THE MAIN PRINCIPLES OF INTENSIVE QUenchING OF TOOLS AND DIES

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ABSTRACT

The paper discusses in details the main principles of intensive quenching process as applied to steel tools, dies and other steel parts. The paper considers one- and two-step intensive quenching process for tools and dies. When applying a one-step intensive quenching method, the cooling is interrupted at the moment of time when the part surface compressive stresses are at their maximum value and the core has not reached the martensite start temperature. When applying a two-step intensive quenching technique, the duration of the first step of cooling depends on the duration of the “self-regulated thermal process”. At the second step of steel parts within the martensite range are cooled very rapidly. The paper presents also a new method of calculation and optimisation of the process of quenching.

Key words: Intensive quenching, one-and two-step quenching, low hardenability steel, optimisation, service life, cheap materials

1. INTRODUCTION

At present time the three main principles are used when developing intensive quenching of steel parts. The first principle means that the reason of additional strengthening (superstrengthening) of a material is high cooling rate within the martensite range. Detailed information is published in [1] The second principle allows choosing conditions of cooling for creation of the maximal compressive stresses at the surface of the quenched steel parts. It means that very intensive cooling should be stopped at the moment of achievement of the maximum compressive stresses at the surface [2] The third principle means, that the chemical composition of steel should be such that after intensive cooling optimum depth of the quenched layer could be formed [3]. Below are three examples, which were realized in the practice.
2. DESIGN OF INDUSTRIAL QUENCH PROCESSES

It is required to determine the speed of movement of the conveyor, which would provide temperature 650 °F (343 °C) at the core of the part when it should be delivered from the quenchant. To make these calculations we are using equation presented in [4, 5], i.e.

\[
\frac{W}{T} = \frac{a L Kn}{(\Omega + b \ln \frac{T_0 - T_m}{T - T_m})K};
\]

where: \(a\) is average thermal diffusivity of the material for the range of temperatures \(T_0 - T_m\); \(Kn\) is Kondratjev number (dimensionless value), \(\Omega = 0.48\) for cylinder-shaped bodies, \(b = 1\) if the core’s temperature is determined, \(T_0\) is austenitizing temperature or temperature at the time of immersing the part into the quenchant, \(T_m\) is temperature of the medium, if convection prevails, or temperature of boiling if nucleate boiling prevails.

Table I Kondratjev number \(Kn\) for 10% aqueous solutions of UCON A and UCON E at temperature of 90 °F (~32 °C) and speed of the stream of 80 fpm (~0.4 m/s). Temperature of the core of probes is 1300 °F (704 °C) [5]

<table>
<thead>
<tr>
<th>Probe diameter in inches (mm)</th>
<th>UCON A</th>
<th>UCON E</th>
<th>(\overline{Kn})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 (12.7)</td>
<td>0.424</td>
<td>0.412</td>
<td>0.415</td>
</tr>
<tr>
<td>1 (25.4)</td>
<td>0.546</td>
<td>0.488</td>
<td>0.512</td>
</tr>
<tr>
<td>1.5 (38.1)</td>
<td>0.578</td>
<td>0.523</td>
<td>0.543</td>
</tr>
</tbody>
</table>

The average thermal diffusivity \(\overline{a}\) of the overcooled austenite within the temperature range of 1550 °F – 200 °F (840°C – 100 °C) is equal to 5.36·10^{-6} m²/s. Having all above-stated facts we calculate what speed of the conveyor should be to provide the core’s temperature 650 °F (343 °C) for a cylindrical part made of AISI 4140 steel and having diameter of 25 mm and height of 50 mm. At the time of immersion the part has the same temperature of 1550 °F through all cross-sections. To answer this question, it is necessary just to determine Kondratjev number \(Kn\). For the determination of \(Kn\) there must be available an experimental database.
3. CRITERION DETERMINING THE ABSENCE OF NON-STATIONARY NUCLEATE BOILING

We can draw the criterion determining the absence of nucleate boiling at the surface of a part to be quenched on the basis of the generalized dependence for the determination of the duration of non-stationary nucleate boiling, i.e., self-regulated thermal process. As is already known, the specified dependence has the following form:

\[
\tau = \left[ \Omega + b \ln \frac{\vartheta_j}{\vartheta_\mu} \right] \frac{K}{a}
\]  

(2)

In this formula the value of \( \Omega \) determines the duration of irregular thermal process and is quite a small value. The duration of the established non-stationary nucleate boiling is determined basically by the second term of dependence (2), i.e. \( b \ln \frac{\vartheta_j}{\vartheta_\mu} \). To avoid nucleate boiling, it is necessary that the second part of formula (2) is equal to zero, i.e., \( b \ln \frac{\vartheta_j}{\vartheta_\mu} = 0 \).

We have obtained equations for \( \vartheta_j \) and \( \vartheta_\mu \), which can be presented as:

\[
\vartheta_j = \frac{1}{\beta} \left[ 2\lambda (\vartheta_0 - \vartheta_j) \right]^{0.3}
\]  

(3)

and

\[
\vartheta_\mu = \frac{1}{\beta} \left[ \alpha_{\text{conv}} (\vartheta_\mu + \vartheta_{ub}) \right]^{0.3}.
\]  

(4)
Equating $\Theta_I$ and $\Theta_H$, we are obtaining the criterion for determining the absence of non-stationary nucleate boiling: 
$$ \left[ \frac{2\lambda(\Theta_0 - \Theta_I)}{R} \right]^{0.3} \equiv \alpha_{\text{conv}}(\Theta_H + \Theta_{ab})^{0.3} $$

or
$$ Bi = \frac{2(\Theta_0 - \Theta_I)}{\Theta_I + \Theta_{ab}} \quad (5) $$

because in formula (2) $\Theta_I \equiv \Theta_H$.

Equation (5) is the basic criterion that determines the absence of non-stationary nucleate boiling (self-regulated thermal process) at steel quenching [6,7].

**Figure 2.** Hoop residual stress distribution on the cross section of the stamp after its partial self-tempering and final cooling to room temperature ($\alpha=20000$ W/m$^2$K)

### 4. QUENCH PROCESS OPTIMIZATION

The optimal residual stress distribution in the quenched steel part occurs in case of optimal depth of the hardened layer. In this case high compressive stresses at the surface and less tensile stresses in the core are observed. It is fair for any size of a part if the condition (6) is met:

$$ \frac{D_I}{D_{opt}} = \text{const.} $$

Where: $D_I$ is the ideal critical diameter or specific size, $D_{opt}$ is size of the steel part with the optimal stress distribution. Ideal critical diameter can be calculated using equation (7):

$$ DI = \left( \frac{ab \tau_M}{\Omega + \ln \theta} \right)^{0.5} \quad (7) $$

$a$ is average thermal diffusivity (m$^2$/s);
$\tau_m$ is limit time of the core cooling from the austenitzing temperature to martensite start temperature, providing the formation of 99% or 50% martensite, $\Omega = 0.48$ for a bar (or cylinder),

$\theta = \frac{T_0 - T_m}{T_M - T_m}$, $T_0$ is austenitzing temperature, $b$ is parameter depending only on form of steel part; $T_m$ is temperature of quenchant; $T_M$ is martensite start temperature at limit time of cooling.

### Table II. Commercial and industrially tested technologies using intensive quenching [8]

<table>
<thead>
<tr>
<th>Steel parts</th>
<th>Steel for IQ process</th>
<th>Steels and technologies which were replaced by IQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylindrical and conical gears of trucks and tractors</td>
<td>58(55PP)</td>
<td>30KhGT (and other carburizing steels, carburizing for 10 hr.)</td>
</tr>
<tr>
<td>Cylindrical gears of electric driven train transmissions and locomotives (m=10 mm)</td>
<td>ShKh4</td>
<td>20KhN3A, 20Kh2N4A, carburizing for 30 hr.</td>
</tr>
<tr>
<td>Small modulated gears (m=4-6 mm) with splined openings (solar, satellite ones)</td>
<td>58(55PP)</td>
<td>18KhGT and others, carburizing for 15 hr.</td>
</tr>
<tr>
<td>Rear wheel truck half-axes</td>
<td>47GT</td>
<td>40KhGRT and others, through hardening in oil</td>
</tr>
<tr>
<td>Dies for punching the bearing bolls</td>
<td>ShKh4</td>
<td>Enhanced alloyed steels, through hardening in oil</td>
</tr>
</tbody>
</table>

### Table III. Steels of low hardenability for Intensive Quenching (IQ) [8]

<table>
<thead>
<tr>
<th>Steel, GOST</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>Ti</th>
<th>Al</th>
<th>Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>58(55PP) GOST 1050</td>
<td>0.55-0.63</td>
<td>0.2</td>
<td>0.1-0.3</td>
<td>0.25</td>
<td>0.15</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.2</td>
</tr>
<tr>
<td>47GT</td>
<td>0.44-0.51</td>
<td>0.95-1.25</td>
<td>0.10-0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>-</td>
<td>0.06-0.12</td>
<td>-</td>
<td>0.30</td>
</tr>
<tr>
<td>ShKh2</td>
<td>1.15-1.25</td>
<td>0.15-0.30</td>
<td>0.15-0.30</td>
<td>0.10</td>
<td>0.15</td>
<td>&lt;0.03</td>
<td>0.06-0.12</td>
<td>0.015-0.03</td>
<td>0.12</td>
</tr>
<tr>
<td>ShKh4 GOST 801</td>
<td>0.95-1.05</td>
<td>0.15-0.30</td>
<td>0.15-0.30</td>
<td>0.30</td>
<td>0.25</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.25</td>
</tr>
<tr>
<td>45S</td>
<td>0.42-0.48</td>
<td>0.17-0.32</td>
<td>0.40-0.65</td>
<td>0.20</td>
<td>0.25</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.15</td>
</tr>
<tr>
<td>70PP</td>
<td>0.66-0.73</td>
<td>0.15-0.30</td>
<td>0.15-0.30</td>
<td>0.25</td>
<td>0.25</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.25</td>
</tr>
<tr>
<td>115PP</td>
<td>1.10-1.20</td>
<td>0.40-0.60</td>
<td>0.15-0.30</td>
<td>0.20</td>
<td>0.25</td>
<td>-</td>
<td>0.06-0.12</td>
<td>-</td>
<td>0.20</td>
</tr>
</tbody>
</table>
CONCLUSIONS

1. Delayed transformation austenite into martensite at the first step of cooling and very rapid cooling within the martensite range at the second step results in decreasing of distortion of steel parts and increasing mechanical properties of a material.

2. Intensive cooling from austenite temperature till the time of the formation of the optimal quenched layer and the maximal compressive stresses at the surface with the subsequent tempering of the quenched layer also reduces distortion and increases mechanical properties of the materials.

3. Low-hardenability steels, which provide optimal depth of the quenched layer in conditions of intensive cooling, reduce distortion and increase service life of steel parts similarly to items 1 and 2.

4. The software and original technique of calculations of optimal conditions of quenching depending on the shape and the sizes of parts, conditions of cooling and chemical composition of steel has been developed.

5. More detailed calculations are carried out on the basis of the software TANDEM developed in Ukraine.


References
4. Ukrainian Patent No 27059
6. Ukrainian Patent No 56189
7. US Patent #6,364,974B1