Practical Applications of Intensive Quenching Methods

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Abstract: - In the paper new methods of quenching, named IQ-2 and IQ -3 processes, are discussed. These new methods are based on regularities of nucleate boiling (self – regulated thermal process) and optimal duration of intensive cooling which provides optimal quenched layer in quenched steel parts. Several examples of using IQ processes in the practice are presented. The proposed technologies are environmentally friendly since they, instead of oils, are using plain water or water solutions. The cost of products manufacturing decreases and service life of intensively quenched steel parts significantly increases.

Key- Words:- New methods, Intensive quenching, Service life increase, Environmentally friendly technologies.

1 Introduction

In this paper, we discuss different applications of intensive quenching (IQ) techniques on actual steel products as well as on steel samples from the part manufacturers. We applied two intensive quenching methods: the IQ-3 technique or "direct convection cooling," and the IQ-2 technique, a two step quenching that uses a water nucleate boiling heat transfer mode for cooling steel parts. We conducted experiments for a variety of steel products including automotive parts (coil springs, kingpins, torsion bars, bearing products, ball studs, etc.), fasteners of different types, tool products (punches, dies, die components, etc.). We utilized the computer software package to determine optimal intensive quenching conditions for the subject parts. For intensive quenching steel parts, we used our two experimental IQ systems and 6000-gallon, full-scale IQ system installed at Akron Steel Treating Co. of Cleveland, Ohio. Sections below summarize the test data obtained during the last several years. Let us review the relationship of the quench cooling rate and hardened part mechanical properties and quenching equipment used for the IQ demonstration studies.

2 Optimal concentrations of water salts solutions

Optimal concentrations of water solutions of salts have the direct relation to their direct use in industrial conditions as quenchants. Such quenchants, on the one hand, are used for the intensification of heat transfer, and on the other hand, for the prevention of corrosion of a hardened surface. These quenchants based on water solutions of salts must meet the above- mentioned requirements [1].

As it is known, optimal concentrations of water solutions of salts are connected with the existence of a double electric layer at the interface of quenchant and metal surface. For the first time this phenomenon was described by Y.I. Frenkel [2]. All the matter is that hot metal at high temperatures loses free electrons and a surface of metal becomes positively charged. Upon immersing positively charged metal in electrolyte, to which aqueous salt solutions belong, negative ions attract to a metal surface, and in some sense, a condenser is formed, one side of which is positively charged, and the other, negatively. Between the sides of the condenser there is a boundary liquid boiling layer in which the electric field acts. The theory of surface tension and contact potential jump at the metal-electrolyte interface was developed by Y. I. Frenkel [2]. He showed that the electric double layer was like a condenser, which one side was metal, and the other was solution layer with a large ion concentration. The capacity of such a condenser depends on the dielectric penetrability of liquid and radius of ion atmosphere of the electric charge, that is, equal to $\varepsilon_0 D \aleph$, where ε_0 is the dielectric vacuum constant.

Carriers of charges in liquid are attracted by forces of electric interaction to the metal - liquid interface. Because the range of the action of these forces is significant, the layer of liquid molecules adjacent to the metal surface is under the pushing action of the second layer of molecules, so the surface tension decreases by the value:

$$\Delta\sigma = \frac{1}{2}\varepsilon_0 D \chi \varphi_0^2, \quad (1)$$

where:

σ is the surface tension;
φ_0 is the difference of potentials between metal and electrolyte;
ε_0 is the dielectric vacuum constant;
D is the dielectric penetrability;
χ is the inverse of the ionic atmosphere.

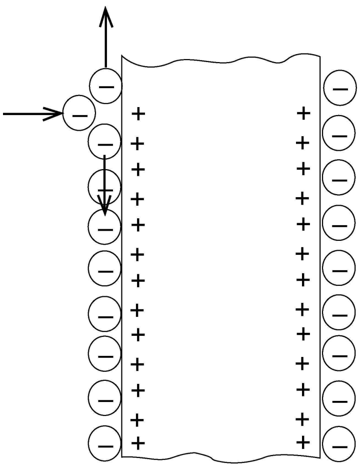

Fig.1. Schematics of the effect of electric forces upon the surface layer of a solution

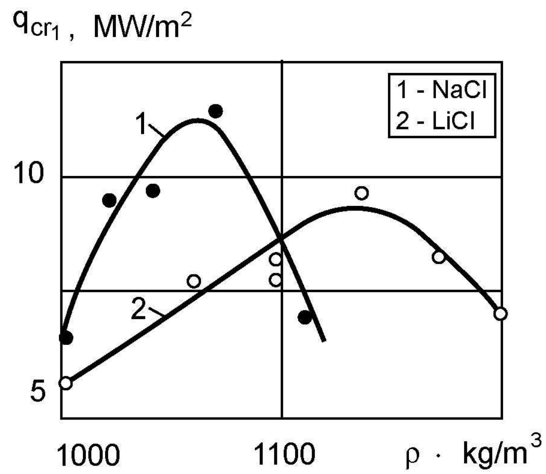

Fig. 2 First critical heat flux density q_{cr1} versus the concentration of NaCl and LiCl in water [1]

3 Main equations for designing IQ-2 and IQ-3 processes

The duration of the self-regulated thermal process is determined by equation (2) and optimal cooling time is evaluated by equations (5), (6) [1]:

$$\tau = \left[\Omega + b\ln\frac{\vartheta_I}{\vartheta_{II}}\right]\frac{K}{a}, \qquad (2)$$

where b=3.21;

$$\vartheta_I = \frac{1}{\beta}\left[\frac{2\lambda(\vartheta_0 - \vartheta_I)}{R}\right]^{0.3}; \qquad (3)$$

$$\vartheta_{II} = \frac{1}{\beta}[\alpha_{conv}(\vartheta_{II} + \vartheta_{uh})]^{0.3} \qquad (4)$$

It is used at development of IQ-2 process. In this case the film boiling is absent and main process is non- stationary nucleate boiling.

The self – regulated thermal process allows implementing isothermal holding in intensively cooling quenchants and optimizing the new technology.

$$Fo_v\ Kn = \left[\frac{k\,Bi_v}{2.095 + 3.867\,Bi_v} + \ln\theta\right] \qquad (5)$$

$$t = \left[\frac{kBi_v}{2.095 + 3.867Bi_v} + \ln\frac{T_0 - T_C}{T - T_C}\right]\frac{K}{aKn} .. \qquad (6)$$

Here t and τ are time of heating and cooling of the steel parts;Bi_v is generalized Biot number; K is Kondratjev form factor; Kn is Kondratjev number; T_o is initial temperature before cooling; T_c is quenchant temperature. K depends on form and size of steel part. Kn depends on cooling capacity of quenchant.

4 Intensive Quenching Equipment Used for IQ Demonstration Studies

For IQ trials, we used our two experimental IQ systems as well as the full-scale production IQ system that are described below. The first fully-automated batch intensive quench system includes a 1,900 – gallon quench tank and a "U" tube placed inside the tank with a ∅61cm x 58 cm electric, atmosphere furnace, a transfer mechanism, loading table and chiller. The propeller moves the water from the tank through the "U" tube back into the tank with the velocity of up to 2.0 m/sec. This unit is capable of quenching batch loads up to 1,000 lb.

We use a low concentration sodium nitrite solution in water as a quenchant in this system and implemented both the IQ-2 quenching process and IQ-3 quenching method. For heating steel parts, we use also a neutral salt bath furnace of ∅51 cm in diameter and 61 cm in depth capable of heating parts up to 927°C (1700°F).

Fig. 3 Fully-automated IQ system

The second experimental IQ system was specifically designed for the implementation of the IQ-3 quenching process (see Fig. 3). It differs from the above 1,900-gallon IQ system by the ability to provide very high water flow velocity along the part being quenched (up to 20 m/sec). The system is able to provide optimum IQ-3 quenching conditions to a variety of steel products. The system is capable to quench steel parts up to 15 cm in diameter and up to 40 cm in length.

Fig. 4 Single-part quenching IQ system

There is also the full-scale production IQ system. The system includes a Surface Combustion atmosphere furnace having a work-zone of 91cm×91cm×122cm (36"×36"×48") and the IQ quench tank of 22.7 m^3 (6,000 gallons). To ensure that quenchant vapor does not contaminate furnace atmosphere, a 2.5 m (98") aisle separates the furnace and the quench tank. A cart is used to move the load from the furnace to the quench tank. A fast rear handler mechanism transfers the load from the furnace to the IQ tank in about 10-15 seconds minimizing the heat losses by the load during transferring. The mild steel IQ tank is equipped with four 46 cm (18") propellers that are rotated by four motors. The tank uses a water/ sodium nitrite solution of low concentration (8-10%) as the quenchant. The quenchant flow velocity in the tank is about 1.5 m/sec (5 ft/sec) as it passes over the parts. An air-cooling system maintains the quenchant temperature within the required limit. The production IQ system is designed for quenching loads of up to 1,135 kg (2,500 lb).

5 Intensive Quenching Demonstration Studies

5.1 Automotive Parts

Bellow, we present the results of IQ trials obtained for steel samples and actual parts and summarized by the following applications: automotive parts, forgings, tool products, and fasteners [3-10].

Table 1 Part property improvements

Steel Part	Property/ Performance Characteristic	Improvement
Springs, shafts, bearing rollers, bearing rings, fasteners, sprockets	Surface hardness	5-10%
	Core hardness	20-50%
	Hardened depth	50-600%
Forklift forks, fasteners, springs	Strength	20-30%
Punches, dies, fasteners	Toughness	30-300%
Punches, coil springs, leaf springs, forklift forks	Service life/fatigue resistance	50-200%

5.2 Torsion Bar Samples

Meritor Automotive, Inc. provided six torsion bar samples for IQ trials. The samples were made of AISI 5160 steel and had the following size: diameter-36 mm, length-180 mm. Six identical samples were made from the same steel heat and were quenched in oil. We quenched intensively torsion bar samples in our IQ experimental system using the IQ-3 method.

Table 2 Torsion bar samples metallurgical analysis results

Parameter		Oil Quench	Intensive Quench
% of Bainite	Surface	5	0
	½ radius	12	2
	Core	29	2.5
Microstructure		Tempered martensite and bainite	Tempered martensite with traces of bainite in the core
Grain size		ASTM 8	ASTM 9

Table 3 Hardness distribution for torsion bar samples

Parameter	As-quenched Hardness, HRC	
Quench Type	Oil	IQ
Near surface	60.0	62.5
½ Radius	59.4	62.1
Core	61.9	63.0

Table 2 presents data on the part structure, while Table 3 presents the part hardness values on the sample surface, at the mid radius and in the core. As seen from Table 2, the IQ samples had fully martensitic structure near the part surface, only 2% of bainite at the ½ radius and 2.5% of bainite in the core. While the oil-quenched samples had 3% of bainite in the surface layers, 12% of bainite in he ½ radius and 29% of bainite in the part core.

The residual surface stresses in the torsion bar samples were compressive after intensive quenching and were tensile after quenching in oil. For the IQ samples, residual surface stresses were still compressive after tempering. Note, that if we could provide higher cooling rates (the fully developed IQ-3 process) the residual surface compressive stresses would be at much greater level. Compressive stresses on the part surface during quenching prevent part cracking and minimize distortion. We intensively quenched several torsion bar samples that had small seams on their surface. In the field conditions, such seams always develop into cracks during quenching in oil due to tensile stresses on the part surface.

5.3 Shock Resisting Punches

The main material properties that determine the performance of the punch are toughness, strength and wear resistance. The strength and toughness are critical in preventing cracking and chipping of the punch under the severe impact of this fabrication process. The wear resistance is required to preserve the cutting edges of the punch, thereby maintaining constant processing parameters and ensuring the dimensional accuracy of the holes. All of these critical properties are affected by the cooling rate during quenching. A faster cooling rate should permit higher hardness levels without compromising the toughness of the punch.

Presently, tool steel punches are oil quenched and tempered. While the performance of the punches is satisfactory, the manufacturer is interested in further improving the useful life of the punches by utilizing a faster cooling rate during the quenching process. The objective of this study was to demonstrate the superior performance of punches quenched by the IntensiQuench® process. During processing the parts are submersed in fast flowing water quenchant, yielding very fast cooling rates, and then the intensive quench is "interrupted" when the compressive surface stresses are at their maximum value. In addition to the microstructural benefits to the punch from the fast cooling rate, the IntensiQuench® process also generates high compressive stresses at the surface that minimize the risk of quench cracking and extend the useful life of the punch.

An experimental program was initiated to evaluate the effect of IntensiQuench® process on the properties and performance of S5 steel for punches. Two commercial heat treaters, a punch manufacturer and Case Western Reserve University of Cleveland, Ohio (CWRU) joined the program. Cylinders of 38 mm (1.5") diameter and 56 mm (2.2") long and punches machined from the same steel batch were quenched in oil and by the IntensiQuench® process. The oil quenching was conducted on batches of punches heated in a vacuum furnace with a rapid transfer mechanism to an integral oil quench tank. The IntensiQuench® process was performed in water on individual cylinders and punches in our IQ system using the IQ-3 quenching method. In this process, the part is submersed in a flow of water, yielding very fast cooling rates of about 90^{o}C/sec at the surface of the cylinder. Quenching was interrupted when surface compresses stresses reached their maximum value. Charpy V-notch samples were cut from the as-quenched and tempered cylinders and evaluated. Hardness measurements were taken from Charpy V-notch samples cut from the cylinders. The distortion of the cylinders was mapped with a Coordinate Measuring Machine. The depth profile of the residual stresses in the surface region of the cylinders was measured by X-Ray diffraction methods. The X-ray diffraction residual stress measurements were made from the surface to a nominal depth of 0.5mm in approximate increments of 50 x 10^{-3} mm. The hardness of cylinders quenched in oil from 900^{o}C (1650^{o}F) was 62-63 HRC while the hardness of intensively quenched cylinders from the same temperature was 63-64 HRC. After three hours tempering at 300^{o}F the hardness of all the cylinders was 60-61 HRC. Hardness measurements were also taken from fourteen Charpy-V-notch samples cut longitudinally from the cylinders. While the as-tempered average hardness of all the cylinders was practically identical, the oil-quenched specimens were more uniform in hardness with a standard deviation of 0.3 HRC versus a standard deviation of 0.6 in the hardness of the intensively quenched samples. This difference is attributed to the faster heat removal in IntensiQuench® process, which generates a faster cooling rate at the surface relative to the center of the cylinders. The hardness at the surface (with the compressive stresses) therefore tends to be slightly higher than in the center.

The toughness levels measured up to 100^{o}C for the cylinders quenched by the IntensiQuench® process were higher than the toughness of the oil quenched cylinders for similar hardness values although both were relatively low because of the high carbon and hardness values of both sets of punches. The average energy absorbed by the oil quenched Charpy V-notch samples at room temperature was 1.36 N·m (1 ft·lb) versus 4.08 N·m (3 ft·lb) for the intensively quenched sample. At 100^{o}C the average energy absorbed by the oil quenched Charpy V-notch was 3.4 N·m (2.5 ft·lb) versus 6.12 N·m (4.5 ft·lb) for the intensively quenched sample. The higher toughness at similar hardness levels is an indication of superior performance. It means the intensively quenched punch should have more resistance to chipping. Alternatively, intensively quenched punches should be tempered to higher hardness, while still maintaining acceptable toughness levels. This in turn should improve the wear resistance of the punch relative to an oil-quenched punch. Some results of experiments are presented in Table 4.

Table 4 Improvement of S5 steel punch sample properties *

Property		Oil Quench	Intensive Quench
Hardness, HRC	As quenched	62-63	63-64
	After temper	60-61	60-61
Impact strength, N·m	@72^{o}F	1.36	4.08
	@100^{o}C	3.4	6.12
Residual stresses, MPa		200	-900

*As measured by CWRU.

The difference in quenching rates between the oil and the IntensiQuench® process also affects the distortion patterns of the cylinders. The distortion map of an oil-quenched cylinder shows that the cylinder is bulged around the center perimeter, with the center diameter about 0.081 mm (0.0032”) *larger* than the top and bottom diameters. The distortion map of an intensively quenched cylinder shows that the cylinder has an “hourglass” shape, with the center diameter being about 0.081 mm (0.0032”) *smaller* than the sides. These differences can be explained by considering the dimensional changes during the phase transformation. The rapid cooling rate during IntensiQuench® process quickly forms a hard and stiff “shell” of martensite over the entire surface of the cylinder. The expansion associated with the martensitic transformation causes high compressive stresses at the surface, which are partially accommodated by this change in shape. The top and bottom of the cylinder expand pushing the adjacent shell outward. At the same time, the longitudinal expansion at the surface is pushing the top and bottom shell perimeters outward.

In the oil-quenched cylinder, the strong martensitic layer does not form as quickly. When the core transforms and expands, it can still push the surface layer of the cylinder out, causing it to bulge. These differences are significant in two aspects. The first aspect concerns the dimensional control of the punches, which has to be kept within tolerance. The second aspect relates to the residual stresses. It was anticipated that the IntensiQuench® process would generate higher compressive stresses in the surface thus minimizing the risk of cracking during the quench and enhance the performance of the punch in use. The distortion pattern (mapped at CWRU) indicates that this is indeed the case.

In the field-testing, the punches punched 17.5 mm (11/16") holes through 15.9 mm (5/8") and 19.1 mm (¾") thick 1085 steel material using a 19.1 mm (¾") square female die in a single station 250-ton mechanical press. "Service life" (as defined by the punch user) is when chipping or wear is "excessive" and the punched holes are no longer acceptable. The press cycled every 15 seconds. Oil quenched punches lasted approximately 1 hour and made on the average approximately 450 holes in the 1085 material. While intensively quenched punches lasted approximately 2 hours and made on average approximately 900 holes. Thus, the IntensiQuench® process improved the service life of the S-5 punches by about two hundred percent or two times.

5. 4 Case Study for H-13 Steel Aluminum Die Casting Dies

Heat treaters know that the higher the cooling rate during quenching the "hot-work" die steels the greater the part thermal fatigues resistance when in service [5-8]. To prove that the intensive quenching technique provides better thermal fatigue resistance and toughness in die casting dies, CWRU and IQ Technologies intensively quenched standardized 50mm×50mm×178mm test blocks made of H-13 hot-work die steel. H-13 steel is widely used for aluminum die casting tools in the U.S. In die casting of aluminum parts, the dies (and gating for channeling the molten aluminum into the die cavity) must repeatedly withstand temperatures of over 1,000°F. After taking a shot of molten aluminum the H-13 tooling undergoes a rapid cooling cycle from the internal water-cooling passages. The water-cooled dies help the aluminum cast part to solidify and become dimensionally stable so the whole process can be repeated. Since molten aluminum has the viscosity of water, the die casting dies must also contain high pressures without distortion.) A duplicate set of test blocks were also made from the same lot of H-13 steel, but quenched in oil. (The usual hardening practice for H-13 steel is to air quench or to gas pressure quench the die in a vacuum furnace.)

The thermal fatigue properties for both the intensively water quenched and the oil quenched H-13 steel test blocks were evaluated by means of a thermal fatigue test methodology developed by CWRU. This test determines the average maximum crack length and total crack area on the four corners after a certain number of cycles of "in process" heating (by immersion into a bath of molten aluminum at 732°C) and cooling (by coolant flow within the test block's internal water passage). Therefore, just as H-13 aluminum die casting dies in production situations, the test blocks have a high thermal gradient throughout the test block cross-section, especially severe at the test blocks' corners. This test simulates the cyclic heating and cooling found in aluminum die casting dies made of H-13 material. (It should be noted there were no cracks present in any of the intensively or oil hardened H-13 test blocks at the inception of the cyclic testing.). The average maximum crack length for the intensively quenched test block is about 27% less than for the oiled quenched test block. The total crack area for the intensively quenched test block is about 42% less than for the oiled quenched test block. Since this test correlates with the actual service life of H-13 dies (albeit conventionally air hardened), the test indicates even greater service life for intensively quenched dies made of H-13 steel. Several of intensively quenched H-13 dies and die components are currently undergoing in service field-testing and evaluation. For some dies service life increased two times and more.

5. 5 Fasteners

We conducted statistical IQ study with two fasteners manufacturers on four types of fasteners [9, 10]. The first three types of these fasteners were truck wheel bolts made of 4140 and 1340 steels. The fasteners of the fourth group were made of 4037 steel and were used in a heavy machinery assembly. The goal of this statistical evaluation was to show that the bolts would not have any cracks after intensive quenching in water and the part mechanical properties would be the same or better compared to the same bolts that were quenched in oil in accordance with the current practice.

We intensively quenched 20 bolts of each of the above groups. The same number and type of bolts were quenched in oil in production conditions. Fifteen bolts from each of the sample were subjected to the tensile strength test conducted at the customer's laboratory facilities. Two bolts from each group were cut to measure the core hardness, and three bolts from the fourth group were subjected to the impact strength test.

In our experiments, we used the same thermal cycles that were used in real production conditions. We heated the parts to austenitizing temperature in a box type atmosphere furnace in batches of 10 bolts per batch. Then we intensively water quenched the bolts one by one in our 500-gallon experimental IQ system using IQ-3 method. Note, that the water flow velocity was not optimum. Therefore, we realized a not-fully developed IQ-3 process. No cracks were observed in the intensively quenched bolts.

Table 5 shows the final results for bolts intensively water quenched and for those that were quenched in oil. As seen from the table, the tensile strength for the bolts made of alloy 4140 and 4037 steels did not practically changed. However, there was an improvement of the tensile strength by about 8% for the bolts made of less alloy 1340 steel. However, there was a significant improvement in impact strength (toughness) for the alloy 4047 steel bolts (see table 5). The impact strength measurements were taken in the temperature range from –100^{o}C to 38^{o}C. As seen, the impact strength of the bolts improved by about 9% - 37% depending on the temperature range.

Table 5 Mechanical properties of tested fasteners

Fastener	Tensile Strength, MPa/m^2		Impact Strength at 20^{o}C, N·m	
	Oil Quenched	IQ	Oil	IQ
4140 steel DBL end stud	465.8	474.9	-	-
4140 steel WHL end stud	1,012.9	977.0	-	-
1340 steel M22 bolt	582.3	627.2	-	-
4037 steel bolt	1,202.2	1,187.5	38.7	48.0

6 Conclusions

The results of more than two hundred different demonstrations on actual production parts and parts samples clearly showed the following benefits of the intensive water quenching techniques [11]:

- ⇒ Increased surface and core hardness;
- ⇒ Increased hardened layer;
- ⇒ Increased depth of hardness with a reduction of the carburization cycle;
- ⇒ Improved part microstructure (finer grain and "super-strengthened" martensite);
- ⇒ Improved fatigue strength properties of the steel parts; and
- ⇒ Less part distortion and no part cracking;
- ⇒ Increase service life of steel parts more than two times.

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