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Effect of Intensive Quenching on Mechanical Properties of Carbon and Alloy Steels

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Abstract

The paper describes the results of study to evaluate the effect of the "intensive quenching" process on: the mechanical properties of plain carbon and alloy steels; the hardness distribution from surface to core; the surface and subsurface hardness of carburized steels, and the hardness distribution and residual stress in various steels. Data from three areas of inquiry are presented: I. Through-Hardening Steels (plain carbon and alloy); II. Carburized Steels; and III. 52100 Rollers. The first investigation compared the tensile and impact properties of 1038, 1045 and 1060 carbon steels and H13 steel after intensive quenching and after traditional oil quenching processes. The second area of investigation compared the hardness and residual surface stresses of carburized, plain carbon, 1018 steel in the intensively quenched condition, to carburized and oil quenched 4320, 5120 and 8620. The third area of investigation examined the hardness and residual stresses of 52100 rollers of 46mm and 75mm diameter. The residual stress distribution was measured by determining the X-ray diffraction at every 0.5mm interval from the part surface to a depth of up to 3.0mm.

Keywords: steel parts, intensive quenching, mechanical properties, residual surface stresses.

Introduction

Intensive quenching (IQ) processes are an alternative method of hardening steel parts. The IQ method uses highly agitated water, then still air, as the quenchant. First, a very high cooling rate is applied uniformly over the entire part surface, creating a cold "shell." When the residual compressive stress at the surface ("shell") reaches its maximum value (as determined by the IQ computer model), the "intensive" water quench is then interrupted and the cooling of the core continues in air, through the cold shell. This is in contrast to conventional quenching when steel parts are hardened using oil or a polymer-water mixture. With conventional quenching, the quench is not interrupted, and the residual surface stresses are usually neutral or tensile at the end of quenching.

The significant difference in quench-cooling rates provided by the IQ processes and by conventional quenching methods results in a different microstructure in the parts after intensive quenching and after quenching in oil [1]. Depending on the hardenability of the steel, the steel subjected to the intensive quench will be harder and have a finer structure than the oil or air quenched steel. These differences are greater as the cross-sectional thickness of the part increases. As with conventional quenching, the higher the cooling rate, the better the mechanical properties of the hardened steel part. In contrast to conventional quenching, however, the improvements to part mechanical properties obtained from IQ are not gained at the expense of additional part distortion or cracking.

Over the last several years [2, 3], IQ Technologies Inc and its customers conducted numerous studies of mechanical properties of actual parts that were intensively quenched. The data were compared to the same parts quenched in oil. In all instances, the oil quenched parts and intensively quenched parts were made from the same steel heat and were tempered to the same surface hardness. The intensively quenched parts have shown superior mechanical properties. The data presented in this work, clearly demonstrates that the IQ process significantly improves steel mechanical properties. Another important benefit of the IQ process is that it improves both the part strength and the part toughness at the same time. In addition, the environmental and cost benefits from the elimination of quench oils or quench polymers when using IQ should be noted.

Procedure

In 2003, IQ Technologies Inc and Case Western Reserve University initiated a material characterization study to evaluate and to quantify the effects of "intensive quench" (IQ) processes developed using the IQ Technologies computer models. This study was a part of the project sponsored by the Edison Materials Technology Center (EMTEC) and funded by the US Department of Energy (DOE), with in-kind contributions from Akron Steel Treating Company and from Euclid Heat Treating Company.

Data from three areas of inquiry are presented: I. Through-Hardening Steels (plain carbon and alloy); II. Carburized Steels; and III. 52100 Rollers. Using the process parameters dictated by the intensive quench computer model, the first investigation studied the effect of the intensive quenching method on several carbon steels, 1038, 1045 and 1060, compared to four types of commonly used alloy steels, 5160, 4130, 4140 and H13. This investigation compared the tensile and impact properties of these steel types after intensive quenching and after traditional oil quenching processes.

The second area of investigation studied the hardness distribution, case depth and residual surface stresses of various steels after case hardening with a conventional oil quench process, and with the intensive quench process. The results compare the hardness and residual surface stresses of carburized, plain carbon, 1018 steel in the intensively quenched condition, to carburized and oil quenched 4320, 5120 and 8620 (all as tempered at 400F). These results show about the same properties for the intensively quenched 1018 plain carbon steel compared to the three varieties of oil-quenched alloy steels.

The third area of investigation examined the hardness and residual stresses of 52100 rollers of 46mm and 75mm diameter. The residual stress distribution was measured by determining the X-ray diffraction at every 0.5mm interval from the roller surface to a depth of 3.0mm. The results show a marked increase in the beneficial compressive residual stress for the 52100 steel rollers quenched in high-velocity IQ system versus conventional oil quenching. The maximum residual stress in compression reaches -838 MPa at the surface of the specimens processed in the high velocity IQ system. The residual compressive surface stresses obtained with the high velocity intensive quench process are compared to those obtained in the "less intensive," batch-type, IQ system.

1. Mechanical Properties for Through-Hardening Steels

The following seven steels: 1038, 1045 and 1060 (plain carbon steels), and 5160, 4130 and 4140 ("oil hardening," alloy steels), and H-13 ("air hardening," high alloy, hot work tool steel) were tested. Small round bars of ∅19 mm and ∅22 mm, large round bars of ∅35 mm to ∅51 mm and large square bars of 51x51 mm were investigated. All the above test bars were of 380 mm in length and from the same heat lot of steel. For each type of steel, the test bars were quenched intensively in water or quenched in oil, then tempered to the same surface hardness. The following steel properties were measured: tensile strength, yield strength, elongation, reduction in area and the impact strength.

After heat treatment, standard tensile sample bars were made from each size test bars of the seven different steels, and a set of V-notch impact samples were produced from the core area of the treated test bars. Depending on the test bar size and on the quenching process employed, different sizes of test bars were used to measure the differences in steel properties in the core of the test sample after quenching and tempering.

Prior to making tensile and impact specimens from the bars, the bars were heat treated in two groups. One set of bars was quenched in oil and the second set of the bars was intensively quenched one-by-one from a neutral salt bath furnace to a high-velocity ("HV") IQ system [4]. Since the bars of H-13 steel must be austenitized at temperatures higher than what the salt bath furnace can provide, they were heated in an atmosphere controlled furnace before quenching.

The test bars were placed in the IQ system quench chamber and cooled at an "intensive" cooling rate with very rapidly flowing water. The optimum intensive water quenching conditions for the test bars of different sizes were obtained by providing the proper water flow rate through the quench chamber of the IQ system, then interrupting the intensive water quench when the model predicted maximum compressive surface stresses had been obtained. Table 1 presents the calculated cooling rates at the core (for a given core temperature) of each for the test bars of different sizes quenched in the high-velocity IQ system and quenched in the oil tank. The values in Table 1 represent the cooling rate of the core when its temperature is equal to 550^{o}C (1,022 ^{o}F) -- the point of the austenite minimum stability (500-550^{o}C). (When conducting the cooling rate calculations, it was assumed that the water temperature was equal to 20^{o}C (72 ^{o}F) and the quench oil temperature was equal to 50^{o}C (122 ^{o}F).)

Table 1 Test bar core cooling rates

Bar Size, mm	Core Cooling Rate @550^{o}C, ^{o}C/sec	
	IQ	Oil
∅19	162	58
∅30	65	23
∅38	40	15
∅51	23	8

The H-13 steel test bars were quenched intensively in the 6,000-gallon, IQ water tank ("WT") out of an atmosphere furnace capable of austenitizing the H13 material. The water flow velocity in the IQ tank is much lower than that in the high-velocity IQ system used for the other intensively quenched samples. (Note that the IQ conditions for the H-13 test bars were not optimized according to the IQT model; without the optimal intensive quenching rate, the maximum improvement in H13 properties was not obtained. In addition it should be noted that the "typical" H13 quench method is gas atmosphere or air quench. The data presented here for "traditional" quenching was obtained with the higher cooling rate of an oil quench.) After intensive quenching or oil quenching, all test bars were tempered to the specified hardness. Table 2 presents the thermal cycles used for quenching and tempering of the above test bars.

Table 2 Thermal cycles used for test bars

Type of Steel	Austenitizing Temperature	Tempering Temperature
1038	860^{o}C (1,580^{o}F)	496^{o}C (925^{o}F)
1045	845^{o}C (1,550^{o}F)	460^o C (860^{o}F)
1060	845^{o}C (1,550^{o}F)	399^{o}C (750^{o}F)
5160	845^{o}C (1,550^{o}F)	371^{o}C (700^{o}F)
4130	850^{o}C (1,560^{o}F)	496^{o}C (925^{o}F)
4140	850^{o}C (1,560^{o}F)	440^{o}C (825^{o}F)
H-13	1,020^{o}C (1,870^{o}F)	Double tempered at: 540^{o}C (1,000^{o}F) and 600^{o}C (1,110^{o}F)

The testing of the room temperature tensile properties was conducted in a Baldwin machine where the yield strength and tensile strength were obtained during testing. The ductility was quantified in the bars by determining their elongation and reduction area. The Charpy tests were conducted on all samples in a Tinius Olsen impact machine at room temperature.

2. Case Depth and Residual Surface Stresses for Carburized Steels

We also studied the hardness distribution and case depth with the high-velocity ("HV") IQ and the lower-velocity water tank (WT") IQ systems for carburized plain carbon, 1018 material with a diameter of 30mm. This work was directly compared to the hardness of carburized 4320, 5120 and 8620 alloy steels that were quenched in oil. All these specimens were soaked at 927^{o}C (1700^{o}F) for 5 hours @ 0.9% carbon potential and stabilized at 788^{o}C (1450^{o}F) for 30 minutes and cooled in the furnace under protective atmosphere. The 4320, 5120 and 8620 material were reheated to 843^{o}C (1550^{o}F) in an integral quench atmosphere furnace and then quenched in oil. Two of the 1018 specimens were reheated to 860^{o}C (1580^{o}F) in an integral intensive quench atmosphere furnace, and then quenched intensively in the 11,000-gallon, "batch" IQ water tank. Another two 1018 specimens were reheated to 860^{o}C (1580^{o}F) in a neutral salt bath furnace and quenched intensively one by one in the high-velocity IQ system. All specimens then were tempered at 204^{o}C (400^{o}F) for 2 hours in a tempering furnace.

All the case hardened specimens were examined for their effective case depth, hardness distribution (from surface to core), and their microstructures. Both the 1018 specimens quenched in the batch water tank and in the high-velocity IQ systems were selected to measure their residual stress levels. The 8620 material quenched in oil was also selected to measure its residual stress and to compare to the residual stresses in the 1018 specimens. Their residual stresses were measured for 9 points, every 0.2mm. The data was gathered to determine whether the IQ processes can provide higher residual compressive stresses in parts made of carburized plain carbon steel, compared to the same parts made of carburized alloy steels quenched in oil. If intensively quenched plain carbon steel can be made to perform equally (or better than) the alloy grades quenched in oil, there should be processing efficiencies and cost savings from substituting the plain carbon steel (e.g., ease of cold forming, better die life, lower material cost, environmental benefits from elimination of oil quench).

3. Hardness Distribution and Residual Surface Stresses in 52100 Steel Rollers

This investigation determined the hardness distribution and residual stress properties for 46mm and 75mm diameter, 52100 steel rollers quenched in the high-velocity ("HV") IQ system and the lower-velocity, water tank ("WT") IQ system. The 51200 steel specimens were heated to 843^{o}C (1550^{o}F) for 3 hours and 2 hours for 75mm and 46mm specimens, respectively, and then quenched intensively in the 11,000-gallon batch IQ water tank or the high-velocity IQ system. All specimens were then tempered at 182^{o}C (360^{o}F) for 2 hours in a tempering furnace. The testing determined the hardness distribution of 52100 steel obtained with the high-velocity and water tank IQ system. The hardness was measured for the surface hardness at both ends at several points per end, and for the circumferential surface hardness at three levels with 16 points per level for the larger ∅75mm specimens and 12 points per level for the smaller ∅46mm specimens. The residual stress was measured for 7 points every 0.5mm for ∅75mm specimens, and 6 points every 0.5mm for the ∅46mm specimens. This work was done to examine whether the IQ process provides bearing rollers made of 52100 steel with high residual compressive stresses to depths that are comparable to deep-case, carburized rollers made of traditional alloy steel grades (e.g. 8620).

Results and Discussion

1. Effect of IQ Process on Mechanical Properties for Through-Hardening Steels

As an example, Figure 1 illustrates the significant difference in the microstructure for ∅19 mm test bars made of 1045 steel after intensive quenching and after quenching in oil. The significantly finer microstructure in turn, improved the mechanical properties of the steel. The results the tensile properties obtained from these steels are shown in Table 3 for the small diameter test bars of ∅19 mm and ∅22.4 mm. These results show the mechanical properties of the IQ steels (except for oil quenched H13 and 4140) are always higher than the comparable oil quenched steels. Despite the differences in hardness, the ductility of the IQ material is only reduced slightly by the higher hardness level. This means that the majority of the IQ samples were stronger, and, at the same time, more ductile when compared to the oil quenched samples.

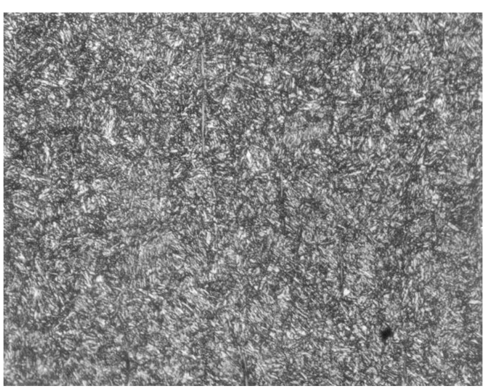
The tensile strength results and hardness at the core for the large samples made of six different steels are shown in Table 4. The diameter of the specimens varies from ∅30 mm to ∅51 mm. With the larger samples, the as-tempered hardness of the intensively quenched steel is usually slightly higher than the oil quenched steel. The higher hardness does not come at the expense of the ductility – in fact the ductility is usually somewhat higher for the IQ material. These differences occur because of the better quench of the intensive quench process and the associated finer microstructure compared to the oil quench process.

Generally, the intensively quenched steels have a higher hardness to a greater depth versus the oil-quenched steels, independent of the section size of the specimen. The rapid cooling from the intensive quench provides a higher strength level and also better impact resistance, even at the higher strength levels. The only exception is the oil-quenched H13 steel, with its high hardenability, and the 4140 steel in the small size sample. In these cases, the strength of the oil-quenched steel was slightly higher. However, the intensively quench material does have a significantly higher impact strength as shown in Table 5 and 6. Also as noted above, the intensive quench from the atmosphere furnace used to austenitizing the H-13 samples, was not optimized per the IQT model. Additionally, in most instances, H13 dies are quenched in gas atmosphere or in air, not in oil.

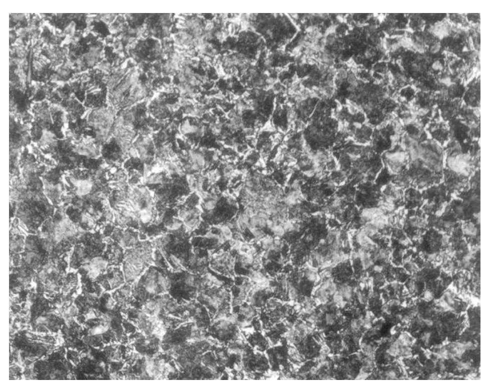
2. Improvement of Case Depth and Residual Surface Stresses for Carburized Steels

The hardness distribution over the entire diameter of the specimens is shown in Figure 2 for the carburized plain carbon steel (1018) quenched in the high-velocity ("HV") IQ system and for the batch (water tank – "WT") IQ system, versus the oil quenched, carburized alloy steels (4320, 5120 and 8620). These results show the improved hardness distribution and illustrate possible substitution of carburized and intensively quenched 1018 steel over the carburized and oil quenched alloy steels. (The differences in the core hardness of the material (below the carburized zone) for the plain carbon steel is due to the somewhat lower carbon, 0.18% C for the 1018, compared to 0.21% for the 4320 and 8620 and 0.20%C for the 5120 alloy steels.)

Figure 3 presents the residual stress values in the part surface layer for the specimens made of plain carbon steel 1018 and quenched intensively in the high-velocity IQ system and in the IQ water tank and for the specimen made of alloy 8620 steel quenched in oil. These results show the significantly improved residual surface stress conditions for both intensively quenched test samples compared to the oil-quenched specimen. Note that the specimen quenched in the high-velocity IQ system had the higher residual surface stresses compared to the test sample quenched intensively in the IQ water tank. This is because the high-velocity IQ system provided optimum quench conditions for the specimen while intensive quenching of the test sample in the IQ water tank was not optimum.



Intensively quenched X250



Oil-quenched X250

Figure 1 Microstructure of ∅19 mm test bars made of 1045 steel

Table 3 Mechanical properties for small test samples

Test Bar Cross Section, mm	Steel/ Quench	Core Hardness, RC	Ultimate Strength, ksi	Yield Strength, ksi	Elongation, %	Reduction in Area, %
∅19	1045 IQ	37	172.6	163.0	13.3	48.3
	1045 Oil	32	143.2	111.0	19.0	60.2
∅19	1060 IQ	44	212.3	199.6	10.8	30.6
	1060 Oil	40	177.9	140.0	12.2	31.6
∅22	4130 IQ	35	157.2	142.7	17.8	63.4
	4130 Oil	30	134.1	117.2	19.3	64.7
∅19	4140 IQ	48	195.7	163.1	13.8	52.7
	4140 Oil	45	218.3	171.2	12.5	48.2
∅19	5160 IQ	48	250.4	229.6	11.5	39.5
	5160 Oil	47	230.7	213.3	11.7	38.2
∅19	H-13 IQ	45	219.5	187.8	15.6	52.5
	H-13 Oil	47	231.3	197.7	14.4	51.5

Table 4 Mechanical properties for large test samples

Test Bar Cross Section, mm	Steel/ Quench	Core Hardness, RC	Ultimate Strength, ksi	Yield Strength, ksi	Elongatio n, %	Reduction in Area, %
∅30	1038 IQ	26	122.2	90.1	21.0	56.4
	1038 Oil	23	116.9	77.1	20.3	51.3
∅50	1045 IQ	28	129,2	102.0	21.0	49.6
	1045 Oil	27	127.5	90.7	18.4	42.2
50x50	1060 IQ	38	178	133.8	14.8	36.8
	1060 Oil	38	176.3	126.2	10.9	23.0
∅50	4140 IQ	44	209.7	155.4	13.8	52.0
	4140 Oil	42	192.6	146.5	14.3	50.2
∅38	5160 IQ	48	273.4	217.2	4.9	7.3
	5160 Oil	48	235.2	187.3	8.3	21.1
∅50	H-13 IQ	44	206.4	187.8	13.9	43.3
	H-13 Oil	45	219.9	179.6	12.7	38.4

Table 5 Impact properties for small test samples

Test Bar Cross Section, mm	Steel/ Quench	Ultimate Strength, ksi	Impact Strength @72^{o}F, lb·ft
∅19	1045 IQ	172.6	40
	1045 Oil	143.2	39
∅19	1060 IQ	212.3	19
	1060 Oil	177.9	20
∅22	4130 IQ	157.2	70
	4130 Oil	134.1	92
∅19	4140 IQ	195.7	30
	4140 Oil	218.3	16
∅19	5160 IQ	250.4	16
	5160 Oil	230.7	16
∅19	H-13 IQ	219.5	22
	H-13 Oil	231.3	21

Table 6 Impact properties for large test samples

Test Bar Cross Section, mm	Steel/ Quench	Ultimate Strength, ksi	Impact Strength @72°F, lb·ft
∅30	1038 IQ	122.2	62
	1038 Oil	116.9	28
∅50	1045 IQ	129,2	25
	1045 Oil	127.5	23
50x50	1060 IQ	178	9
	1060 Oil	176.3	8
∅50	4140 IQ	209.7	15
	4140 Oil	192.6	14
∅38	5160 IQ	273.4	7
	5160 Oil	235.2	7
∅50	H-13 IQ	206.4	14
	H-13 Oil	219.9	12

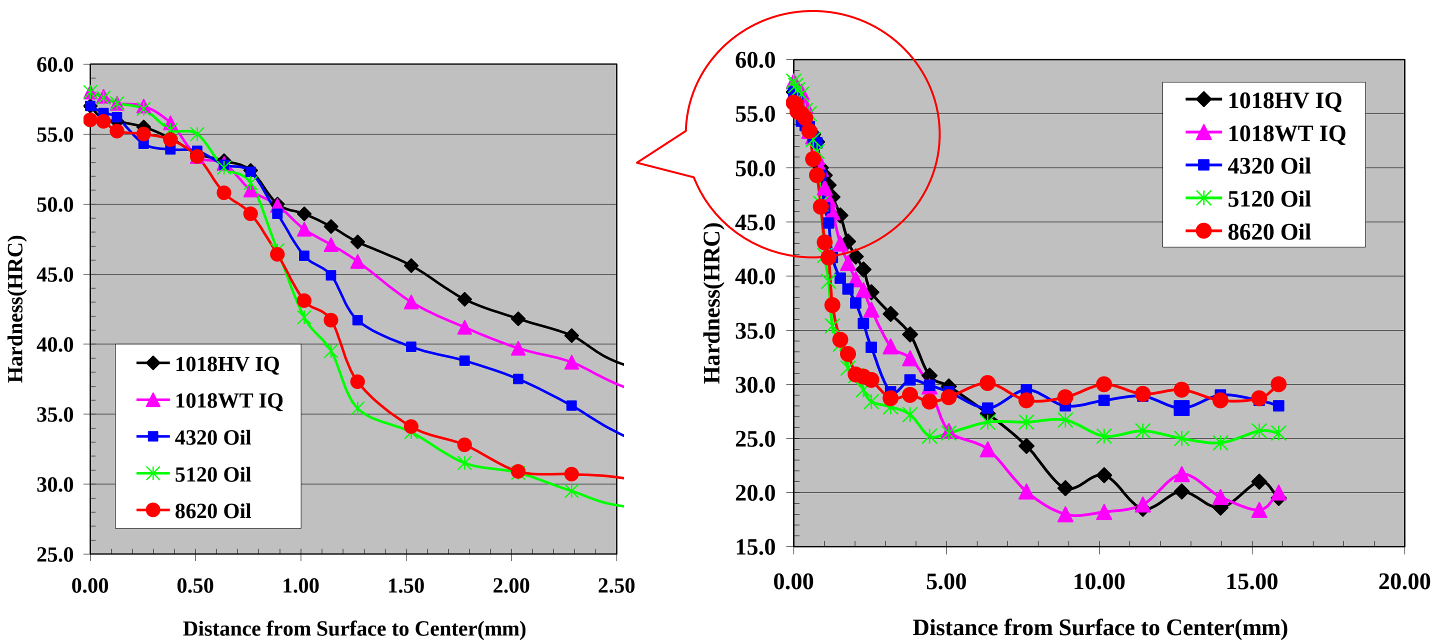


Figure 2 Hardness distribution of carburized 1018, 4320, 5120 and 8620 steels

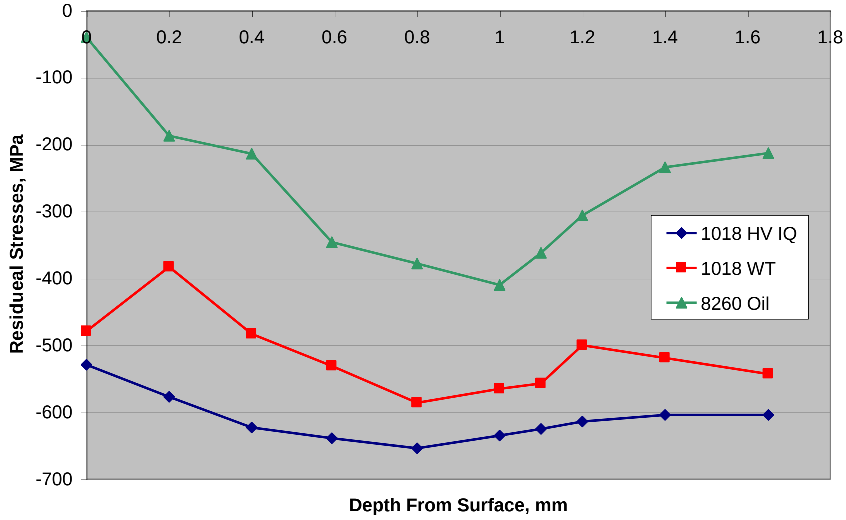


Figure 3 Residual surface stress distribution of carburized 1018 and 8620 Steels

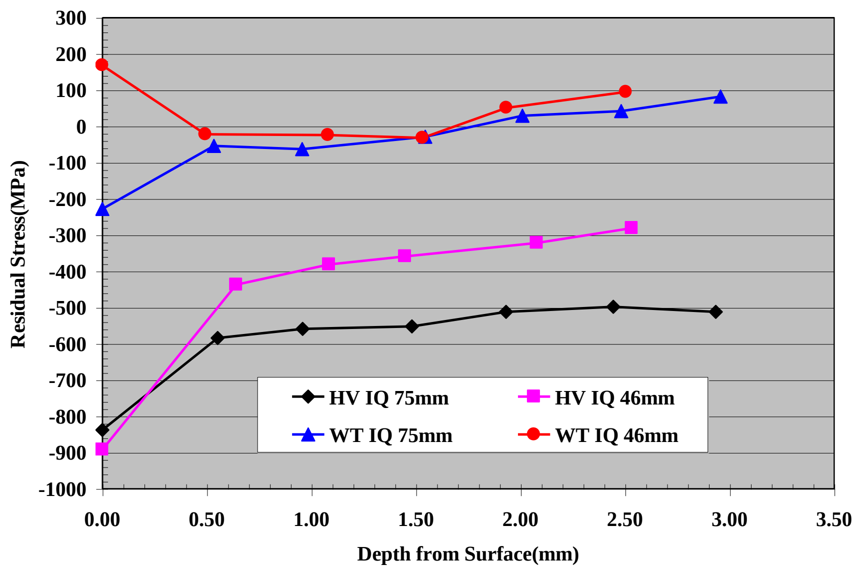


Figure 4 Residual stress distribution for 52100 steels

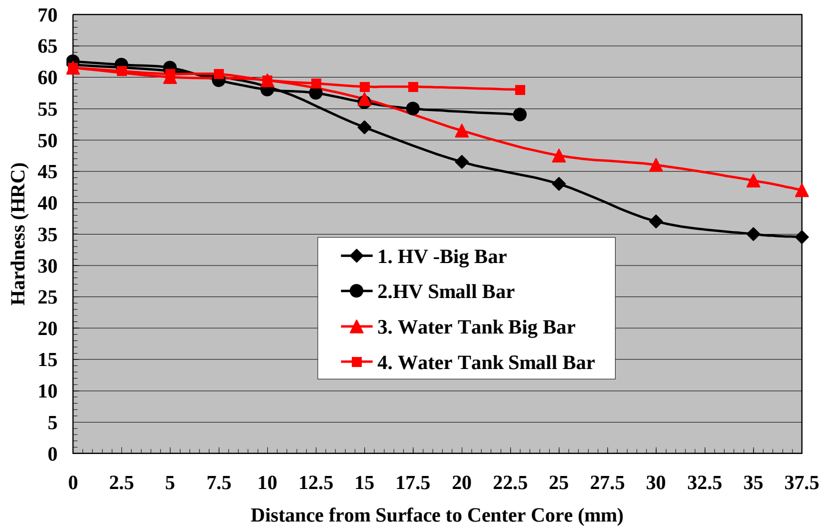


Figure 5 Hardness distribution of 52100 steel

3. Hardness Distribution and Residual Stresses in Intensively Quenched 52100 Steel Rollers

The 52100 steel processed in high-velocity IQ system had the higher compressive residual stresses for both the small and large diameter specimens compared to quenched in the batch type, "lower-velocity" water tank, IQ system. These results are shown in Figure 4. The higher compressive residual stresses were obtained from the larger diameter specimens. The as tempered hardness distribution of this material is relatively uniform at the surface – approximately 61.5 HRC to 62.5 HRC. The hardness distribution from surface to core is shown in Figure 5

Conclusions

1. For a given type of steel of the same section size, the intensively quenched steel specimens generally develop a higher strength, and, at the same time, a higher ductility than the steel samples quenched in oil.

2. The impact properties obtained from intensively quenched steels are generally superior to the impact properties from oil-quenched steels.

3. While the strength level varies depending on the section size and type of steel, because of the rapid cooling rate obtained at the surface of the part and the finer microstructure obtained throughout the part section, the intensively quenched material does exhibit better mechanical properties than the oil quenched material.

4. For carburized grades of steel, the intensive quenching process provides both the higher effective case depth and the greater and deeper residual surface compressive stresses.

5. The intensively quenched specimens made of plain carbon steel showed deeper effective case depth and higher residual surface compressive stresses than the specimens made of alloy carburized grades and quenched in oil.

6. For through hardened steel test rollers, the compressive residual stresses below the surface were the highest for the samples given the high-velocity intensive quench process. These residual stresses extended under the surface to a depth of 2.5 to 2.9mm.

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