientation. For example, if a ring was quenched in the IQ system slightly offset from in-plane, around 5-10°, the ring would manifest cracking along the “mid-radius” of the fork, with the cracks typically appearing in symmetry. This is what occurred to ring 57, which is shown in Figure 6. If a ring was placed nearly, or exactly in plane, <5° offset, the cracking would manifest across the fork at around the middle of the fork height. This seems to be due to the high concentration of quenchant at this point, causing a fully martensitic “bridge” to the inner radius of the sample, which acting as a point of tension during the cooling of the part above and below this point. This is shown in detail n Figure 7. Within the samples that were not cracked, the distortion tended to show in the same orientation-dependent manner. When a ring was placed slightly off axis, the forks would become misaligned, protruding along the axis of the thickness. However, when placed in-plane, the ring would distort by “opening” or “closing” the gap perpendicular to the thickness.

The rings quenched at 45° offset to the nozzles showed much less distortion than those quenched in plane. The fork gap changes ranged from 0.5% to 3%, which is in line with that of the FCB testing. One of the rings showed visible distortion in a similar manner to the slightly misaligned rings from the in-plane set, with the forks misaligning along the thickness axis. Lastly, the offset orientation seems to be more forgiving to slight changes in angle from the nozzle. This is most likely due to the slightly increased distance between the nozzle and ring, causing a larger spray pattern and a larger zone of coverage for water spray.

LOM Analysis

The microstructure of the sectioned samples showed a martensitic structure, with minimal change between quenchant methods. MnS inclusions were found, which is typical for a steel of this grade. Slight decarburization occurred, with a higher decarburization depth near the base of the sample, shown in Figures 8&9. This is likely caused by small gaps in the stainless steel wrap near the base of the sample, where the fitting bar was attached.

Conclusions

In this study, an examination of quenchant delivery was conducted using 4340 C-rings. An FCB system, used as a control, was compared to two different orientations in an IQ spray system. The two orientations, in-plane and 45° offset, produced different amounts and types of distortion. In-plane quenching produced higher distortion than the FCB system, with a crack rate of over 50%. Points of cracking and distortion of these parts also highly depended on whether the part was perfectly aligned in-plane with the nozzles. The rings quenched offset to the nozzles distorted much less, showing no cracking and similar distortion measurements to that of the FCB system.

Current and Future Work

Work is currently in progress to characterize whether these phenomena described to this point change with the added stress of mechanical defects in these parts. Work is also being completed on directly cast rings as opposed to machined specimens.

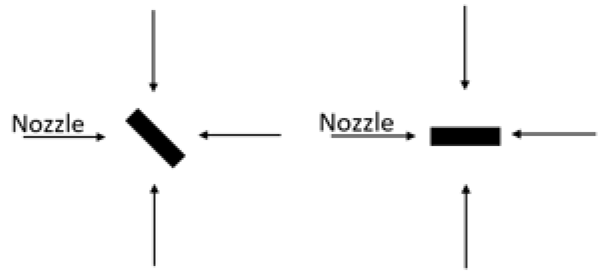

Figure 1: Orientation for IQ spray system, 45° offset (left) and in-plane (right).

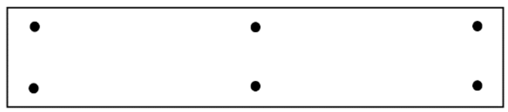

Figure 2: Fork gap point measurements viewed from between forks.

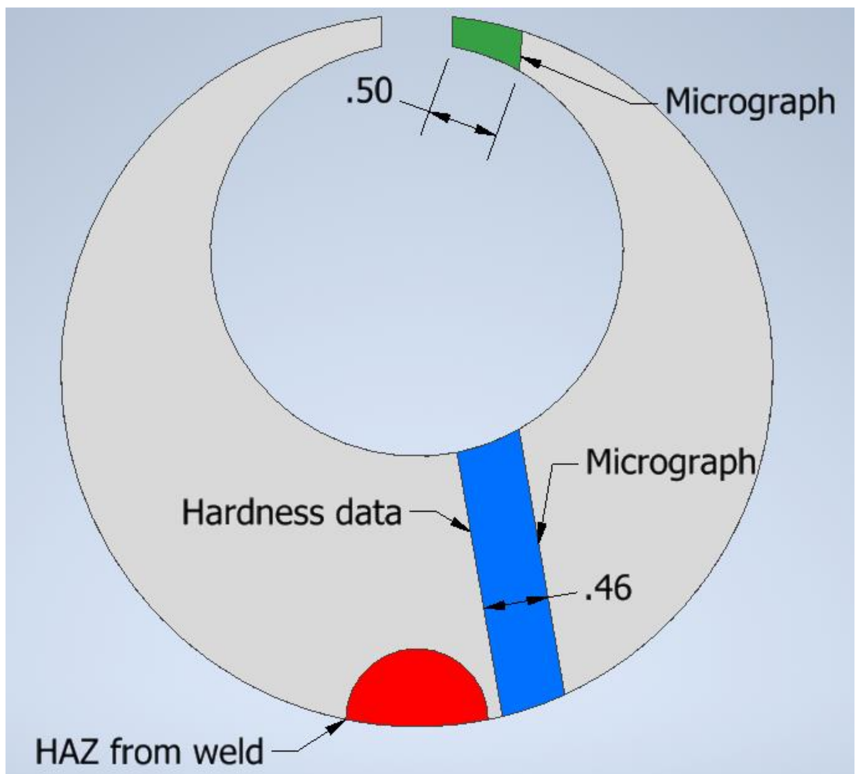

Figure 3: Sectioning procedure for C-rings.

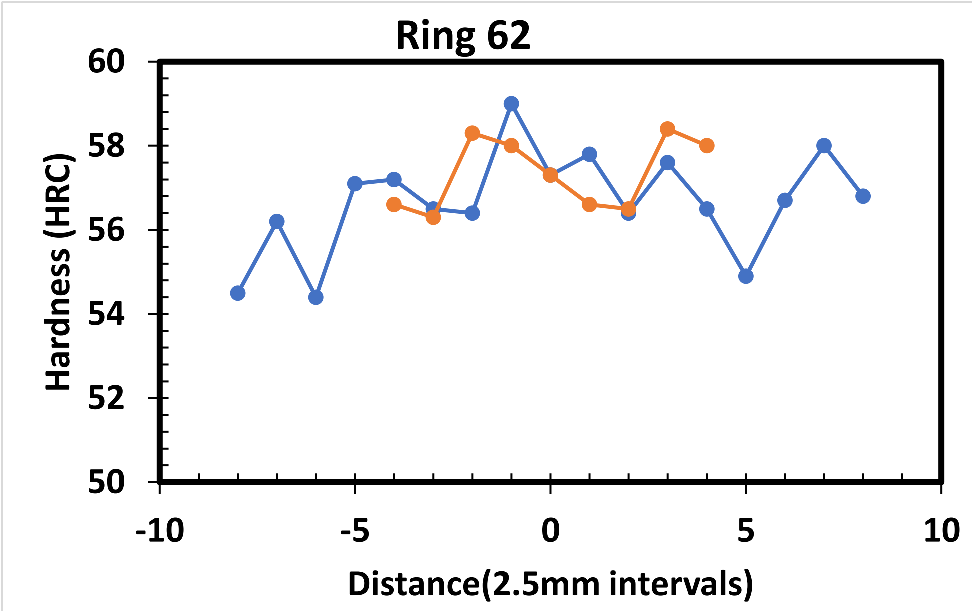

Figure 4: Hardness Map for FCB sample, ring 62. Orange line represents thickness direction, blue line represents height direction.

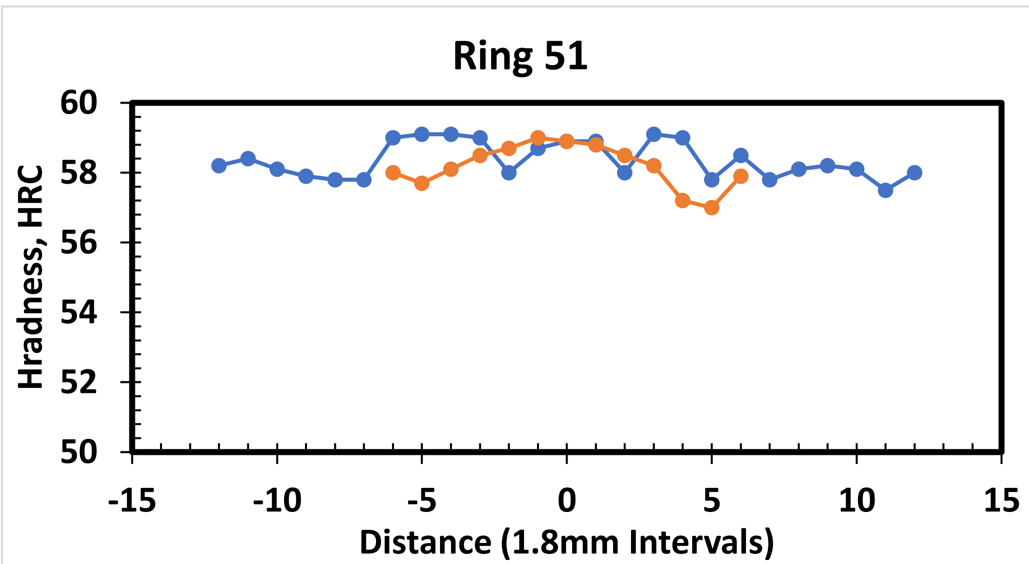

Figure 5: Hardness Map for IQ sample, ring 51. Orange line represents thickness direction, blue line represents height direction

Figure 6: Crack in ring 57, another crack is present with 180° symmetry to this crack.

Figure 7: Crack in ring 55. Unlike 55, there is not a symmetrical crack present.

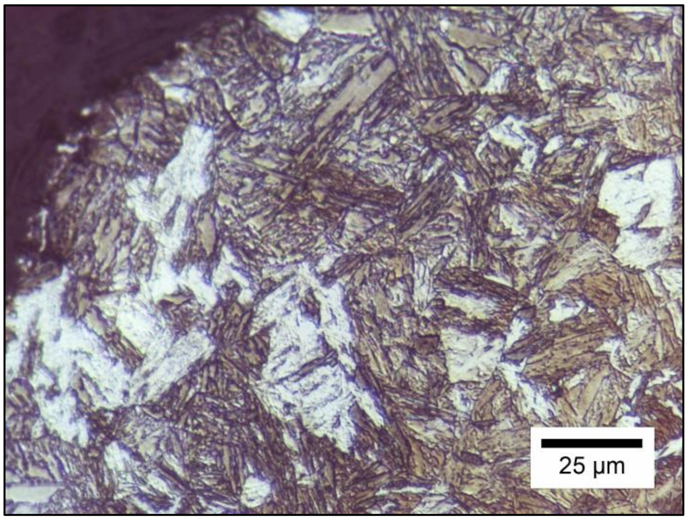

Figure 8: LOM image of base of ring 62, showing about 200 µm of decarburization due to loose steel wrap.

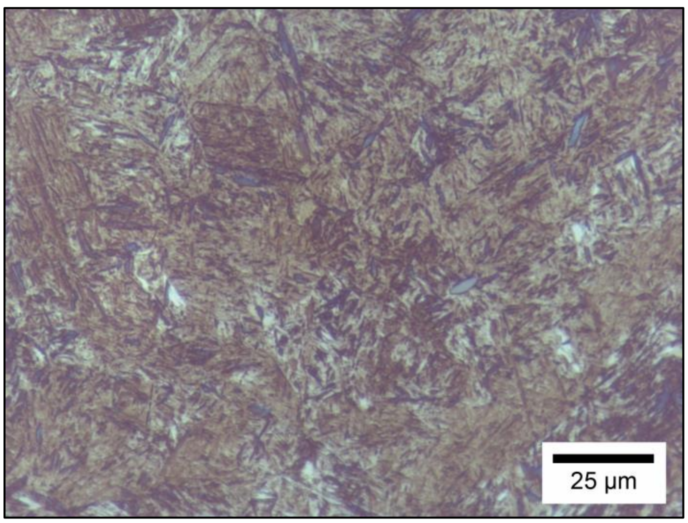

Figure 9: LOM image of base of ring 51, showing about 350 µm of decarburization due to loose steel wrap.

Table 1: Chemistry results from OES and Leco C-S testing.

Element	C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	Ti	V
Wt. %	0.408	0.163	0.859	0.0545	0.0074	1.06	0.3	1.69	0.036	0.214	0.006	0.029

Nomenclature

Austenitized: Heat treatment procedure in which a steel part is brought to the temperature where austenite is stable.

Austenitic: Consisting of a majority austenite.

Decarburization: The removal of carbon from the surface a steel part, typically due to reaction at high temperature with oxygen.

Hardenability: Characteristic of steel describing the ability to transform from austenite to martensite under a variety of cooling conditions, measured with DI.

Ideal Diameter (referenced as DI above): Measurement of hardenability used to describe the theoretical largest section size which can be made fully martensitic. A higher DI indicates a more hardenable steel more likely to suffer quench cracking.

Kaowool: Fiber blanket made from alumina-silica clay, used for its insulative properties.

Martensitic: Consisting of a majority martensite.

Quenchant: The fluid which is used to cool a part during quenching, usually oil or water.

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URGC Reflection

In my time working on this project, I have come to understand the research process much deeper than what is established in classroom labs. In metallurgy, the research institutions, professors, and research assistants are few and far between. Research projects can be quite varying, spanning from a 2-3 month corrosion study to a 4 year alloy development project. As effective materials are the backbone of most new technologies, the need from industry often drives projects and new developments. A prime example is the need for lighter materials for vehicles to increase fuel efficiency. This extends as far as reducing weight for armor plating on tanks without reducing protection, which is an ongoing project we have at Missouri S&T.

Often, in other disciplines, breakthroughs are made to fulfill a specific purpose with well-defined characteristics. However, when creating new materials and techniques for processing, there are often unforeseen consequences, both positive and negative. For example, the entirety of this study I am reflecting on, which has been published in journals and presented at conferences, arose due to one nuance of our new intensive quench spray tank. This led to two differing opinions on the most effective quenching method, which is a large part of what was tested in this study.

This project has also helped me understand the most valuable resource that a metallurgy student has at Missouri S&T: their professors. My professors have given me many valuable tools: healthy skepticism, creative thinking, initiative, and intuition just to name a few. They did this in relatively simple ways. For example, when I would come into their office with a more abstract question, their first response would often be, “Well, what do you think?”, which invariably led to an educational and useful conversation. I also found that my fellow undergraduates and graduate students were often invaluable in their ability to provide useful experience and tips. In terms of actual dedicated informational resources, I was able to learn how to effectively find useful data and relevant studies using S&T’s library system along with ASM and ASTM databases.

The process in which this project progressed showed me the constant evaluative nature of the design process and how, often, it is impossible to take all the required variables into account before the process begins. So, for an effective experimental design, it requires not only extensive preparation, but the ability to adapt to unexpected results. For example, in the time since my project has finished, further work has been done to evaluate more variables related to C-rings in the intensive quench system. However, we encountered a problem where all the C-rings cracked upon quenching. We had several effective tools to measure distortion, but those measurements are compromised once the part cracked. So, I was tasked with creating an evaluative tool to measure cracking in the same manner that we had been measuring distortion. This, for me, was a bit jarring, as we had to create a tool to fit the data, where we normally are working to create data to input into our tools. This really helped me realize that everything useful in research can and should be constantly reevaluated.

Interpretation of results has become one of my favorite parts of the experimental process. The abstraction of data and the conclusions made from that abstraction often drive the next steps or proposals for projects. In metallurgy, the testing setup and execution are often the easy parts, and the interpretation of the results is often the hardest. “It depends” is often the mantra of a good metallurgist, and this applies even more so to research. However, the difficulty of interpretation can be made lower with a good testing setup and making results repeatable. In our project specifically, the results were evaluated to ensure that we no erroneous variables had impacted our data. Once that was done, the conclusion became much easier, akin to simple correlation. Overall, this project has made me a better student and more effective researcher. On top of that, I have found the things within research that I enjoy doing, and that a graduate career would most likely fit me best. I am very thankful to my professors for taking a gamble on me with this project, and to the sponsors, Defense Logistics Agency and Nucor Steel Memphis, for making this project possible.