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Intensive Quenching Method

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1. Introduction

As is well known, historically, water was the first cooling medium used for quenching of steel. Later, mineral oils became the most common quench media. Then, quenching in water polymer solutions and a high-pressure gas quenching method were introduced. Nowadays, a rapid water quenching method is used more seldom than a slow cooling gas quenching process. The main reasons for this are the following:

- High probability of part cracking when quenching rapidly in water
- High part dimensional and shape distortion due to a non-uniform cooling in water.

One of the coauthors of this paper originated a new water quench method based on the fact that quench cracking does not occur when austenitized parts are cooled very rapidly and uniformly in water. Moreover, in this case, part distortion due to quenching may be minimized. This new cooling method is called Intensive Quenching Process. Hereinafter in the paper, it is referred to as the "IQ" method.

The IQ method uses plain water or low concentration water-salt solution as a quenchant. These water quenchants are environmentally friendly and much less expensive than quench oils or water polymer solutions. Also, the quenched parts do not need post cleaning as required after oil quenching. Due to a high cooling rate provided by intensive water quenching, a deeper hardened layer can be achieved compared to slower cooling rates of oil quenching or high-pressure gas quenching. The IQ process also provides high residual surface compressive stresses. Both the deeper hardened layer and the higher residual surface compressive stresses improve the part strength and fatigue life. The IQ process when applied to carburized grades of steel shortens the duration of the carburization cycle. With the IQ method, alloy steels can be replaced by intensively quenched carbon steels resulting in significant material cost reductions. The IQ method is presently successfully used in the USA and in India.

2. What is IQ method?

2.1 Cooling rate

Figure 1 shows a relationship between the cooling rate and the probability of quench cracking obtained for 6mm diameter test specimens made of JIS SCr440H steel (Russian 40X steel). As seen from the figure, the probability of cracking is extremely low for the cooling rate of 160°C/sec

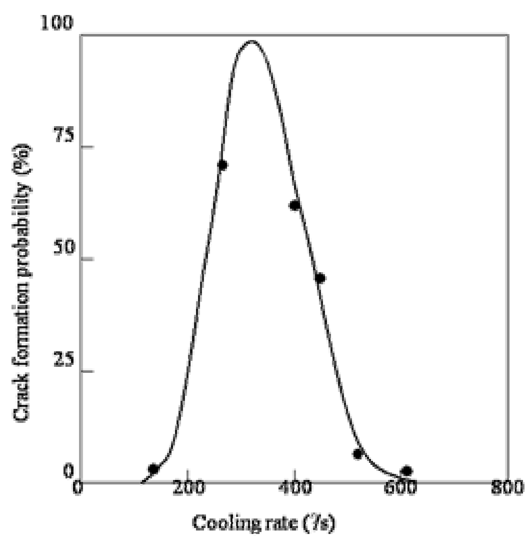


Figure 1 Relationship between cooling rate and quench cracking

achieved by oil quenching. For a higher cooling rate of 250°C/sec, 75% of test samples had quench cracks and for a cooling rate of 300°C/sec, 100% of test specimens cracked. This is in agreement with a conventional wisdom that the higher the cooling rate during quenching, the greater the probability of part cracking.

However, Dr. Kobasko discovered experimentally a phenomenon that the probability of quench cracking can be reduced at a faster cooling rate (at 400°C /sec., see Figure 1). It was proved that at a rate of 550-600°C /sec., no cracking was observed. Therefore, the desired cooling rate in the IQ method is about 3 to 4 times greater than the cooling rate during oil quenching.

2.2 The reason for IQ eliminating quench cracks

In a conventional water quenching process, that provides a faster cooling rate compared to oil quenching, it is not easy to have homogeneous cooling conditions throughout the load being quenched. The cooling rate varies within the load. The vapor blanket formation on the part surface is also not uniform during the film-boiling mode of heat transfer. Non-uniform film boiling on the part surface means that the rate of martensite formation, as well as the part stress conditions, vary from location to location, directly affecting the amount of non-predictable part distortion from heat treatment. In general heat-treating practice, to avoid non-uniform part cooling, the cooling speed of the quenchant is kept low, rather than high to provide uniform cooling at any location. (Note, that this slow cooling requires the use of higher hardenability materials).

In contrast to conventional water or oil quenching, the IQ method provides rapid and uniform cooling throughout the workload. This method creates high residual surface compressive stresses, low and repeatable distortion and prevents parts from quench cracking.

Figure 2 shows a cross section of a wedge type specimen that was quenched conventionally in oil (a) and intensively in water (b). In the figure, "M" indicates martensitic structure, and "A" indicates austenitic structure. During conventional oil quenching, the cooling rate of the part's thinner section (the upper portion of the specimen) is faster

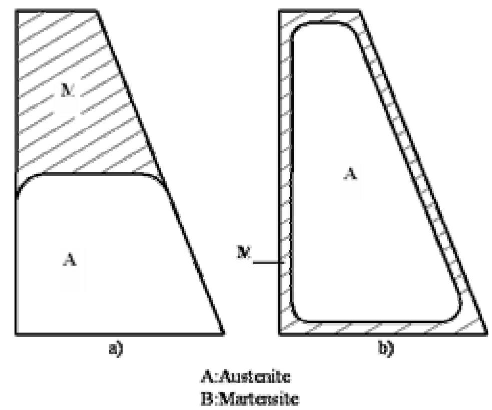


Figure 2 Cross section of a wedge type specimen

than that of the part's thicker section (the lower portion of the specimen). At a point of time when the thinner part section transforms to the martensitic structure, the thicker part section is still austenitic. As the part temperature continues to drop, the austenite in the surface layers of the part's thick section start transforming to martensite. The final structure in the part core can be bainite or troostite depending on the steel hardenability. In contrast, the IQ process provides so high cooling rate that martensite forms uniformly throughout the part surface, regardless of the cross sectional thickness, creating a hardened layer, like a shell, with high surface compressive stresses. High surface compressive stresses prevent part from cracking during intensive quenching [(2)(3)(4)].

3. Distribution of hardness

A difference in the hardness distribution after conventional oil quenching and intensive water quenching was investigated using round steel bars made of SAE 1018 and SAE 8620 steels and having diameter of 25mm. All bars were carburized in the same furnace to the same carbon profile. Figure 3 shows a distribution of the carbon content in the test bars after the carburization process. Figure 4 shows the hardness distribution in the test specimens after conventional oil quenching and after intensive water quenching. It is clear from Figure 4 that the material hardness for the same carbon content depends very much on the cooling rate. It is apparent that the deeper hardened layer can be achieved with the IQ method compared to conventional oil quenching. Since the materials used have an inherently poor hardenability (without carburization), the quenched depth obtained depends on the severity of quench (for the same part thickness).

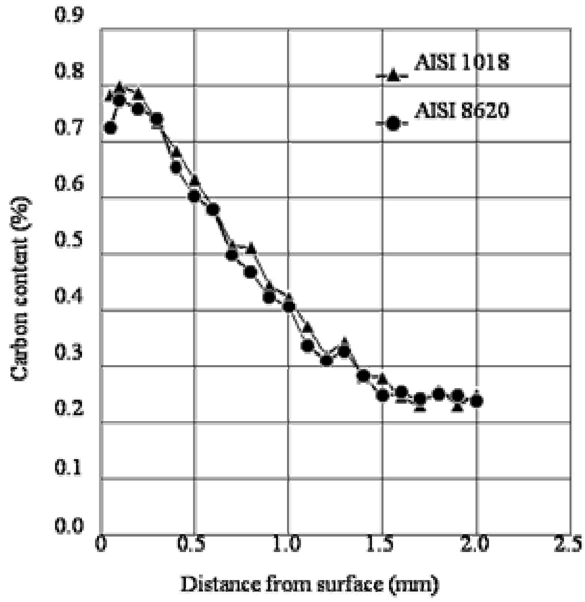


Figure 3 Carbon distribution curves for AISI 1018 and AISI 8620 steel samples

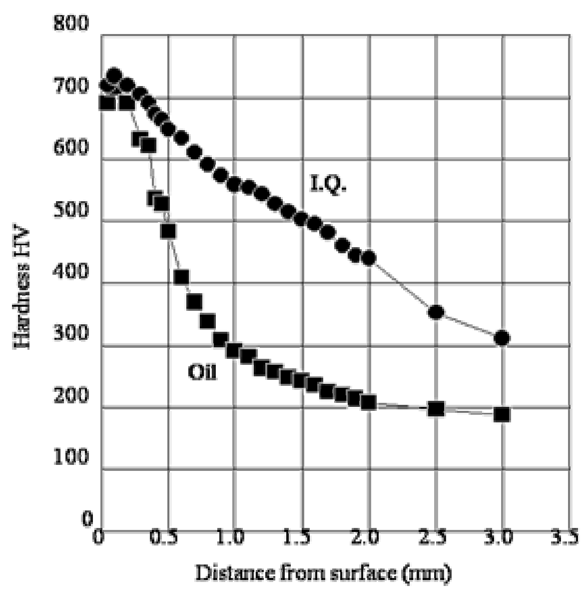


Figure 4 Hardness distribution curves for carburized sample made of AISI 1018 steel

Figure 5 presents the hardness distribution in the AISI 8620 steel test sample after conventional oil quenching and after intensive water quenching. AISI 8620 material has better hardenability than AISI 1018 steel. Due to a higher AISI 8620 material hardenability, there is no variation in the hardness values down to 1 mm of depth from the part surface regardless of the cooling rate. It is clear that hardness differs at the deeper location than 1mm for oil quenched sample and intensively quenched sample due to the difference of the cooling rates of these two quench methods.

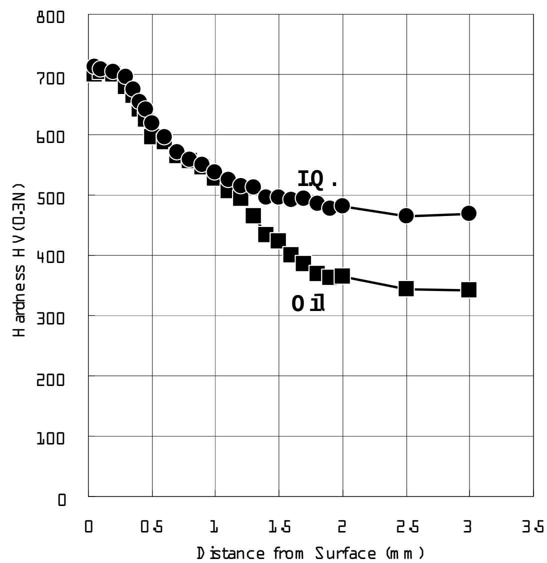


Figure 5 Hardness distribution curves for carburized sample made of AISI 8620 steel

Figure 6 shows the hardness distributions after intensive quenching for the samples made of AISI 8620 and AISI 1018 steels. It is clear from the figure that the hardness profiles are about the same for both samples throughout the depth of about 1.5mm. This means that with the IQ method, a lower hardenability steel can be used to achieve the same hardness profile as alloy steel.

4. Microstructure

Photos 1 a) and b) show photographs of the microstructure within the effective case depth: a) for the AISI 1018 steel intensively quenched sample (the microstructure is 100% martensite), and b) for the AISI 8620 steel sample quenched in

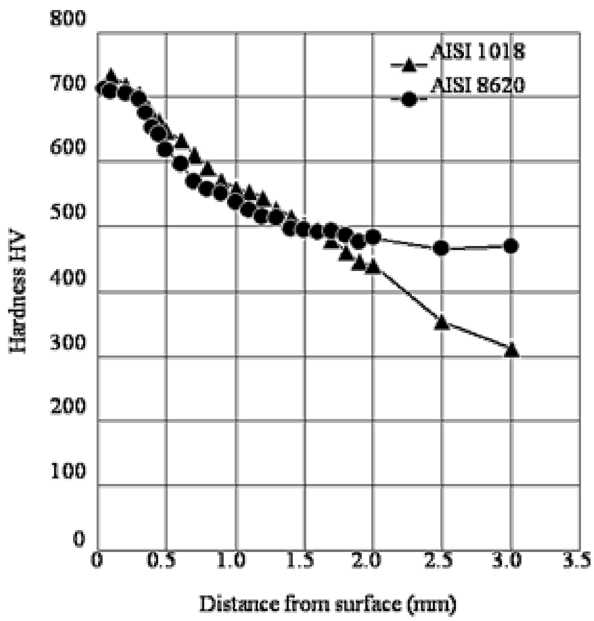
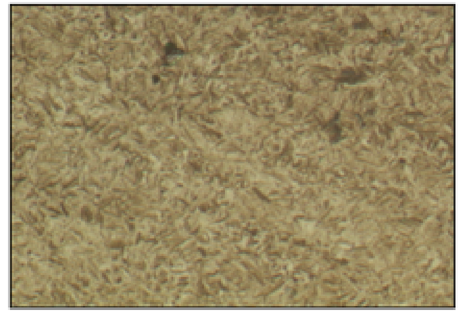
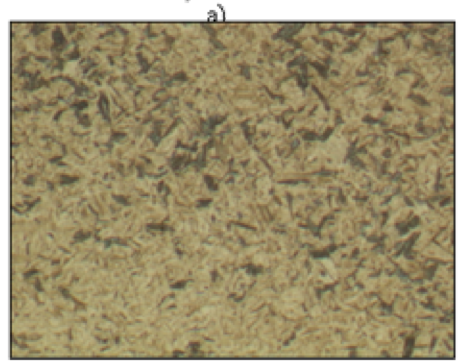


Figure 6 Hardness distribution for IQ method shown in Fig.4 and Fig.5



a)



b)

Photo 1 Photographs (x300) of microstructures at the depth with effective hardness of:
(a) HV547 (at that point carbon is 0.29%).
(b) HV550 (at that point carbon is 0.28%).

oil (the microstructure consists of martensite and diffusion transformation products - bainite and troostite). The carbon content at a HV550 hardness location is the following: a) 0.29 % and b) 0.42%.

5. Relationship between carbon content and hardness

The relationship between the carbon content and material hardness has been well known for a long time. A graph showing this relationship is presented in Figure 7[5]. In the figure, round white marks indicate previously obtained data[5]. Round black marks represent the hardness data acquired from the 10×1.5mm specimens made of JIS SCM415 steel. The specimens were carburized to various carbon contents and then were cooled down from 850°C in water. These data show that the carbon content of 0.28% provides the hardness of HV550 that determines the effective case depth. According to the data presented in the handbook of LOI ThermoProcess Company of Germany, a threshold of the carbon content is 0.29% for providing hardness of HV550. Accordingly, judging from the data of a 100% martensitic structure with the hardness of HV547 or its carbon content of 0.29% as shown in Photo 1a) and also

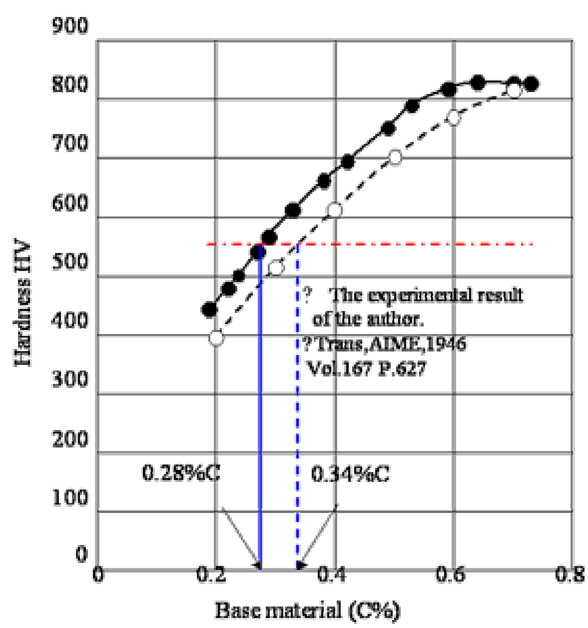


Figure 7 Relationship between carbon content and as-quenched hardness

the data of 0.28% carbon content to have HV550 as shown in Fig. 7, it is possible to get the hardness of HV550 with 0.28 – 0.29%C by rapid cooling.

6. Benefits from IQ method

6.1 Improvement of mechanical properties

Table 1 shows mechanical property data for three steels that were quenched in oil or quenched intensively in water. All test samples were austenitized at 850°C before quenching in oil or in water. Intensively quenched samples and oil quenched samples were tempered to the same surface hardness. Regardless of the steel type, material mechanical properties were better after intensive quenching compared to that after oil quenching: the tensile strength was improved by about 10%, the yield strength increased by about 20% and impact strength improved by 2 to 3 times comparing to the average values of these parameters.

6.2 Shortening of carburizing process time

The IQ Technologies Inc authors of this paper and M. Gopal, P. Ghorpade, et al, of HighTemp Furnaces of India, carburized a load of universal joint crosses (shown in Photo2) and quenched them in oil. An effective case depth obtained was 1.5 mm. Another set of universal joint crosses was subjected to a 60% shorter carburizing process followed by intensive quenching parts in water. The effective case depth obtained was also 1.5mm. Figure 8 shows the hardness distribution in two universal joint crosses subjected to the above carburizing processes. These data proved the capability of the IQ process to shorten substantially carburization cycle times versus oil quenching.

Photo 2 Universal joint cross

Table 1 Data on steel mechanical properties

JIS AISI	Quenching	Tensile Strength MPa	Yield Strength MPa	Impact Strength J/m^2	Hardness HRB
JIS SCr440 AISI 5140	Oil	780	575	113	217
	I.Q.	860	695	168	269
JIS SCM440 AISI 130	Oil	960	775	54	285
	I.Q.	970	820	150	285
JIS SCM421 AISI 4118	Oil	755	630	70	229
	I.Q.	920	820	170	285

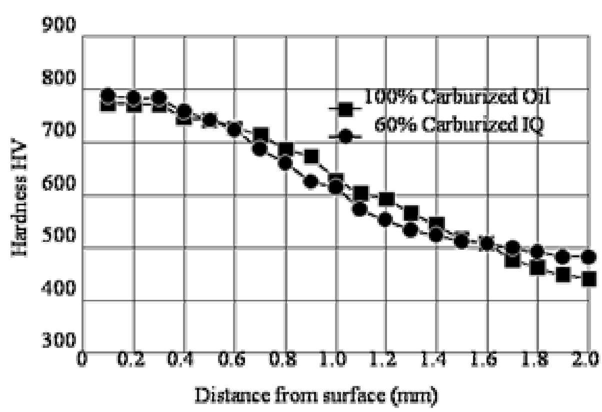


Figure 8 Hardness distribution curves for 2 different carburizing times

6.3 Improved residual compressive stresses

A conventional oil quenching process and an IQ method were applied to punches made of AISI S5 material (0.55%C; 2.00%Si; 0.80%Mn; 0.40%Mo). Photo 3 shows a picture of the punch used. Residual surface stresses measured after both heat treatment processes are presented in Fig. 9. It was shown that the residual surface stresses are tensile after oil quenching and they are compressive after intensive water quenching.

Photo 3 Punch used

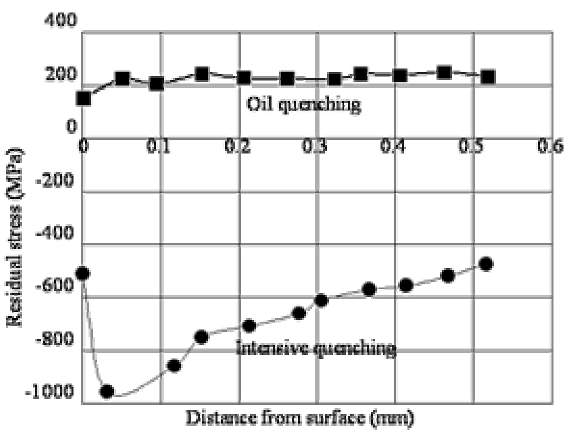


Figure 9 Residual stress distribution curves for oil quenching and IQ

The part service life was also evaluated. The punches were installed in a pressing machine making 175 holes per minute in structural steel. The service life of the intensively quenched punches was 2.5 times longer compared to that of the oil quenched punches.

6.4 Distortion due to heat treatment

One of the authors of the paper evaluated a heat treatment distortion of a pinion gear after carburizing and water-spray cooling (the water-spray equipment provided a severity of quench [8] of $3.5in^{-1}$). The gear characteristics were as following: module - 14, number of teeth - 11, width of tooth - 140mm. Figure 10 shows gear distortion before and after quenching. The following parameters were measured: the tooth lead error, the tooth profile error and the amount of crowning. Figure 10 presents the change of the average value and standard deviation of each of the above parameters. When characterizing the part distortion, the most important parameter is a value of the standard deviation. The less the standard deviation the smaller the part distortion. It is clear from Figure 10 that at the quench severity of $3.5in^{-1}$ the standard deviation of the above parameters is insignificant. Note that this severity of quench is comparable with the cooling rate of the IQ process. Thus, the value of distortion before heat treatment and after quenching is almost the same when rapid cooling is applied. This makes possible the reduction of the part distortion by adjusting the part green sizes during the machining operation. In addition, when rapid cooling is applied, the required grinding time can be shortened compared to that of conventional quench methods.

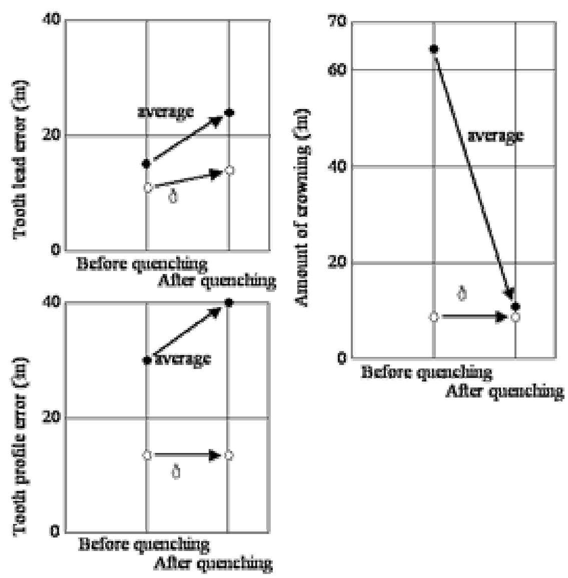


Figure 10 Effect of rapid cooling on heat treat distortion (each piece is individually hardened from 850°C)

7. Conclusions

A discussion regarding the differences between conventional oil quenching method and intensive water quenching method was conducted. The advantages of the IQ process are as follows:

1) Rapid cooling provided by the IQ process produces residual surface compressive stresses that protect the work from quench cracking.
2) The IQ technology allows replacing alloy steels with carbon steels, because IQ method provides a deeper hardened layer compared to conventional oil quenching.
3) The IQ process allows shortening of the carburization cycle.
4) The use of the IQ technology improves the service life of tool steels.
5) The IQ process reduces the deviation of distortion.
6) IQ makes it possible to tighten the machining dimensions by minimizing deviation of distortion after quenching and post-heat treat finishing.
7) Since the IQ technology uses water as the quenchant, it is an environmentally friendly process and there is no need for post-cleaning of the parts.

The IQ technology has been applied to a variety of steel parts: shafts, pinions, hubs, coil springs and tools. As of March 2008, the IQ method has been successfully applied to 23 types of steel products. It is expected that the IQ technology will contribute significant benefits to the heat-treating industry.

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