IDENTIFICATION OF MACHINE COMPONENTS CRACKING WITH SOUND EMISSION DURING STEEL QUENCHING

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Abstract

Quenching and tempering often represent a stage near the end of the manufacturing process of machine components. The purpose of selecting the most suitable quenching parameters and controlling the hardening process is to ensure the required hardness and the residual stresses, particularly in the surface layer of a machine part. This is most important in mass production, in which the best mechanical properties are required in order to obtain the lowest cost and the best quality. This paper includes the investigation of certain acoustic events during steel quenching. The possibility of understanding the relation between a connection between sound emission with the wetting kinematic of the quenching agent and a hot specimen with other phenomena during quenching was examined. It was determined that the captured acoustic signals could identify the suitability, i.e. the quality of the quenching process to ensure better control of the quenching process. For this purpose, a system with a hydrophone was designed to capture acoustic emissions. An investigation of sound emission was carried out with a few cylindrical specimens, i.e. different shapes made of heat-treatable steel quenched in quenching agents with different cooling severities. Furthermore, the possibility of acoustic signals caused by workpiece deformation and crack formation due to high internal stresses were examined. A comparison of results shows that this possibility can lead to an applicability approach to controlling the hardening process and quality of steel parts.

Keywords: cooling rate, cracking, nucleate boiling, sound emission, quenching

1. Introduction

Efficient use of the material requires that most machine parts manufacturing processes conclude with quenching and tempering to obtain the desired mechanical properties, i.e. hardness profile and strength.

The most important parameters affecting quenching results are: (Figure 1):
- The material of the workpiece (chemical composition and initial microstructure and physical properties),
- The form of the workpiece (relation between the surface and volume of the workpiece, state of the surface of the workpiece),
- The quenching media (type, the temperature, and physical properties),
- The kind of quenching process (immersion, steering, spraying, etc.).

During the quenching process by immersion in fluids, the occurrence of three wetting phases of heat transfer to quenching media with Leidenfrost temperature between 100 and 200°C and consequently the varying of the heat transfer coefficient \( \alpha \) is characteristic [11]:

- **Film boiling**: heat transfer coefficient \( \alpha_{FB} = 100 \) to 250 W/m\(^2\)K when quenched in water,
- **Nucleate boiling**: vapourizing of media enables heat transfer coefficient \( \alpha_{NB} = 10 \) to 20 kW/m\(^2\)K when quenched in water,
- **Free heat convection**: \( \alpha_{conv} = \text{approx.} 700 \) W/m\(^2\)K when quenched in water.

The spreading velocity of the wetting front depends on several physical properties of the specimen and the quenching medium:

- disposition of the temperature throughout the specimen,
- heat transfer coefficient \( \alpha \) throughout the specimen,
- surface conditions (roughness, different surface coatings, i.e. oxides, organic substances, etc.),
- the geometry of the specimen,
- Leidenfrost temperature of the quenching media,
- dynamic viscosity, specific heat and surface tension, and
- the temperature of the quenching media during cooling and forced convection.

Specimen cooling is, therefore, subject to a considerable local variation that influences the microstructure and mechanical properties of the specimen obtained [6]. During the quenching of a workpiece with complex shapes, all three phases occur simultaneously on different workpiece surface areas which produces considerable internal stresses and also a definite influence on microstructural stresses leading to distortion and residual stresses, or even to cracking of the workpiece. [5].

### 1.2 Sources of sound emission

The sources of sound emission of different shapes, duration and frequencies can be as follows:

- Various mechanisms of heat transfer, which causes the motion of the cooling media, changes of the physical state of the cooling media and vapour forming of the cooling media: these are the predominant phenomena of high intensity during the quenching, typical of the audible frequencies of the sound spectrum.
- Moving the workpiece causes more or less intense heat transfer, a low-intensity effect, which could be considered to be noise. This is a phenomenon typical mainly of the audible part of the sound spectrum.
- Changes on the surface of the workpiece: cracking and shelling of the oxides on the surface. This is a phenomenon typical mainly of the audible part of the sound spectrum.
- Microstructure changes in the material of the workpiece: a martensitic phase transformation represents changes of form and volume of the local microstructure from face-centred to the cubic body-centred tetragonal structure. It is reflected in the local changes in form and volume that cause internal stress fields and other mechanisms. When relaxing internal stresses, they represent the mechanism for generating acoustic emission. Speich and Schwoeble researched the effect of cooling speed on acoustic emission. Their results are summarized in Table 1 [8]. This effect is typical of the ultrasonic part of the sound spectrum.
- Microstructure changes, primarily transformation in martensite connected with volume changes in the solid state of the material, cause high internal stresses, which result in a sudden fracture of the workpiece material. This phenomenon comes in the form of a very short impulse, typical of the audible part of the sound spectrum.
- Technological process accompanied by the surrounding noise, which is a phenomenon typical mainly of the audible part of the sound spectrum. In our case, the surrounding noise was evaluated as more than 10 dB lower than the emission caused by the quenching. We considered this value to be a criterion for the validity of the measurements [12].

Table 1: AE during continuous cooling of plain carbon steel

<table>
<thead>
<tr>
<th>Transformation Product</th>
<th>Acoustic Emission Activity</th>
<th>Phase Transformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearlite</td>
<td>Not detectable</td>
<td>Diffusion-controlled simultaneous growth of lamellar ferrite and cementite.</td>
</tr>
<tr>
<td>Bainite</td>
<td>Not detectable</td>
<td>Diffusion-controlled growth of small (&lt; 1 µm) carbides and lath ferrite.</td>
</tr>
<tr>
<td>Martensite</td>
<td>Very energetic signals detected</td>
<td>Diffusion-less transformation in which laths or plates 20 µm in diameter and 4 µm thick transform from face-centred cubic to body-centred tetragonal structure at about 30% of shear wave speed.</td>
</tr>
</tbody>
</table>

The formation of vapour bubbles, their oscillation, and disappearance in the fluid generate noise, which is strongest in the transition layer between film boiling and nucleate boiling of the quenching medium. Detection of emitted sound signals and their analysis can, therefore, provide useful information on the quenching process [4]. The sound generated by bubbles in the boiling water in different thermal conditions was examined by Leighton [7] who developed a numerical model of the dynamics of a bubble. The Minnaert model of bubble formation frequency during immersion indicates a relation between the bubble size and the frequency of bubble formation. In the initial phase of nucleate boiling, bubbles of smaller diameters are formed, and their frequency is higher, and vice versa when the nucleate boiling of the quenching medium is nearing its end. Such conditions can be achieved during quenching in water and in different concentrations of polymeric water solutions. However, the noise produced due to material cracking is in the upper end of the audible noise spectrum. A measuring setup should be adapted to the expected frequency of sound phenomena. Thus, the frequencies of bubble formation and decay occurring predominantly in the audible range and which are slightly below this threshold should be known [1].

The conditions at which the signals were detected should be monitored via temperature measurement of the specimen during the quenching process. The phenomena occurring at the workpiece/medium interface should then be significantly interrelated in film boiling, including additional environment sound effects [5]. Furthermore, bubble formation and sound generation phenomena should be interrelated with material properties and failures obtained.
1.3 Bubbles' oscillation

Minnaert [7] discovered sounds generated in water boiling under different thermal conditions and at different pressures and developed a numerical model of the dynamics of a bubble; the bubble responds to pressure changes in the liquid that reinstate the new balance of pressures with volume changes. This restoration leads to the bubble's oscillation; Minnaert's frequency of oscillation bubble:

$$\omega_M = \frac{1}{R} \sqrt{\frac{3n p_0}{\rho}}$$

where:

- $p_0$ is hydrostatic pressure of the liquid around the bubble in conditions of static equilibrium,
- $n$ polytrophic coefficient,
- $R_0$ radius of the bubble in the equilibrium, and
- $\rho$ the density of the liquid.

Calculation for common quenching conditions in the water and polymeric solution shows that expected frequencies should be as illustrated in Figure 2.

Figure 2: Expected frequency range dependent on the size of the bubble and immersion depth

2. Experimental procedure

2.1. Experimental setup

One requirement for the experimental setup for detecting sound signals in wetting processes is independence from the quenching medium type used and from the quenching mode. Although the quenching process takes some seconds or even up to several minutes, the experimental system should register individual events up to 0.1 seconds [5].

The measuring setup for detection and processing of sound signals comprises:

- A high sensibility adjustable hydrophone, B&K type 8103.
- A multi-channel measuring amplifier/pre-amplifier, B&K type 2636.
- A Sound Blaster card. Analog/digital transformation of the signal captured permits 16- or 24-bit resolution and a sampling rate up to 96 kHz.
Software: SpectraLAB FFT Special Analysis System, Version 4.32.14, a product of Sound Technology Inc., USA. This is designed for the detection, recording, and processing of sound signals in its original and digitized form.

- An IBM notebook with MS Windows XP Professional operating system.

The hydrophone was immersed in the flow channel where a constant flow of 0.5 m/sec of the quenching medium was ensured, and the specimen observed through a glass window (Fig. 1).

2.2. Specimen description

![Specimens shapes](image)

Figure 3. Flow channel

Figure 4. Specimens shapes
Low-alloy Cr-Mo heat-treatable steel AISI 4140 was selected for the specimens. This steel shows high hardness after heat treatment, i.e. even up to 57 HRC. It is characterized by good through-hardening and high strength after heat treatment [2]. Therefore, it is widely used in the production of statically and dynamically loaded components of vehicles, motors, and machine components with large cross sections. Its chemical composition and mechanical properties are given in Table 2.

Table 2: Chemical composition and recommended heat treatment for hardening AISI 4140 (EN - 42CrMo4) steel

<table>
<thead>
<tr>
<th>Element</th>
<th>C [weight %]</th>
<th>Si(_{\text{max}})</th>
<th>Mn [weight %]</th>
<th>P(_{\text{max}})</th>
<th>S(_{\text{max}})</th>
<th>Cr [weight %]</th>
<th>Mo [weight %]</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>0.38 – 0.45</td>
<td>0.40</td>
<td>0.60 – 0.90</td>
<td>0.035</td>
<td>0.035</td>
<td>0.90 – 1.20</td>
<td>0.15 – 0.30</td>
</tr>
</tbody>
</table>

Recommended heat treatment conditions: Austenitization temperature of 820-850, 830-860 °C; quenching in water or oil.

The purpose of the experiment was to achieve cracking of the specimen during quenching due to overly high internal stresses. The forms of the specimens chosen were graded cylinder with drill hole on the bottom by some samples as shown in Figure 4.

2.3. Quenching medium

For the low alloy steel chosen, an adequate quenching medium ensuring a cooling rate slightly higher than the critical one should be used [3]. Thus, the required through-specimen hardness and strength can be obtained, and internal stresses can be optimized in the specimen during quenching and distortion with residual stresses as a result of quenching. To compare the results of regular quenching and material cracking, two different quenching media were chosen. The first was pure water to ensure proper mode of quenching, and the second was a more severe salt solution to ensure a higher cooling rate rather than a critical one. The consequence of high cooling rate was the specimen cracking.

2.4. Procedure

The specimen was preheated to a temperature of approximately 600 °C, and then progressive heating to the austenitizing temperature, i.e. 860 °C, followed. When the temperature stabilized, the specimen was quickly moved to a quenching flow channel to be quenched in the chosen quenching media.

The initial quenching-medium temperature was 18 °C, whereas the final temperature varied between 25 and 30 °C. The volume of the quenching medium in the flow channel was 30 l with the constant flow of 0.5 m/s.

On the IBM notebook, the sound signal-processing software was running. The captured sound signals were subsequently evaluated with the same software.

3. Results

3.1. Sound pressure signal identification

The results of sound pressure are presented in several diagrams showing the varying sound pressure level \( L_p \) depending on frequency and time:

- Time series diagram displays the raw digitized audio data with the amplitude shown on the vertical axis and time on the horizontal axis in linear or logarithmic views. The amplitude ratio between the maximum level at the start of the quenching process and background noise level at the very end of the process is sufficient to identify different stages of the quenching process (Fig. 5A, Fig. 5B).
The spectrogram view is a calculated time record of sound signals. The digitized audio signal is passed through an algorithm known as a Fast Fourier Transform (FFT), which converts the signal from the time domain (amplitude v. time) to the frequency domain (amplitude v. frequency). This view displays the spectral data over time with the amplitude shown in colour in which frequency is seen as the ordinate value and signal intensity in colour scale: cold - blue → low intensity; hot - red → strong intensity (Figure 8A, Figure 8B).

The calculated average spectrum shows a relative amplitude level depending on the frequency. This view is a two-dimensional plot of the spectrum. The horizontal axis shows the frequency, and the vertical axis shows the amplitude of each frequency line (Figure 9A, Figure 9B).

The data-logging tool produces an output data file containing selected spectrum values along with a timestamp showing when the event occurred (Figure 10).

### 3.2. Analysis of the sound signals generated by quenching process

The sound spectrum obtained during quenching comprises the emitted sound pressure level. Comparing obtained sound pressure diagrams indicates significant characteristics shown with differentiation in sound intensity and frequency ranges. The analysis provides detailed information on individual events in the quenching medium used. Figures 5, 6, 7 and 8 show sound pressure level signals detected with the hydrophone and calculated spectrograms, giving the frequency of events during the quenching of specimen No. 3 in pure water and the salt solution. By comparing signals of both quenching media, the following may be concluded:

- A significant change of the amplitude can be determined when quenching in the salt solution: after approximately 16 seconds of quenching, a significant amplitude peak shows the moment when specimen cracking occurs (Figure 6 B).
• Typical events are recognized: background noise, the beginning of the cooling process and specimen cracking (Figure 7 A). Time zooming shows that the duration of the cracking signal is less than 0.05 seconds when four peaks follow one after another (Figure 7 B).

![Typical events](image)

**Figure 7.** Time series sound pressure signal when quenched in salt solution

• A significant change of the amplitude shown as a sudden colour change can also be determined in the spectrogram of the sound pressure signal when specimen cracking occurs (Figure 8 B). The spectrogram shows that the change occurs in all frequency ranges for a very short time, shown as a more intense red colour.

![Spectrogram of sound pressure signal](image)

**Figure 8.** Spectrogram of sound pressure signal

• Figure 9 shows the calculated average spectrum for both quenching media. Figure 9B shows a significant change of the intensity in the frequency range between 6 and 7 kHz in the cracking moment.
A detailed investigation of the sound pressure signal enables the evaluation of frequency signals. Figure 8 shows the curves of high-frequency signals of 19, 20, 21.2, 22.4, and 23 kHz as functions of time. At the moment of the cracking of the specimen, between 16.2 and 16.25 seconds, a significant leap of the signal amplitude can be recognized in the frequencies.

Data logging allows us to produce an output text file containing the selected spectral parameters along with a timestamp of when the event occurred. Using those data, we were able to investigate in detail the sound pressure signals.

A detailed investigation of the sound pressure signal enables the evaluation of the signals. Figure 11 shows the curves of high-frequency signals in the duration of 24 seconds during the entire quenching process. In the moment of the cracking of the specimen, between 16.2 and 16.25 seconds, a significant leap of the signal amplitude can be recognized by the frequencies.

- Figure 11 A shows the amplitudes of high frequencies on the upper audible frequency range: 99.5 dB at 19 kHz; 96.3 dB at 20 kHz; 105.6 dB at 21.2 kHz; 114.6 dB at 22.4 kHz, and 11.9 dB at 23 kHz.
- Figure 11 B shows the amplitudes near the marginal area of 2 kHz: 105 dB at 1.9 kHz; 104.3 dB at 2.0 kHz; 102.2 dB at 2.12 kHz, and 100.7 dB at 2.24 kHz.
Figure 11: The curves of the frequency signals during the quenching process at the upper audible frequency range (A) and near the marginal area of 2 kHz (B).
Figure 12: The curves of frequency signals as functions of time in a time frame between seconds 16 and 17. The results of a more detailed investigation of the time frame between seconds 16 and 17 after the start of the quenching process, when cracking occurs, are shown in Figure 8.10.

- Figure 12 A shows the amplitudes of the high frequencies at the upper audible frequency range: 99.5 dB at 19 kHz, 96.3 dB at 20 kHz, 105.6 dB at 21.2 kHz, 114.6 dB at 22.4 kHz, and 11.9 dB at 23 kHz.
- Figure 12 B shows the amplitudes near the marginal area of 2 kHz: 105 dB at 1.9 kHz, 104.3 dB at 2.0 kHz, 102.2 dB at 2.12 kHz, and 100.7 dB at 2.24 kHz.
- Figure 12 C shows frequencies with extreme amplitudes of 22.3; 23.2; 23.3 in 24.2 kHz. The highest amplitude reaches the value of more than 161 dB at 23.3 kHz, followed by the frequencies of 23.2 kHz with an amplitude of 163.2 dB, 22.2 kHz with an amplitude of 150.3 dB and 24.2 kHz with an amplitude of 159.9 dB.

At the moment the cracking occurs, a significant increase in the amplitudes can be perceived, especially those belonging to the highest frequencies at the upper limit of the audible frequency range. More amplitude peaks are observable at the highest frequencies. This means
that the cracking does not occur in one single moment, but over a short time interval, which is approximately 0.3 seconds in our case.

4. Conclusions

This paper describes the signals captured by measuring sound emission caused during quenching. The sound pressure signal, which is seen as the amplitude and duration of the signal during quenching, was captured with the hydrophone. During the recording of the sound pressure, a change of the signal shape appears, corresponding to the formation of a vapour film phase on the specimen surface and to the nucleate boiling phase on the specimen/quenching-medium interface. A significant change of the signal follows when specimen cracking occurs. This change was connected with the high internal stresses during the quenching process, which caused rupture of the specimen in the axial direction. The signal was audible throughout the quenching process, and the capturing of the sound emission with a hydrophone was satisfactory. A significant change of the signal was easily visible and could be recognized when the specimen is cracking. On the basis of the experiment, it could be concluded that the experimental setup of the sound emission capturing was reliable and has given satisfactory results. The analysis of the results offers an interesting new approach to the evaluation and, more importantly, to the monitoring, controlling, and optimizing of the quenching process itself.

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