Vacuum Pressure Quenching of Oil-hardenable Materials

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High pressure gas quenching has been identified as an important advancement in heat treating technology. While an abundance of documentation exists on the hardenability, mechanical properties, and microstructures of water and oil-hardening grades of steel, there is relatively little or no available information on the metallurgical properties that can be achieved when these materials are quenched in a high pressure gas environment. This article compares the metallurgical effects of high pressure quenching in a vacuum furnace, as opposed to oil quenching, for various oil-hardening grades of materials.

When hardening steel parts, the ultimate goal of any heat treater is to achieve the best possible microstructure containing 100% martensite, without severely distorting or quench-cracking the steel. Quenching, therefore, is a very important process in the successful hardening of steel.

Commercial heat treaters have not received any specific mandates from industry or government agencies to modernize their heat treating equipment. Because there are high capital expenditures involved with the installation of fast quenching "state-of-the-art" vacuum furnaces, less costly and outdated methods have prevailed. The objective of this project was to identify the advantages and disadvantages of using high pressure gas quenching to optimize metallurgical properties of oil-hardening steel parts.

Experimental Procedures

Two pieces of equipment were used for this study. A VFS HL50 10-bar gas quenching furnace with a 42″ wide x 54″ deep x 36″ high hot zone using a 300 HP high velocity fan was used for gas quenching. A Leeds and Northrup furnace with a 14″ wide x 24″ deep x 12″ high hot zone with an integral 300 gallon oil quench tank was used for oil quenching. Nitrogen was used as the quenchant in the vacuum furnace, which was re-circulated through a convection dominated water-cooled heat exchanger. The quenchant used in the electric atmosphere furnace was Park AAA quench oil at 130°F - 140°F (54°C - 60°C).

Six pieces of bar stock for each of the four grades of oil-hardening steel (01 tool steel, 4140, 4150, and 4340 alloy steels) were used for this test. The sample lot for each material consisted of two 1″ diameter bars, two 2″ diameter bars, and two 3″ diameter bars, all measuring 6″ in length.

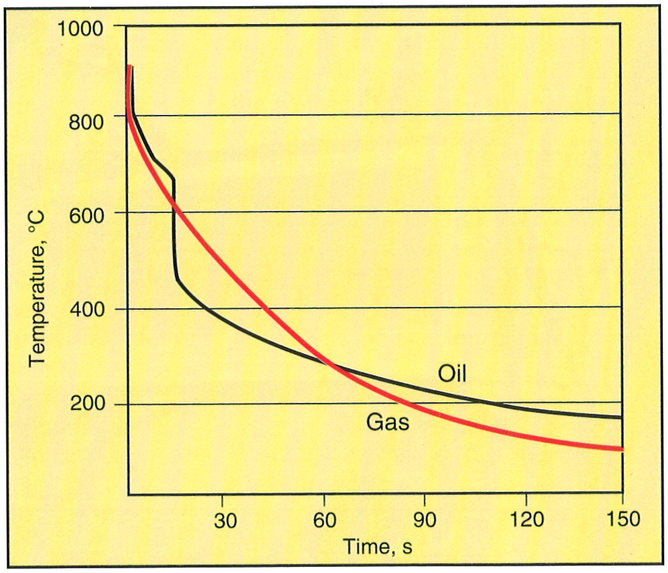

Fig. 1 Representative cooling curves for gas and oil quenching of austenitic stainless steel. Gas quenching provides uniform cooling throughout the quenching cycle.

Holes measuring 3/16″ were drilled to fixed depths in each bar (i.e., center, 1/2 rad., 1/4 rad., etc.) to accommodate thermocouples for monitoring the temperature variation from the surface to the core of the part. All specimens were fully austenitized in the two hardening furnaces. The temperature of each specimen was monitored using the work thermocouple located at the core of the work piece. Each specimen was subsequently quenched in either 130°F - 140°F (54°C - 60°C) oil or 10 bar nitrogen. Each specimen was then snap-tempered at 350°F for three hours.

Finally, each bar was sectioned approximately one diameter from the end of each bar. Transverse hardness readings were taken at the surface, 1/4 radius, 3/4 radius, and core of each specimen. The specimens were ground, polished and etched with a 10% nital solution to reveal the microstructure.

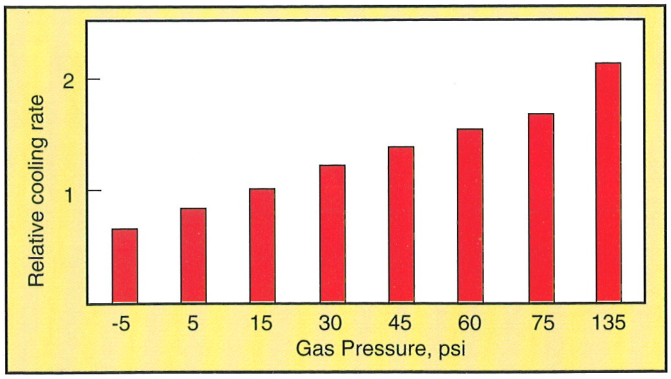

Fig. 2 *The effect of gas pressure on the relative cooling rate for gas quenching.*

Photomicrographs were taken from the center cross-section of each bar.

Comparison of Quenching Methods

There are significant differences in the cooling rate characteristics of oils and gas (Fig. 1). Liquid quenchants possess three different stages of cooling: vapor phase, boiling phase, and convection phase, while in gas quenching only convection cooling occurs. Oil quench rates are higher in the beginning of the quench cycle (at higher temperatures), but are lower at the end of the cycle. Each regime can be clearly distinguished on a cooling curve. In gas quenching, only the convection phase exists.

Continued advances in high pressure gas quenching have allowed the cooling rates of gas quenching to compete with those of oil quenching. In addition, the cooling capability of industrial gases used for quenching increases typically with increasing pressure (Fig. 2). The cooling rate during gas quenching may be slower at the beginning of the cycle, but soon exceeds the cooling rate of oil during the convection stage. Due the the consistent nature of convective cooling, the gas cooling curve is uniform and exceeds the cooling rate of oil at temperatures below about 662ûF (350°C). The data implies that by using high-pressure gas quenching, it is possible to harden parts with small and medium sized cross sections made of high and intermediate alloy steels to the same hardness as if using oil. In addition, the uniform cooling conditions dramatically reduce quench distortion.

Results

The hardness results for the gas and oil quenched materials are displayed in Figs. 3 through 6. The hardness of the 4140 steel samples quenched in both oil and gas were very similar for the 1″ diameter samples (Fig. 3). For the 2″ and 3″ bars, the hardnesses of the oil quench samples were slightly higher than the gas quenched samples. Noteworthy, however, is that the hardness appears more uniform through the cross-section for the gas quenched samples, possibly due to the nature of convective heat transfer in gas quenching. The results from the 4150 alloy are quite comparable to the results of 4140, except for the 2″ diameter which shows a more uniform through-thickness hardness than that of 4140.

The results of tests on the 4340 samples showed that the hardness was rather uniform, regardless of quenching medium or part size. For the 01 tool steel, the gas quenched samples show consistently higher hardness values than the oil quenched samples for all sample sizes.

Photomicrographs were taken of the microstructure at the center of the cross-sectioned bars (Fig. 7). The microstructures of the steels that were heat treated in the vacuum furnace were very similar from those that were oil quenched. A few subtle differences were noted between the microstructures of the larger gas quenched samples and the oil quenched samples. The gas quenched samples possessed more upper martensite and lower bainite than the oil quenched specimens. The larger vacuum heat treated samples typically yielded an austempered structure.

Discussion

A better understanding and the application of heat transfer fundamentals will lead to additional improvements in gas quenching technology. Theoretically, there seems to be no limit to the increased cooling rate that can be achieved by increasing gas velocity and pressure. However, practical considerations revolved around the financial requirements required to achieve another atmosphere of pressure.

The type of gas used as the quenching medium has an effect on cooling rates. 10-bar pressure may be an upper limit for gas quenching in nitrogen, due to the high fan motor horsepower needed to quench at higher pressures. In some cases, faster cooling can be obtained using a lighter gas, such as helium, at 20 bar because of reduced

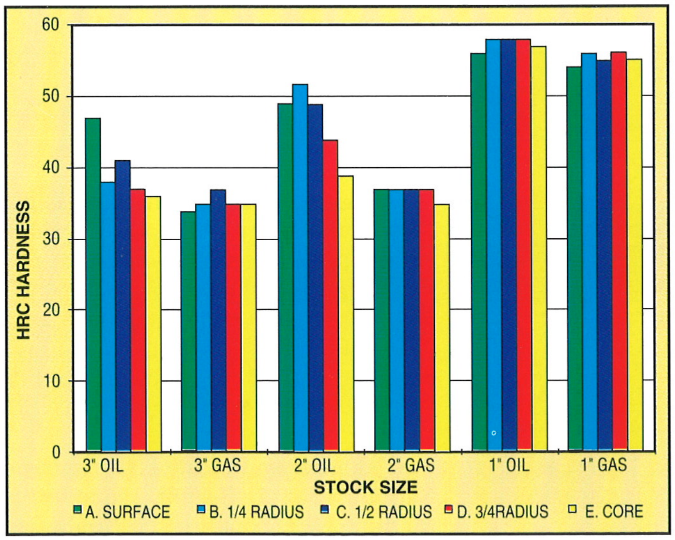

Fig. 3 *Hardness of gas-quenched and oil-quenched 4140 bar stock of various diameters.*

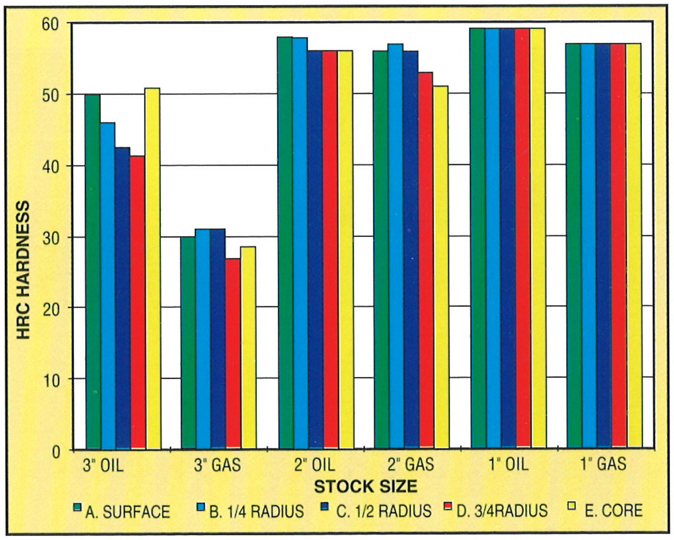

Fig. 4 *Hardness of gas-quenched and oil-quenched 4150 bar stock of various diameters.*

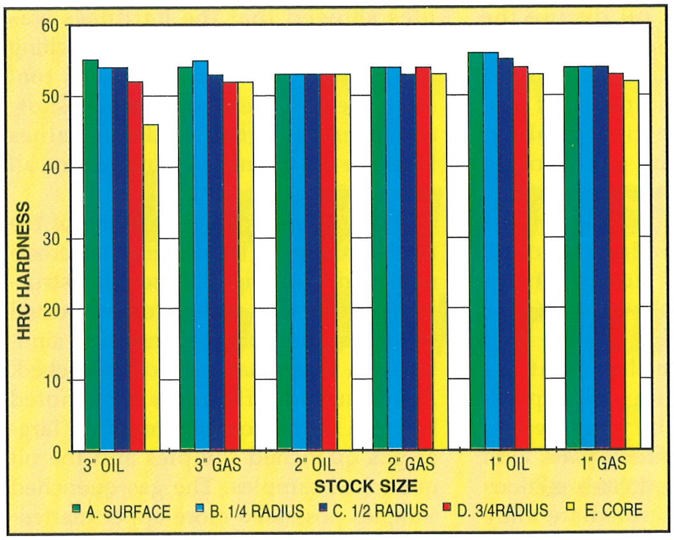

Fig. 5 *Hardness of gas-quenched and oil-quenched 4340 bar stock of various diameters.*

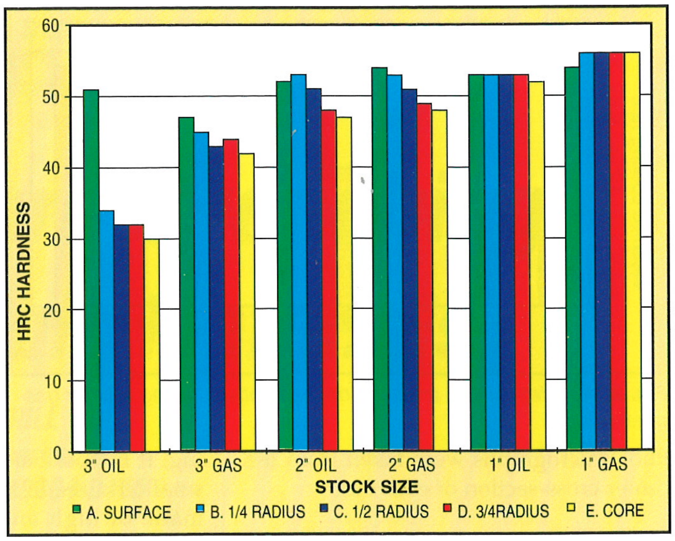

Fig. 6 *Hardness of gas-quenched and oil-quenched 01 tool steel bar stock of various diameters.*

horsepower needed to re-circulate the gas. Hydrogen has the potential for cooling faster at a lower cost than helium, but safety concerns have been an obstacle to its use. Compared to nitrogen (at 6 bar), hydrogen has 30% shorter cooling times and 40-50% higher heat transfer coefficient. Therefore, more heat treaters are employing hydrogen-nitrogen, helium-argon, and helium-nitrogen blends for quenching. The development and commercialization of a relatively inexpensive helium recovery system would significantly increase the use of helium.

There are several indisputable advantages of gas pressure quenching versus conventional liquid quenching:

- Gas quenched parts are clean, bright, and scale free;
- Distortion is dramatically reduced due to the more uniform cooling rates;
- There is more flexibility to change cooling rates easily with the use of microprocessor-based controls and directed gas flows to maintain cooling uniformity;
- Quenching with gas is the most environmentally friendly way to rapidly cool parts;
- Toxic or combustible waste gases are not produced with this method.

The limitations of gas pressure quenching versus conventional liquid quenching are:

- Gas quenching of larger cross-sections of some oil hardening grades can result in lower hardness, lower tensile properties, and lower ductility or fracture toughness;
- Certain alloys and carbon steels must be liquid quenched regardless of cross section size (e.g., 1045, 1075, 4130).

CONCLUSION

Extending the range of high gas pressure quenching to 10 bar and beyond could possibly meet or exceed the properties obtained previously in oil, salt, synthetic and even water quenchants. The race to higher operating pressure is only one factor in improving gas quenching capabilities. Uniform cooling velocities in the hot zone and more efficient re-circulation of the quenching gas are issues that require study by furnace manufacturers. A better understanding of fan efficiency and its relationship to the water-to-gas heat exchangers needs to be examined.

The desire to increase productivity and improve metallurgical properties while minimizing distortion and environmental impact exists for all heat treaters. Optimizing pressure gas quenching parameters and processes appears to be one solution to meeting this need.

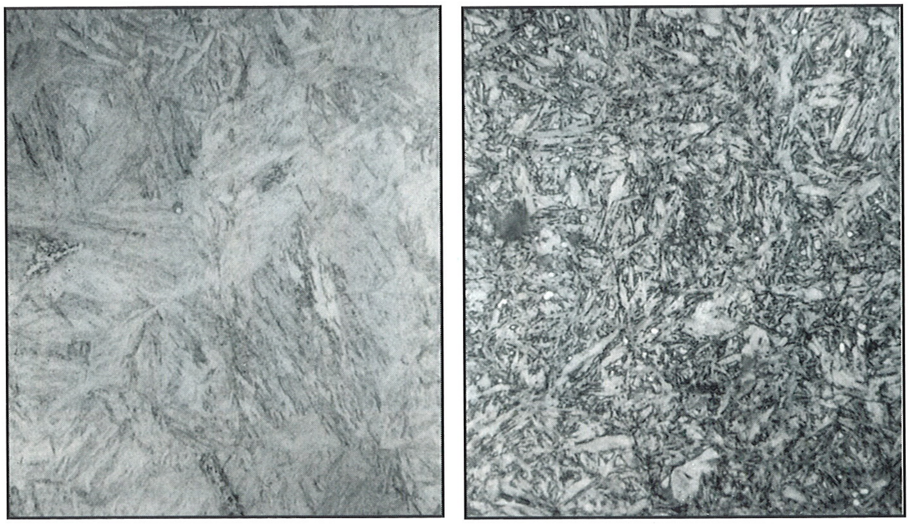

Fig. 7 *Core microstructures of the 3" diameter bars of (a) 4340 steel and (b) 01 tool steel.*

BIBLIOGRAPHY

- K. Moyer, "Microstructure of Oil Quenched and of Vacuum Heat Treated Steels," Project 97167, Magnatech P/M Labs, Cinnaminson, NJ.
- G.C. Carter, "Optimizing Gas Quenching," Advanced Materials and Processes, February 1996.
- "Development of High Pressure Gas Quenching," ALD Vacuum Technologies GmbH, Member of the ALD Thermo Technologies Group
- "Environmental Hazards and Safety Risks of Quenching Media," ALD Vacuum Technologies GmbH 24.04.1995-Py, Member of the ALD Thermo Technologies Group.
- "Comparison of the Heat Transfer Number for Different Quenching Media," ALD Vacuum Technologies GmbH. Member of the ALD Thermo Technologies Group.