INTENSIVE QUENCHING TECHNOLOGY

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I. INTRODUCTION

History of Intensive Quenching

- The first investigation of cooling rate effect on probability of crack formation was published 1964 by N.I. Kobasko in the former Soviet Union. Contrary to generally accepted belief that high cooling rates within the martensite formation range would cause cracking, he found that the probability of crack formation is low for low cooling rates, increasing with higher cooling rates reaching a maximum, but then decreases at very high cooling rates, as shown in Fig.1.

- In other words, a very high cooling rate within the martensite range will actually prevent quench cracking.

Fig.1 Effect of cooling rate within the martensite formation range on crack formation in cylindrical specimens 6 mm in diameter made of steel 41Cr4 (DIN)
In USA Roy Kern has published (1986) an article about intense quenching, and a Japanise researcher Ovaku Sigeo has published (1987) a paper on intensive cooling.

Since 1967 the focus of investigations has been on using intensive quenching to enable the substitution of high-alloy steels for lower alloy-steels, and to use water as quenchant, instead of oil.

Kobasko and his coworkers have later performed a numerical study of phase changes, current and residual stresses when intensive quenching workpieces of complex configuration (1985), and have published several papers about the possibility of increasing the service life of machine parts and tools, by means of cooling intensification at quenching (1986).

The first industrial application of intensive quenching was realized in 1965 at the Likhachov automotive plant in Moscow.

Until now the Intensive Quenching (IQ) technology has found some industrial applications in USA, Russia and Ukraine. Europe is lagging behind, but the method has been intensively investigated at the IWT Institute, the University of Bremen, Germany.
**Principle of Intensive Quenching**

- Intensive Quenching is a very rapid and uniform cooling of steel parts. The cooling rate is several times greater than that of agitating oil or even water (it goes up to 10 m/s) and in contrast to the conventional quenching technique, fast cooling continues through the martensite range.

- The residual stresses developed at cooling can be represented as a function of a generalized Biot number $Bi_v$. The BIOT number is a dimensionless common used characteristic value in the heat transfer:

  $\frac{\alpha}{\lambda} \times \frac{R}{\sqrt{V}}$

  and the generalized Biot number, valid for different workpiece shapes is

  $Bi_v = \frac{\alpha}{\lambda} \cdot \frac{S}{V} \cdot K$,

  where:

  $\alpha = \text{heat transfer coefficient} \ (W/m^2K)$
  $\lambda = \text{thermal conductivity of the body} \ (W/mK)$
  $S = \text{surface area of the workpiece} \ (m^2)$
  $V = \text{volume of the workpiece} \ (m^3)$
  $K = \text{Kondratjev form factor of the workpiece} \ (m^2)$.

  (Kondratjev form factor for cylinder: $K = \frac{R^2}{5.783}$ where $R$ is the radius)
Fig. 2 shows residual circumferential stresses at the surface of a cylindrical specimen vs. the generalized Biot number \( (Bi_v) \), which is directly related to the heat transfer coefficient \( (\alpha) \) i.e. to the cooling rate. At higher values of \( Bi_v \) (in this case \( > 4.3 \)) compressive residual stresses develop. The absence of quench cracking under intensive cooling (see Fig. 1) conditions is due to high compressive stresses that form at the surface of the workpiece.

The degree of intensive cooling can be characterized by the \( Bi_v \) number, or by the Kondratjev number \( Kn \). There is a universal interconnection between these two numbers:

\[
Kn = \psi \cdot Bi_v = \frac{Bi_v}{\sqrt{Bi_v^2 + 1.437 \cdot Bi_v + 1}}
\]

that is valid for bodies of various configurations.

\[
\psi = \frac{1}{\sqrt{Bi_v^2 + 1.437 \cdot Bi_v + 1}}
\]

is the parameter criterion characterizing the temperature field non-uniformity. If the temperature distribution across the body is uniform \( (Bi_v \to 0) \) than \( \psi = 1 \). The higher is the temperature non-uniformity, the less is \( \psi \). At \( \psi = 0 \), the temperature distribution non-uniformity is the highest \( (Bi_v \to \infty) \).
Thus Kondratjev number characterizes not only the temperature field non-uniformity but also the intensity of interaction between the body surface and the environment.

Kondratjev number is the most generalizing and the most universal value which may serve to describe the cooling conditions under which compressive stresses occur at the surface of various bodies. For rather high compression stresses to occur at the surface of the workpiece being quenched, it is sufficient to meet the following condition:

\[ 0.8 \leq Kn \leq 1 \]

The main feature of Intensive Quenching technology is to cool workpieces under the condition of high intensive heat transfer \((Kn \geq 0.8)\), and to interrupt rapid cooling when compressive stresses on the surface are at their maximum.

If the process of intensive cooling is stopped at the moment of achieving the maximum compression stresses, and isothermal holding is realized at the temperature of the onset of martensite transformation \((M_s)\), than the martensite phase advance would cease and sufficiently high compression stresses can be fixed. An optimal depth of the quenched layer that depends on part dimensions corresponds to maximum compression stresses.

Computer aided model has been developed to calculate the time of achieving maximum compression stresses for bodies of arbitrary axisymmetric form being quenched under various heat transfer conditions.
Intensive Quenching produces a firm martensite shell that forms simultaneously over the whole surface area of the workpiece with compressive stresses developed in it. This strong martensite case and high compressive stresses prevent the workpiece from cracking and distortion.

Fig. 3 illustrates the martensite formation through the workpiece with different cross-sectional thickness during quenching.

During conventional quenching the martensite forms first in the thinner section of the workpiece, since this area cools faster and reaches the $M_s$ point earlier than the thicker section (Fig. 3a).

The martensite specific volume is greater than the specific volume of the remaining austenite. Therefore the thin section expands in volume, while the thick section continues contracting due to cooling. At the interface between the martensite and the austenite phases there are stresses resulting in distortion and possible workpiece cracking.

In the case of Intensive Quenching, when the workpiece is cooled very rapidly and uniformly the martensite forms simultaneously over the entire surface of the workpiece creating a strong hardened "shell" (Fig. 3b) containing high compressive stresses, resulting in lower distortion and lower probability of workpiece cracking.
The Computer Model for Intensive Quenching Process

- N.I. Kobasko who has many patents on Intensive Quenching (among others the U.S. Patent No: 6,364,974 B1 from Apr. 2, 2002) has developed a computer model to adapt Intensive Quenching process to almost any steel part. The process begins by analyzing the thermal and stress profiles within the workpiece during quenching, using a finite element approach. The model includes a non-linear transient heat conduction equation and a set of equations for the theory of thermoplastic flow with kinematics strengthening under the appropriate boundary conditions of the workpiece's surface.

- An interactive technique is used to solve the above system of equations. At each time and cooling step, the calculated results are compared with the thermokinetic (CCT) diagram of the supercooled austenite transformation, and new thermophysical and mechanical characteristics for the next step are chosen depending on the structural components. This analysis seeks the point along the cooling curve where surface compressive stresses are maximized.

- The calculation results are the following:
  - Temperature field
  - Material phase composition
  - Stress distribution
  - Distortion distribution

- The results have been validated by numerous laboratory and field experiments.
II. DEVELOPMENT OF COMPRESSIVE RESIDUAL STRESSES ON THE SURFACE

- The reason why Intensive Quenching results in high compressive stresses can be explained using a simple mechanical model (Fig.4).

- Imagine a cylindrical steel part. Assume that the part's surface layer consist of a set of "segments" joined together by "springs" to form an elastic ring.

- When the whole steel part is heated above $A_C_3$ temperature before quenching, there is no tension in the springs and there are no stresses between the segments ($\sigma = 0$), see Fig.4a. During quenching the surface layer cools rapidly resulting in the contraction of segments. To compensate for the contraction in cooling, the springs expand simulating the development of tensile thermal stresses (Fig.4b).

Fig.4
When the surface layer reaches the martensite formation temperature ($Ms$), the austenite in the segments transforms into martensite. The martensite's specific volume is greater than the austenite's. This results in the expansion (swelling) of the surface segments, causing the springs to contract. The contraction of the springs illustrates the development of surface compressive stresses (Fig. 4c).

Within a short time (a matter of seconds) the martensite starts forming in the part core, resulting in core swelling (Fig. 4d). Due to the core expansion, the distance between the surface segments increases resulting in the expansion of the springs.

The spring expansion reflects the reduction (but not elimination) of compressive stresses on the part surface. Fig. 5 illustrates phases of stress development and the final residual stress in the surface layer, achieved by Intensive Quenching.

\[ A = \text{Austenite} \]
\[ M = \text{Martensite} \]
III. THREE TYPES OF INTENSIVE QUENCHING PROCESSES

- Three types of Intensive Quenching: IQ-1, IQ-2 and IQ-3 are distinguished by three different heat transfer modes on the surface of the workpiece during quenching.
  - At IQ-1 process, film boiling and nucleate boiling are both present on the part surface.
  - At IQ-2 process, the film boiling is absent and the main mode of heat transfer on the part surface is the nucleate boiling, followed by convection cooling.
  - At IQ-3 process, the intensity of cooling is so great that the film boiling and nucleate boiling are completely avoided, and the sole heat transfer mode is convection (direct convection cooling).

- The IQ-2 process is used mainly for batch quenching, and IQ-3 process for single part quenching.

- Before analysing particular types of intensive quenching one should bear in mind the following: Film boiling is the least uniform phase (and the cause of the most distortion), since the "film" or steam pocket is not stable or uniform at the part/quenchant boundary. Film boiling does not provide fast heat removal. It is also difficult to maintain it uniformly over the entire part surface.
First Type of Intensive Quenching (IQ-1)

The IQ-1 method is a two step cooling process. It is used for medium-alloy and high-alloy steel parts. At the first step of quenching, the parts are cooled relatively slowly from the austenitizing temperature down to the martensite start temperature ($M_s$), e.g. in hot oil or in high-concentration water/polymer solution. There is an insignificant temperature gradient throughout the part cross-section within this slow cooling step. Therefore the initial temperature throughout the entire part can be assumed equal to the temperature $M_s$, at the beginning of the second step of cooling. The second step is very intensive and it takes place within the temperature range of martensite formation. Water jets or directed streams of quenchant around the steel part provide high cooling rates, which result in the formation of compressive stresses on the part surface and in the reduction of its distortion.

However a shortcoming of the IQ-1 process is that the second step of cooling has to be performed in a separate chamber which complicates the hardening process and makes it difficult to realize in practice.
Second Type of Intensive Quenching (IQ-2)

- The second type of intensive quenching is a three step cooling process. In contrast to the IQ-1 process, the first step of the IQ-2 technique is very intensive. Film boiling is fully eliminated by using a proper quenchant (e.g. salts in water), and nucleate boiling starts immediately on the part surface, after the part is put into the quench media. Nucleate boiling results in very high heat transfer coefficient on the part surface, and high surface compressive stresses develop by the end of nucleate boiling.

- After the nucleate boiling step is completed, the parts are taken from the quench bath to continue cooling in the air. In this second step, the residual heat transferred from the hot part core tempers the martensite that was formed in the part surface layer (self tempering). In this second step compressive surface stresses developed in the first step of cooling, are fixed.

- Than in the third step parts are again cooled intensively (e.g. by water jets) to complete the phase transformation in the part core. In this third step of the IQ-2 process, convection cooling cooling takes place.

- A key element of the IQ-2 process is to determine the duration of the first step of cooling i.e. nucleate boiling. The heat transfer in this case is based on regularities of a self-regulated thermal process, determined by the characteristic boiling point ($T_s$) of the quenchant.
The essence of the self-regulated thermal process during nucleate boiling is as follows: The part surface temperature changes very little during this stage of cooling, since the part surface temperature is very close to the quenchant boiling temperature – see Fig.6. Only when the temperature of the part core drops considerably, does the convection start on the part surface the temperature of which comes down to the quenchant temperature.

The quenchant boiling point can be regulated either by the change in pressure above the bath surface, or by use of various substances that are soluble in water. Thus the part surface temperature \( (T_s) \) for nucleate boiling can be shifted upward or downward. The duration of non-stationary nucleate boiling (self-regulated thermal process) \( t_{NB} \) is determined by relevant formula.

**Fig.6** Temperature on the surface and in the core of a part being quenched versus time during the self-regulated thermal process: 1 – Surface, 2 – Core
If the boiling point of the quenchant corresponds on the CCT diagram to 50 % martensite, then no more than 50 % of martensite can be formed on the surface during nucleate boiling. The rest of martensite transformation resumes in the convection cooling stage.

With about 50 % martensite formed within the part surface layer and high compressive stresses, by the end of nucleate boiling, the residual austenite in the part surface layer plastically distorts being under high compressive stresses. This results in forming an extremely high density of dislocations and a so-called "packet martensite", which has improved mechanical properties resulting in additional strengthening ("super strengthening") of the part material – see Fig.7.

![Fig.7 Scheme for explanation of mechanism of additional material strengthening ("super strengthening")](image-url)
Third Type of Intensive Quenching (IQ-3)

- In contrast to the multi-step cooling rates of the IQ-1 and IQ-2 processes, IQ-3 is a one-step method. The part is cooled so fast that both the film boiling and the nucleate boiling are completely avoided and the basic heat transfer mode on the part surface is convection (direct convection cooling).

- This quenching process is the most intensive and efficient hardening method in terms of creating high compressive surface stresses to an optimum depth. Both the amount and depth of compressive surface stresses, and the commensurate super strengthening of the material appear to a greater extent, because the part surface temperature drops rapidly to the quenchant temperature, without the process of nucleate boiling, providing enough drastic cooling rate.

- In the IQ-3 process intensive cooling is continuous and uniform over the entire part surface, until compressive stresses on the part surface reach their maximum value and optimal depth, which depends on part geometry. These maximal compressive stresses would be diminished if the core of the part is cooled further down to the quenchant temperature. Therefore the cooling must be interrupted at the proper time.
There is a formula for calculation when the cooling should be interrupted ensuring maximal compressive stresses on the part surface (valid for steel parts of different configurations):

\[
\tau_{\text{sec}} = \left[ \frac{k \cdot Bi_v}{2.095 + 3.867 \cdot Bi_v} + \ln \frac{T_0 - T_C}{T_{\text{core}} - T_C} \right] \frac{K}{a \cdot Kn}
\]

where:

\( k = 1,2,3 \) – correspondingly for plate-shaped; cylinder-shaped and ball-shaped bodies

\( Bi_v = \) generalized BIOT-number

\( T_0 = \) initial austenitizing temperature (K)

\( T_C = \) quenchant temperature (K)

\( T_{\text{core}} = \) core temperature of the part (K)

\( K = \) Kondratjev form factor (m²)

\( a = \) thermal diffusivity of the body (m²/s)

\( Kn = \) Kondratjev number \( 0.6 \leq Kn \leq 1 \)
There is a proven database for determination of Kondratjev form factor $K$ and Kondratjev number $Kn$ for parts of different geometries. A database has been also developed to determine the core temperature $T_{\text{core}}$, which corresponds to the core temperature when the surface compressive stresses reach their maximum value.

The basic steps for implementing the IQ-3 process are the following:

- Quenching is performed in a liquid media (usually water) with very rapid and uniform flow to insure that both the film boiling and the nucleate boiling do not occur.
- The surface temperature drops almost instantly to the quenchant temperature and maintains on this level during the whole quenching process.
- When compressive surface stresses reach their maximum value and optimal depth (as determined by the above formula) the parts are removed from the quench bath and can be placed in the furnace for tempering.

The IQ-3 process is used for single part quenching when it is easy to provide high quenchant flow rates uniformly around the steel part. It is the most thoroughly investigated and most applied method.
IV. PRACTICAL APPLICATION OF INTENSIVE QUENCHING

- Intensive quenching has been evaluated and compared with conventional oil-quenching for various types of parts and different steel alloys.

Example I: Comparison of surface residual stresses

- Automotive coil springs (coil O.D. 152 mm; length 547 mm; spring wire diameter 21 mm) Fig.8, made of AISI 9259 were intensively quenched. The results were compared with coil springs made from the same lot of this steel and quenched in a conventional oil. The as-quenched microstructure for the intensively quenched springs was superior to that of the oil quenched springs, as shown in Table 1.

Table 1: Metallurgical analysis results

<table>
<thead>
<tr>
<th>Test parameter</th>
<th>Oil quench</th>
<th>Intensive quench</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bainite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface</td>
<td>5-10 %</td>
<td>0 %</td>
</tr>
<tr>
<td>Core</td>
<td>15-20 %</td>
<td>2-5%</td>
</tr>
<tr>
<td>Microstructure</td>
<td>Tempered martensite and bainite</td>
<td>Tempered martensite with traces of bainite in the core</td>
</tr>
<tr>
<td>Grain size</td>
<td>ASTM 8</td>
<td>ASTM 9</td>
</tr>
</tbody>
</table>
Fig. 9a and b compare the surface residual stresses in the intensively quenched and oil quenched springs in both the as-quenched and as quenched-and-tempered conditions.

Fig. 9 Surface residual stress for AISI 9259 coil spring: (a) as quenched; (b) quenched and tempered at 204 °C for 2 hours.
Example II: Comparison of part distortion

- The effect of intensive quenching on hardness and distortion was studied using a set of 25.4 mm diameter × 254 mm long shafts made of AISI 1045 having a keyway (6.4 × 6.4 mm) milled along entire length, as shown in Fig. 10. As it is well known such shafts with keyway are particular susceptible to distortion.

- The shafts were ground and polished to ±0.025 mm. Some of the shafts were heated in a salt bath furnace and four were quenched under one of two conditions:
  1. Conventional cold oil quenching with normal agitation
  2. Intensive quenching in water

- Eight shafts were also quenched in a sealed-quench furnace in hot oil with moderately greater agitation.

Fig. 10 AISI 1045 steel shaft with keyway (a) and (b) measurement of its distortion
As quenched distortion was determined by placing the shafts on a block with certified flat granite surface. The amount (height) of bowing of the shaft was measured using feeler gauges, as shown in Fig.10. The accuracy of these measurements was ±0.025 mm. The resulting data summarised in Table 2 show that the intensively quenched shafts acquired the highest surface and core hardness, whilst also exhibiting substantially less distortion than after either method of oil quenching.

\[\text{Table 2: Measurement of shaft hardness and distortion (1045 steel, 25.4 mm diameter shaft with 6.4 \times 6.4 mm keyway)}\]

<table>
<thead>
<tr>
<th>Process route</th>
<th>Salt bath heated/cold oil quenched</th>
<th>Sealed-quench furnace heated/hot oil quenched</th>
<th>Sealed-quench furnace heated/intensively quenched</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRC, surface</td>
<td>43.2</td>
<td>51.4</td>
<td>57.4</td>
</tr>
<tr>
<td>HRC, core</td>
<td>32.1</td>
<td>31.0</td>
<td>50.0</td>
</tr>
<tr>
<td>Distortion, mm</td>
<td>0.20-0.36</td>
<td>0.25-0.51</td>
<td>0.08-0.12</td>
</tr>
</tbody>
</table>
Benefits of intensive quenching

- Both the improvements in mechanical properties and the presence of residual compressive stresses on the part surface result in significant increase of the product service life. Table 3 shows the improvement in service life for different still parts. Truck half-axles and shafts that were intensively water quenched were made of plain carbon steel AISI 1045, and compared to same parts made of alloy steel AISI 4340, quenched in oil.

- As seen from Table 3 the service life time of intensively quenched parts increased by 7 to 8 times.

\[ \text{Table 3:} \]

<table>
<thead>
<tr>
<th>Steel Part</th>
<th>Type of Steel</th>
<th>Life Time Improvement, Times</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck half-axles</td>
<td>AISI 1045</td>
<td>7.6</td>
</tr>
<tr>
<td>Shaft</td>
<td>AISI 1045</td>
<td>8.0</td>
</tr>
<tr>
<td>Punches</td>
<td>M2</td>
<td>1.5-2.0</td>
</tr>
<tr>
<td>Dies</td>
<td>AISI 52100</td>
<td>1.5-2.0</td>
</tr>
</tbody>
</table>
Generally there are following advantages of intensive quenching:

- elimination of cracking
- minimisation of distortion and associated cost
- high residual compressive stresses on the surface, for greater part durability
- reduction or elimination of carburising cycles
- improved mechanical properties (yield and ultimate strength, wear resistance, depth of hardness)
- reduction of part size/weight with comparable physical properties
- using lower-alloy steels while maintaining physical properties
- replacement of hazardous quench oil with environmentally-friendly water or salt/water solutions.