High Pressure Gas Quenching Typical Oil Hardening Grades of Steel

Authors

ROBERT HILL, JR.
Vice President of Heat Treating
PHILIP M. DeHENNIS, PE
Corporate Metallurgist
Solar Atmospheres, Inc.
Souderton, Pennsylvania

ABSTRACT

High pressure gas quenching has been identified as one of the most important advancements in recent developments of heat treating technology. Over the decades, an extensive amount of research and documentation has been published on the hardenability of water and oil hardening grades of steels. To date, there is relatively little or no information on the hardenability of oil hardening grades of steel quenched in a high pressure, gas environment. The purpose of this article is to compare the transverse hardenabilities of various oil hardening grades of steel; quenched in both oil and in 10-bar pressure gas environment. The results were obtained at Solar Atmospheres, Inc located in Souderton, Pennsylvania.

INTRODUCTION

The purpose of this study is to compare some of the metallurgical effects of high-pressure gas quenching in a vacuum furnace, as opposed to oil quenching various oil hardening grades of materials. Recently, high pressure gas quenching has been identified as important advancement in heat treating technology. Over the decades, an abundance of documentation exists on the hardenability, mechanical properties, and microstructures of water and oil hardening grades of steels. To date, there is relatively little or no available information on the metallurgical properties that can be achieved when quenched in a high-pressure gas environment.

Therefore, the purpose of this paper is to impart useful information for the new commercial application of high-pressure gas quenching of typical oil hardening materials in a vacuum furnace.

BACKGROUND

The ultimate challenge of any heat treater is to achieve the absolute best microstructure with as close to 100% martensitic transformation as possible, without severely distorting or quench cracking the steel. As such, the quenching process is one of the most important aspects involved when considering successful heat treating.

The commercial heat treating industry has not had any specific mandates from industry or government agencies to modernize their salt pots and/or hardening furnaces. Since there is a high capital expenditure involved with fast quenching "State Of The Art" vacuum furnaces, less costly and out dated methods are still currently being used. The objective of this project is to identify the advantages and disadvantages of high pressure gas quenching in optimizing the desired metallurgical properties. In this report, as-quenched hardness and metallurgical structure are examined.

PROCEDURE

The two pieces of equipment that were used for this study were a VFS Model HL50, 10 bar (135 PSIG) pressure quench furnace, and a Leeds and Northrup, oil quench atmosphere furnace.

The VFS furnace has a 42" wide x 54" deep x 36" high hot zone which uses a 300 HP high velocity fan operating at 10 bar (or 10 atmospheres, 150 PSIA, 135 PSIG) pressure. The quenchant used in the vacuum furnace was nitrogen, which is then recirculated through a convection dominated water-cooled heat exchanger. The Leeds and Northrup furnace has a 14" wide x 24" deep x 12" high hot zone with an integral 300 gallon recirculating oil quench tank. The quenchant used in the electrically fired L and N was 130°F – 140°F (54°C – 60°C) Park AAA quench oil.

Six bars of each "oil hardening" grade material were used for this test. They were 01 tool steel, 4140, 4150, and 4340 alloy steels. Two bars of each material were 1" (2.54 CM) OD x 6" (15.24 CM) long, two bars of each material were 2" (5.08 CM) OD x 6" (15.24 CM) long, and two bars of each material were 3" (7.62 CM) OD x 6" (15.24 CM) long.

Each of the six bars were deep hole drilled with a 3/16" (4.76 MM) hole to the center, mid-radius and 1/4" (6.35 MM) from the surface. The purpose of the drilled holes is for deep thermocouple placement to monitor the temperature variation from the surface to the core of the part.

All specimens with similar cross sections were fully austenitized in the two hardening furnaces. Each specimen was monitored by the work thermocouples that were at the core of the work piece. A Honeywell DPR 1500 Process Recorder was used. Each specimen was subsequently quenched in either 130°F – 140° F (54°C – 60°C) oil or 10-bar nitrogen quench. Each specimen was then snap-tempered at 350°F for three hours on the work thermocouple.

Finally, each bar was diamond cut approximately one diameter back from the end of each bar. Transversal hardness readings were taken at the surface, 1/4 radius, 3/4 radius, and core of each specimen (see Tables 1 – 4). The specimens were then ground, polished, and etched with a 10% nital solution to reveal the microstructure. Photomicrographs were taken of the microstructure that was in the center of the cross section of each bar.

ANALYSIS

Hardness tests were conducted and recorded for each of the test specimens The actual hardness results for the gas and oil quenching of 4140 material were very similar for 1" diameter (2.54 CM). The core hardenability decreased dramatically for diameters greater than 1" (2.54 CM) for this alloy (TABLE 1). The 4150 alloy was quite comparable for both quenchants up to a 2" (5.08" CM) diameter. The surface to core hardenability decreased dramatically for the 4150 material in the 3" (7.62 CM) diameter (TABLE 2). The results of hardenability of the 4340 and 01 materials, displays a tremendous success rate up to 3" OD (7.62 CM). In fact, the pressure gas specimens actually yielded a slightly higher hardness than the oil quench specimens for the most of the sizes tested (TABLES 3 & 4).

Photomicrographs were taken of the microstructure that existed in the center of the cross-sectioned bars. Examples are shown in FIGURES 1 and 2. The microstructures of the steels that were heat-treated in the vacuum furnace were very similar from those that were oil quenched. The few subtle differences in microstructures were in the larger gas quenched specimens. They possessed more upper martensite and lower bainite than the oil quenched specimens. The larger diameter material, which was vacuum heat-treated, typically yielded an austempered structure.

Although different, there are many arguments that can be made for the gas-quenched heat treated steels. Arguments persisted over the years that bainite may be more beneficial than martensite as a microstructure. Martensite is a brittle phase, and if retained austenite is present in the microstructure, the problem of brittleness is accentuated. Bainite, on the other hand, is a transformation product that occurs because there is time for the structure to transform to a product that is more ordered. Therefore, the steel containing bainite rather than martensite can be considered to be tougher, without too much loss in hardness and wear resistance. Austempering is therefore deemed by many to be the preferred heat treatment rather than full conversion to martensite.

CONCLUSIONS

With the increased pressures in quenching, the 10 bar vacuum furnace is approaching the cooling rates of the oil quench furnace. There exist great differences in the cooling rate characteristics between oils and gas (see Exhibit A). Liquid quenchants possess three phases; vapor phase, boiling phase, and convection phase. Oil quench rates are usually faster in the beginning of the quench cycle at higher temperatures of the quench cycle, however, they tend to be slower at the end of the cycle. Each phase is clearly shown in the cooling curves. However, with gas quenching, only the convection phase exists. The quench rate, therefore, is slower at the beginning, however, it begins to approach and then exceeds 100°F per minute, depending on mass and geometry of the part. The gas cooling curve is very uniform and is even faster than that for oil at temperatures below 662°F (350°C). Therefore, the data from this study confirms that by using high-pressure gas quenching, it is possible to harden parts with small and medium size cross sections made of high and intermediate alloy steels to the same hardness as if using oil. In addition, the uniform cooling conditions dramatically reduces quench distortion.

ADVANTAGES AND LIMITATIONS OF GAS QUENCHING

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

> Gas quenched parts are clean, bright and scale free and do not require post cleaning or blasting.
>
> Distortion is dramatically reduced due to the more uniform cooling rates.
>
> There exists more flexibility to change cooling rates easily with the use of microprocessor-based controls and directed gas flows to maintain cooling uniformity.
>
> Quench cracking is minimized or eliminated.
>
> Quenching with gas is the most environmentally friendly way to rapidly cool parts because toxic or combustible waste gases are not produced with this method.

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

> Larger cross sections of some oil hardening grades, results in lower hardenability, lower tensile properties, and lower ductility or fracture toughness.
>
> Certain alloys and carbon steels must be liquid quenched no matter what the cross section is (e.g. 1045, 1075, 4130) to achieve full hardenability.

FUTURE CONSIDERATIONS

Better understanding and application of heat transfer fundamentals will lead to additional improvements in gas quenching technology. There is considerable room for vacuum furnace gas quench technology to increase cooling rates which can be achieved by increasing gas velocity and pressure. The constraints are economic considerations in order to achieve another atmosphere of pressure and other recirculation gas quenching design factors.

Inert gas types have an effect on cooling rates. Ten 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. Faster cooling can be obtained with light gases, like helium, to 20 bar because of reduced horsepower to recirculate the gas. Even more rapid cooling is possible with hydrogen, but the safety concerns have been an obstacle to its use. Hydrogen has the potential for cooling faster at a lower cost than helium. 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. The development and commercialization of a relatively inexpensive helium recovery system would significantly increase the use of helium.

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. However, the race to higher operating pressure is only one key to improved quenching with gas. Uniform cooling velocities in the hot zone and more efficient, lower pressure drop, in the recirculated 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 explored.

At Solar Atmospheres, Inc, we have modified one of our VFS vacuum furnaces to operate with helium gas and with an over-speed gas blower motor fan, operating at 6000 rpm by the use of a variable frequency motor controller. This has yielded further improvement, as much as 30% in gas rates, by increasing the motor horsepower loading and with helium gas.

The need exists for all heat treaters to increase productivity, and improve metallurgical properties while minimizing distortion and environmental impact. Optimizing pressure gas quenching appears to be the answer to this need.

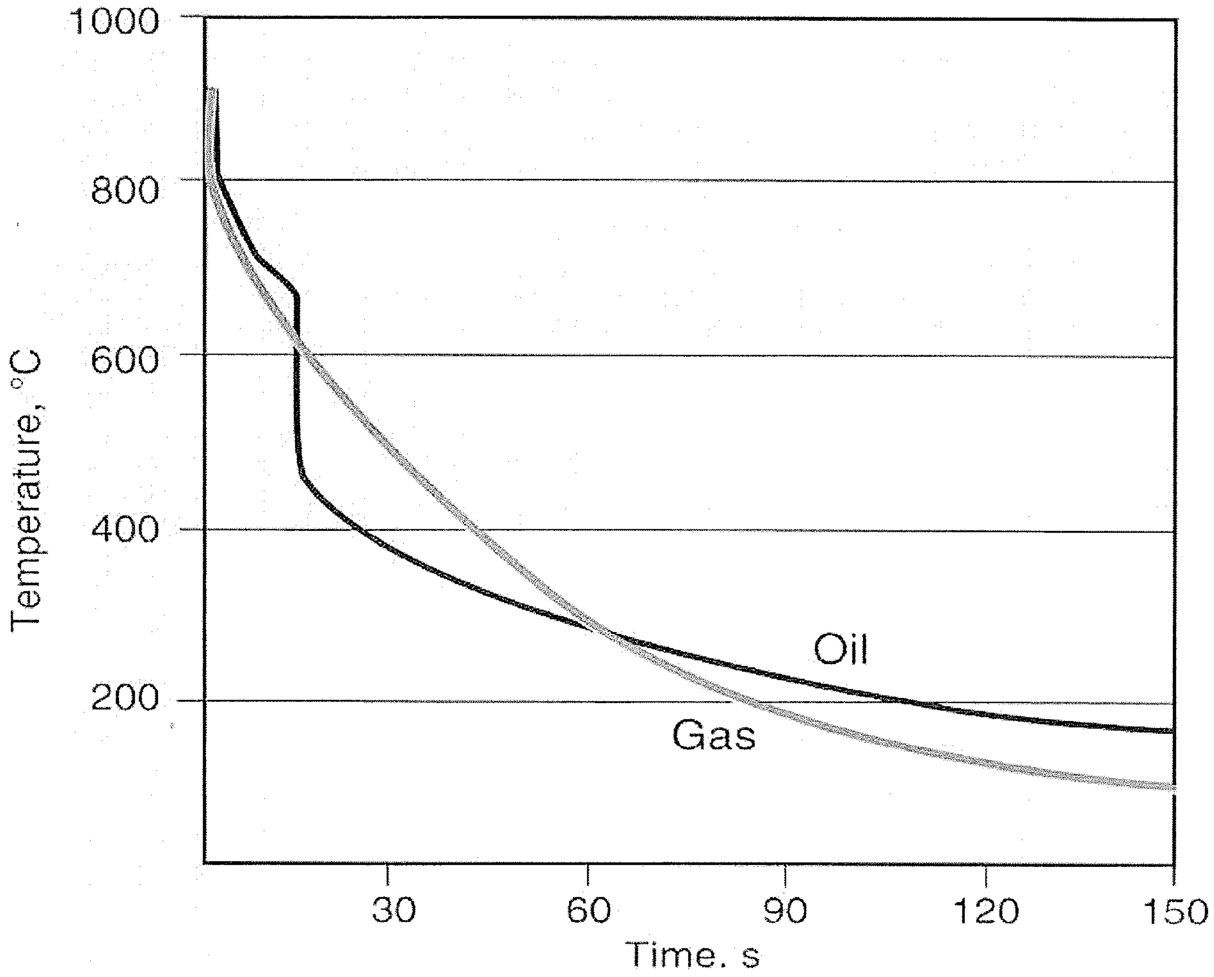
References:

Microstructure of Oil Quenched and of Vacuum Heat Treated Steels: Project 97167
by Ken Moyer, Magnatech P/M Labs, Cinnaminson, NJ

Vacuum Heat Treating for M2 High Speed and D2 Tool Steels
Proceedings of the 16th ASM Heat Treating Society, March 1996
by W. R. Jones, Solar Atmospheres, Inc. Souderton , PA

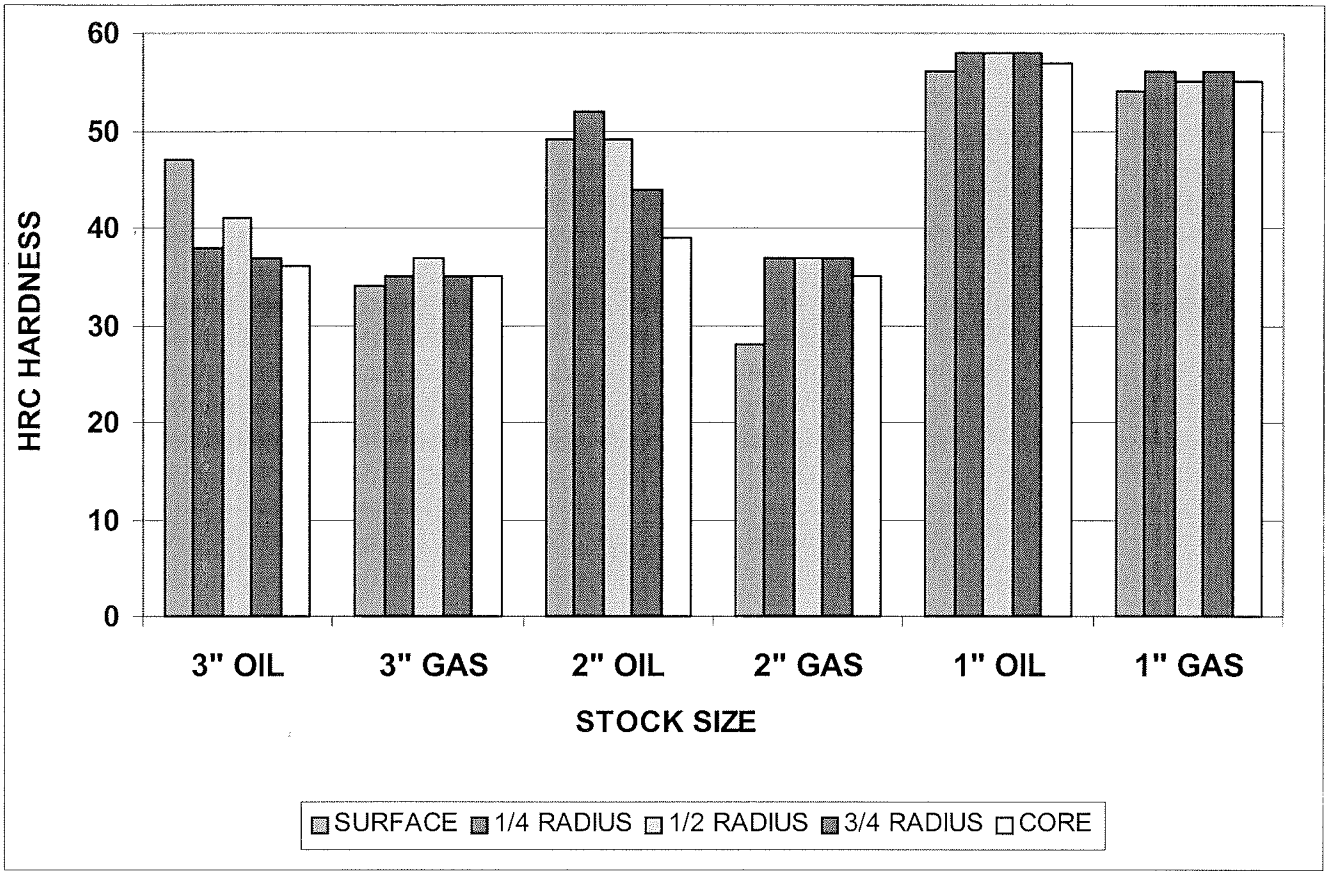
Optimizing Gas Quenching – Advanced Materials and Processes
February, 1996
by George C. Carter, Vacuum Furnace Systems, Souderton, PA

Development of High Pressure Gas Quenching
ALD Vacuum Technologies GmbH
*Member of the ALD Thermo Technologies Group



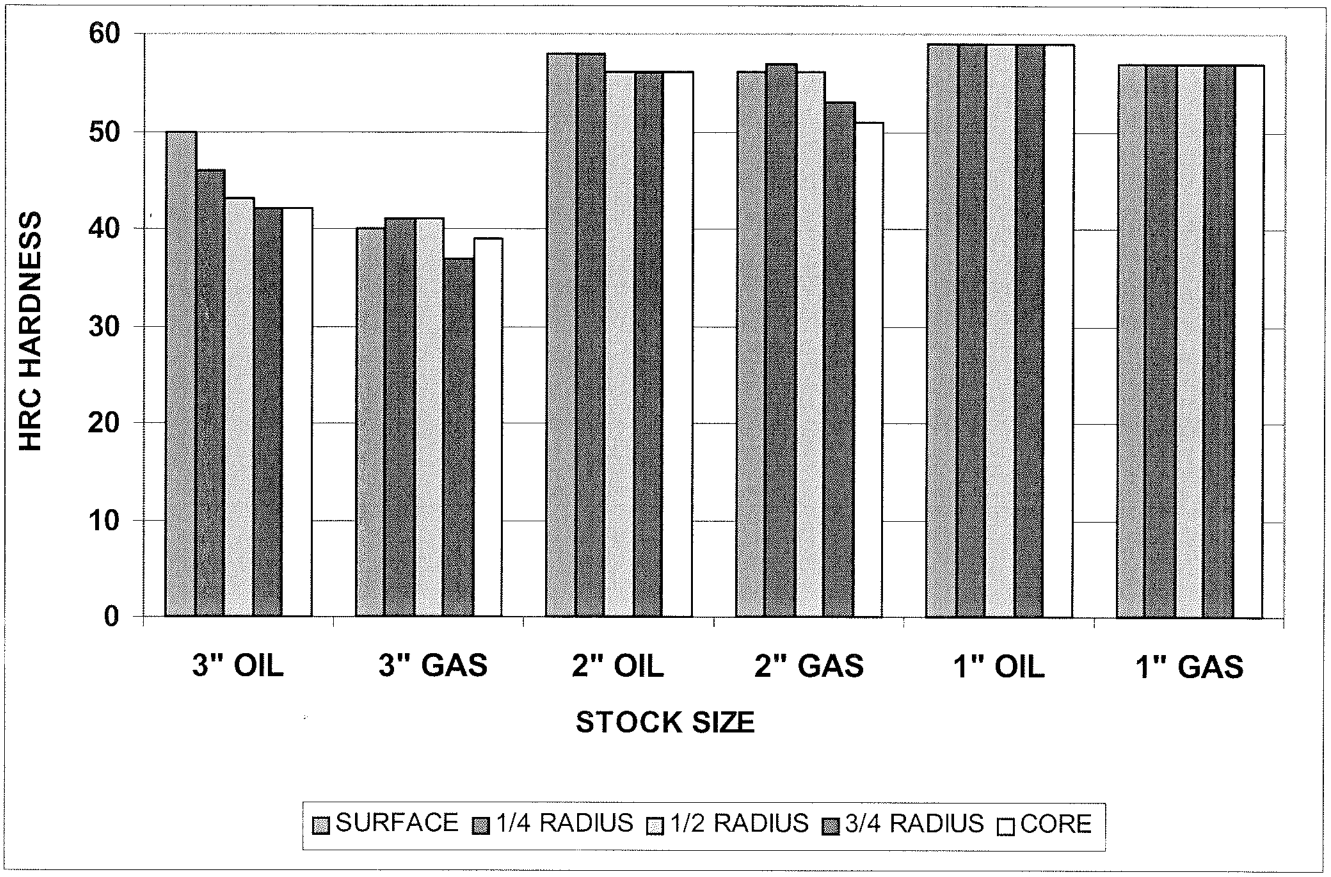
Graph showing uniform cooling provided by gas quenching. Shown are cooling curves for a 1.1” (28 mm) diameter cylinder quenched from 1550° F (850° C) in hot oil 230° F (110° C) with 0.4 m/s agitation compared with a premixed blend of Hydrogen –nitrogen at 10 bar. (Courtesy of XXXXXXXXXXXXXXX)

EXHIBIT 1



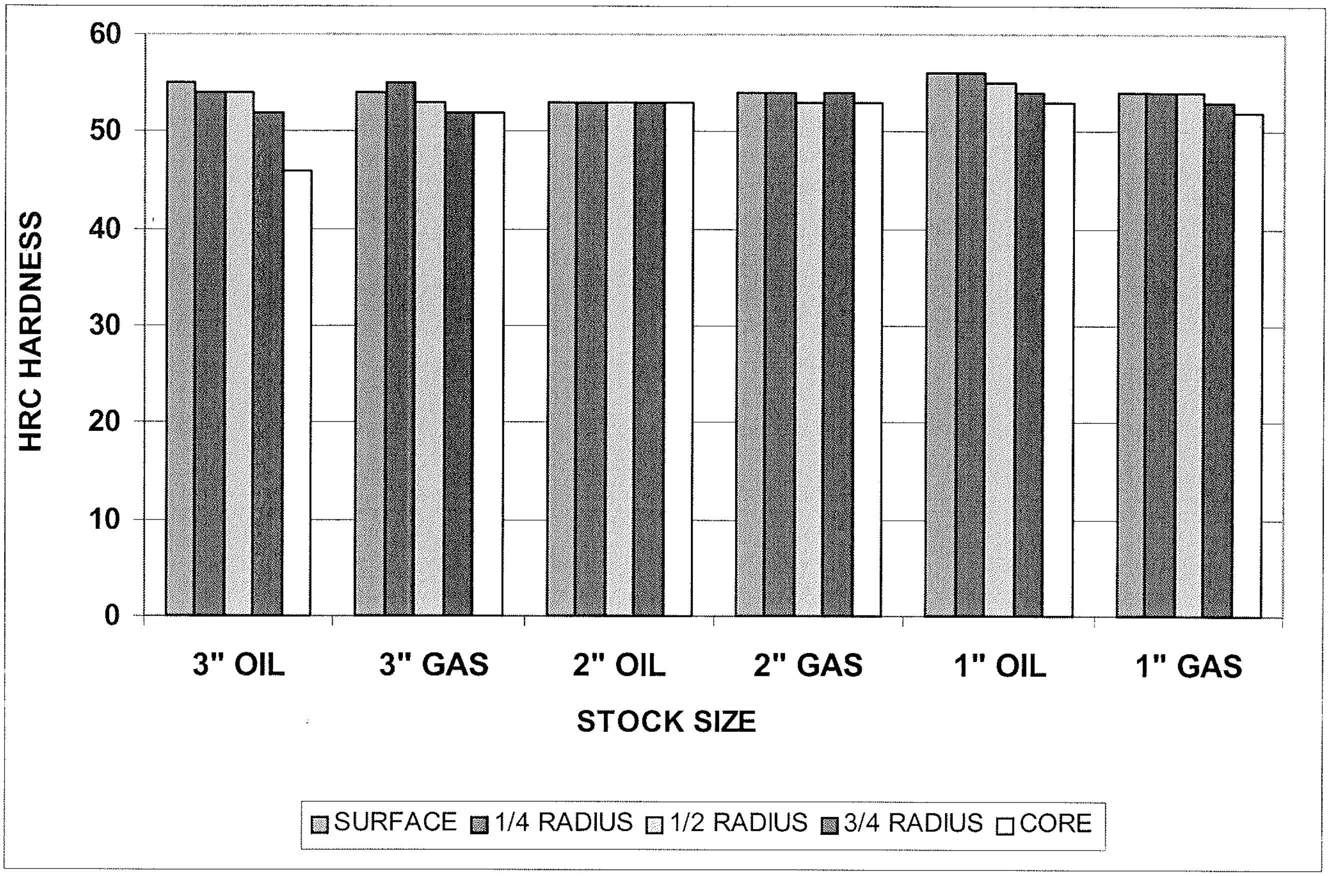
HARDENABILITY OF 4140 MATERIAL TEST DATA 10 BAR VERSUS OIL QUENCH

TABLE 1



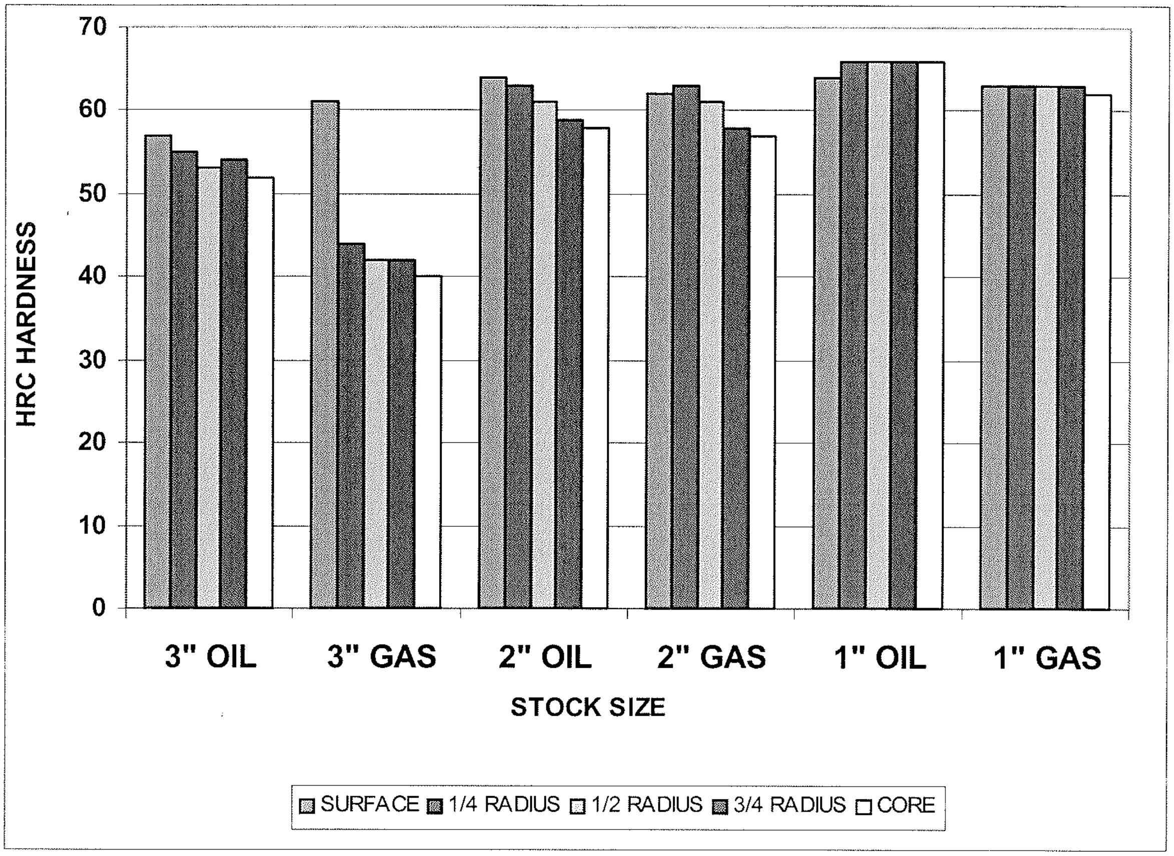
HARDENABILITY OF 4150 MATERIAL TEST DATA 10 BAR VERSUS OIL QUENCH

TABLE 2



HARDENABILITY OF 4340 MATERIAL TEST DATA 10 BAR VERSUS OIL QUENCH

TABLE 3



HARDENABILITY OF O-1 MATERIAL TEST DATA 10 BAR VERSUS OIL QUENCH

TABLE 4

(SEE ORIGINAL REPORT FOR PHTOMICROGRAPH)

4140 ALLOY 1500X

TYPICAL CORE OIL QUENCHED MICROSTRUCTURE

FIGURE 1

(SEE ORIGINAL REPORT FOR PHTOMICROGRAPH)

4140 ALLOY 1500X

TYPICAL CORE GAS QUENCHED MICROSTRUCTURE

FIGURE 2