Sound Emitted at Boundary Layer During Steel Quenching

Franc Ravnik[*] - Janez Grum
University of Ljubljana, Faculty of Mechanical Engineering, Slovenia

Quenching and tempering often represents the final stage in the manufacturing process of machine parts. The choice of optimum parameters of a quenching process and monitoring of the process itself ensures the achievement of the specified hardness and residual stress in the surface layer of the machine component. A hardening process can be controlled by selecting different quenching parameters (quenching media, its temperature, specimen temperature, ...). In order to control the hardening process, one should be able to monitor the quenching process in real time. This paper treats an experimental setup comprising detection of sound emission and some of the results obtained during the quenching process. Due to the heat transfer from the specimen to the quenching medium, film boiling and nucleate boiling occur around the heated object, which strongly affects quenching. Bubble formation, their development and implosions, and disappearing around the surface causes sound emission whose intensity depends on the intensity of the bubbles' oscillation and the speed of their disappearing, i.e. on the quenching process. Sound-pressure signals demonstrated by different amplitudes depending on time, at different frequencies, are shown in 3D diagrams. It was established that an analysis of sound emission signals can provide useful information that confirms the differences occurring in quenching with different quenching media and under different quenching conditions. Analyses of sound emission demonstrated that sound emission during quenching process can be used for monitoring the hardening process. Analysis of the quenching results and sound emission signals during the process itself confirm the applicability of the new approach to the controlling of steel quenching.

0 INTRODUCTION

Most manufacturing processes of machine parts finished with heat treatment, which includes hardening and tempering, that provides higher strength and consequently higher material hardness which improves wear resistance. A purpose of quenching is to provide a cooling rate higher than the upper critical cooling rate in a certain depth of a machine component in order to obtain the desired mechanical properties. Critical cooling rates of carbon steels and low-alloy steels can be achieved by cooling a machine part by immersion into a quenching media such as water, oil, polymeric water solutions, and emulsions.

The depth of the hardening of steel through the whole workpiece body depends on several factors: chemical composition, i.e.: alloying elements, the type of steel, the size of the workpiece and/or its mass, microstructure prior to heat treatment, i.e.: austenitic grain size, the type of quenching medium applied, the quenching method, and the quenching process itself.

During the quenching process in fluids, the occurrence of three heat transfer phases of the heated machine component is characteristic. In the initial phase of machine-component immersion, a stable vapour film of a fluid quenching medium forms around the workpiece for a while, so that the heat transfer to the quenching medium is considerably slowed down (Fig. 1) [1]. In further cooling the vapour film gradually decays so that a phase of nucleate boiling occurs at some parts of the workpiece surface having a temperature lower than the Leidenfrost temperature. In nucleate boiling, a surface section is wetted with the liquid quenching medium and the heat transfer from the workpiece increases. At lower temperatures, a third phase of convective cooling occurs at the interface. The three phases are characterized by different modes of heat transfer which contributes to different cooling intensities: film boiling, nucleate boiling and free convection. During the cooling of a workpiece with exacting shapes, it often happens that all three phases occur

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[*]Corr. Author's Address: Faculty of Mechanical Engineering, Aškerčeva 6, 1000 Ljubljana, franc.ravnik@fs.uni-lj.si
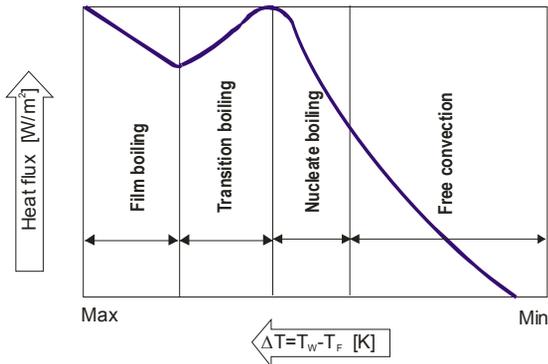
Fig. 1. *Nukiyama boiling curve and different stages of boiling (heat transfer)*
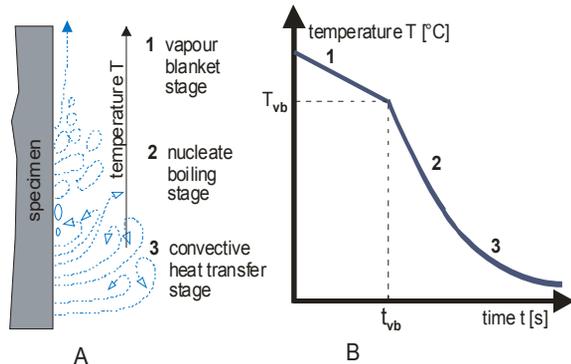
Fig. 2. *A) cooling stages on the specimen's surface B) Temporal course of the surface temperature during quenching*

simultaneously on different workpiece surface areas: vapour blanket stage (1), nucleate boiling stage (2) and convective heat transfer stage (3) as shown in Fig. 2, which, however, produces considerable internal stresses during quenching and also an explicit influence on microstructural stresses leading to distortion and residual stresses, or even to distortion, residual stresses and cracking of the workpiece. Therefore, a distribution of heat transfer coefficient is an important parameter for the distortion of the whole part [2]. Consequently, the control of the wetting behaviour of the workpiece is essential for the control of the quenching process. Steel quenching starts at the austenitizing temperature of a given steel (over 800 °C), the quenching process in fluid quenching media always being accompanied by an evaporation phase of the quenching agent in contact with the workpiece surface, since a boiling point ((T_{vb})) of most of quenching media ranges between 100 and 300 °C at normal pressure [10].

The vapour bubble process formation, their oscilation and disappearing in the liquid are connected with noise generation, which is strongest at the transition 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 [3].
Leighton [11] studied sound generated by bubbles in the water, under different thermal conditions and at different pressures. The Minnaert model of

bubble formation frequency during immersion quenching of the workpiece indicates a relation between a bubble size and the frequency of bubble formation (Fig. 3). In the initial phase of nucleate boiling, bubbles of smaller diameters are formed and their frequency is higher, and vice versa when nucleate boiling of the quenching medium is nearing its end. Such conditions can be achieved during quenching in water and in polymeric water solutions of different concentrations.

Consequently, a measuring setup is adapted to the expected frequency of sound phenomena. Thus it should be known which frequencies of bubble formation and decay occur predominantly in the range of hearing and which slightly is below this threshold [5, 6].

Generation of sound depends on the temperature gradient occurring at the workpiece surface and the momentary temperature of the quenching medium. Thus it is possible that a sound signal detected with a hydrophone during the quenching process follows the Minnaert model of bubbles and sound signals formation in the quenching medium (Fig. 3).

The conditions at which the signals were detected should be monitored with temperature measurement on the specimen during the quenching process. The phenomena occurring at the workpiece/medium interface should then be logically interrelated in film boiling, including additional sound effects due to material failure [4].

Minnaert's frequency of oscillation bubble:

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

where:

p_0 [N/m^2].. is hydrostatic pressure of the liquid around the bubble in conditions of static equilibrium,

χ.............. polytrophic coefficient,

R [m] .... radius of the bubble in the equilibrium and

ρ [kg/m^3] . the density of the liquid
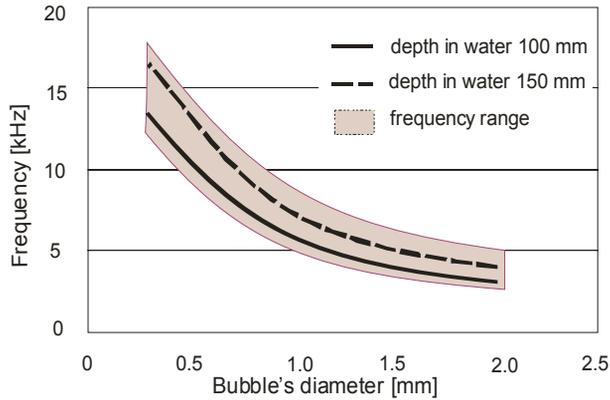
Fig. 3. *Expected frequency range depends on the size of the bubble and immersion depth*

1 EXPERIMENTAL PROCEDURE

Because of the influence of the workpiece surface temperature on the occurrence of film boiling and nucleate boiling, an experimental procedure was elaborated for temperature monitoring in the cylindrical specimens and on-line detection of sound signals in the entire temperature range of the quenching process.

1.1 Experimental Setup

Figure 4 shows the experimental setup for detecting sound signals during quenching. It comprises a vertically adjustable hydrophone carrier providing a stable position perpendicular to the specimen surface, and a small wire basket enabling fast and simple putting of a specimen in a stable position to provide quenching free of additional heat removal. The entire equipment is immersed in a container having the form of a glass aquarium filled with the quenching medium. A preliminary test showed that a 6 mm thick soft rubber lining, which considerably reduces reflection of sound waves from the container walls, considerably reduces noise.

The experimental setup for detecting sound signals in wetting processes is to be independent from the quenching medium type used and of the quenching mode. Although the quenching process takes some seconds or even up to several minutes, the experimental system should register individual events sensed up to 0.1 second or less [7].

The designed experimental setup comprises two independent setups, i.e.:

- a setup for monitoring the temperatures at the surface and in the core during the quenching and monitoring of the medium temperature itself;
- a setup for detection and processing of the sound pressure level (L$_p$) of emitted noise.

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

- A hydrophone, B&K type 8103, suitable for laboratory and industrial applications. Its high sensibility permits sound capturing in liquids in frequency ranges from 0.1 Hz to 180 kHz, in a wide range of working temperatures.
- A multi-channel measuring amplifier/pre-amplifier, B&K type 2636.
- A two-channel Sound Blaster card, CREATIVE type Live 24 Bit external. Analogous/digital transformation of the signal captured permits 16- or 24-bit resolution and sampling rate up to 96 kHz.
- Sofware: "SpectraLAB" FFT Special Analysis System, Version 4.32.14, a product of Sound Technology Inc. USA. The program package is specially designed for detection, recording and processing of sound signals in its original and digitized form, which permits subsequent evaluation and monitoring of events in the specimen during quenching.
- An IBM notebook with Intel ® Pentium ® M Processor 1.6 MHz, and 760 MB RAM. Operating system: MS Windows XP Professional 2002.
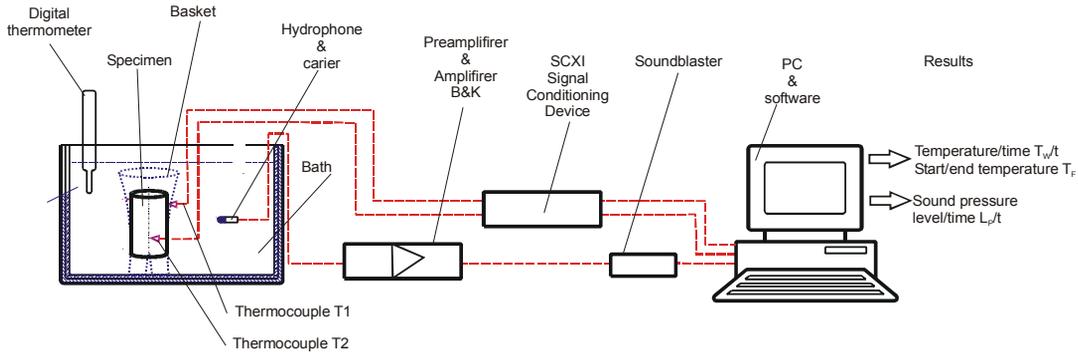
Fig. 4. *Experimental setup for the measurement of temperature and emitted sound during quenching*

In addition to sound emission, temperature variations at the specimen surface (T_W) and in the core and quenching-medium temperatures (T_F) prior to, during and after quenching were also monitored. Each of the ten specimens was equipped with two thermocouples. The first one was in the first third of the height from the top, 2 mm below the cylinder surface, and the second one in the second third of the height, in the core centre, i.e. in the specimen axis. The measuring setup for monitoring temperature variations at the specimen surface and in the specimen core comprised:

- thermocouples mounted at the surface and in the core for measuring temperature variations during quenching;
- National Instruments SCIXI 16-bit USB I/O platform for signal processing. It enables detection of temperature signals with a 16-bit resolution and sampling rate of 200 kHz.
- Lab VIEW Software for monitoring time-dependent temperature and signal processing.

Within the experimental setup for temperature measurements in the specimen, the temperature of the quenching medium prior to, during, and after quenching was also measured, using a model 30 digital thermometer, a product of Macken Instruments Inc.

1.2 Specimen Material and Size

The specimens were made of low-alloy Cr-Mo heat-treatment steel (EN - 42CrMo4) which shows high hardness after heat treatment it, i.e. even up to 57 HRC. It is characterized by good through-hardening and high strength after heat treatment [10]. It is widely used in the production of statically and dynamically loaded components of vehicles, motors, and machine components with a large cross section. Its chemical composition and mechanical properties are given in Table 1.

Specimen form

Test specimens had a cylinder form with diameters of 45 and 53.5 mm and a height that provides equal mass, i.e. 0.92 kg. A ratio between the specimen volume and area was taken into account, because it affects the cooling rate with the same specimen mass. Table 2 shows two different cylindrical specimens (type A and B) with different P/V ratios.

Table 1. *Chemical composition and recommended heat treatment for hardening 42CrMo4 steel*

Element	C	Si_{max}	Mn	P_{max}	S_{max}	Cr	Mo
[weight %]	0.38 – 0.45	0.40	0.60 – 0.90	0.035	0.035	0.90 – 1.20	0.15 – 0.30
Recommended heat treatment by hardening:	Austenitization temperature of 820 to 850, 830 to 860°C quenching in water or oil.						

Table 2. *Cylindrical specimen forms and different sizes*

Spec. type	Diameter D [mm]	Length L [mm]	Mass M [kg]	Area P [cm^2]	Volume V [cm^3]	P/V --
A	φ 45.0	75.0	0.92	138	119	1.16
B	φ 53.5	53.5	0.92	132	119	1.11

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Table 3. *Quenching medium*

Quenching medium	Ratio		
	Water [%]	Aquatensid BW [%]	"Olmakal Rapid 90" [%]
Pure water	100	--	--
5% polymeric water solution	95	5	--
10% polymeric water solution	90	10	--
15% polymeric water solution	85	15	--
"Olmakal Rapid 90" oil	--	--	100

1.3 Quenching Medium

For the steel chosen, an adequate quenching medium and a suitable quenching mode ensuring a cooling rate slightly higher than the critical one should be used [8]. 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. Five types of quenching media were chosen for heat treatment of steel 42CrMo4; they are given in Table 3.

A cold specimen was introduced in the furnace preheated to a temperature of approx. 600 °C. Then progressive heating of the specimen to the austenitizing temperature, i.e. 850 °C, followed. When the temperature stabilized, the specimen was quickly moved to a quenching bath to be quenched in the different quenching media.

During the experiment, the specimen was fixed in a stable position to ensure identical quenching conditions for all the specimens and to reduce noise that could be generated due to stirring of the quenching medium. The initial quenching-medium temperature amounted to 18 °C, whereas the final temperature varied due to the different specific heat of the quenching media. It was lowest within pure water and highest within oil. The volume of the quenching medium in the container was constant, i.e. 14 l.

Two program packages, *"SpectraLAB"* for sound-signal processing and *"Temperature"* program for temperature-signal processing on the LabView platform, were running simultaneously on the IBM notebook. The captured sound signals were subsequently evaluated with the same program package, and the temperature signals with MS EXCEL.

2 RESULTS

The results of the sound pressure spectrum analysis of are given in diagrams showing the varying sound pressure L_p in dependence of frequency and time.

A typical raw sound signal captured during quenching, recorded from the hydrophone in the quenching media, is presented in Figure 5. The amplitude ratio between 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.
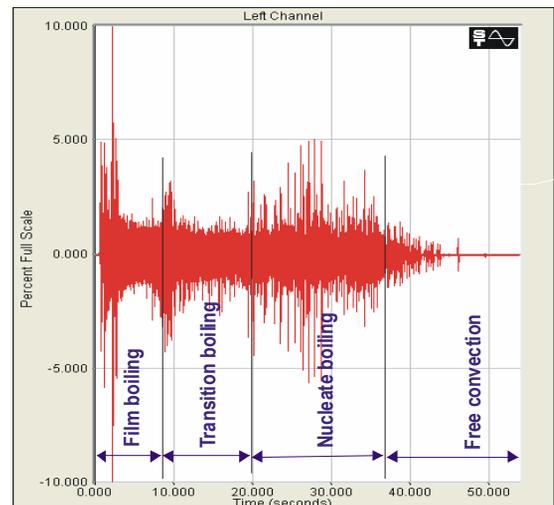
Fig. 5.   *Typical sound pressure signal*

2.1 Frequency Analysis of Sound Generated by the Quenching Process

A spectrogram is a time record of sound signals, in which frequency is seen as the ordinate value at and signal intensity as colour intensity: cold - blue colour - low intensity; hot - red colour – strong intensity.
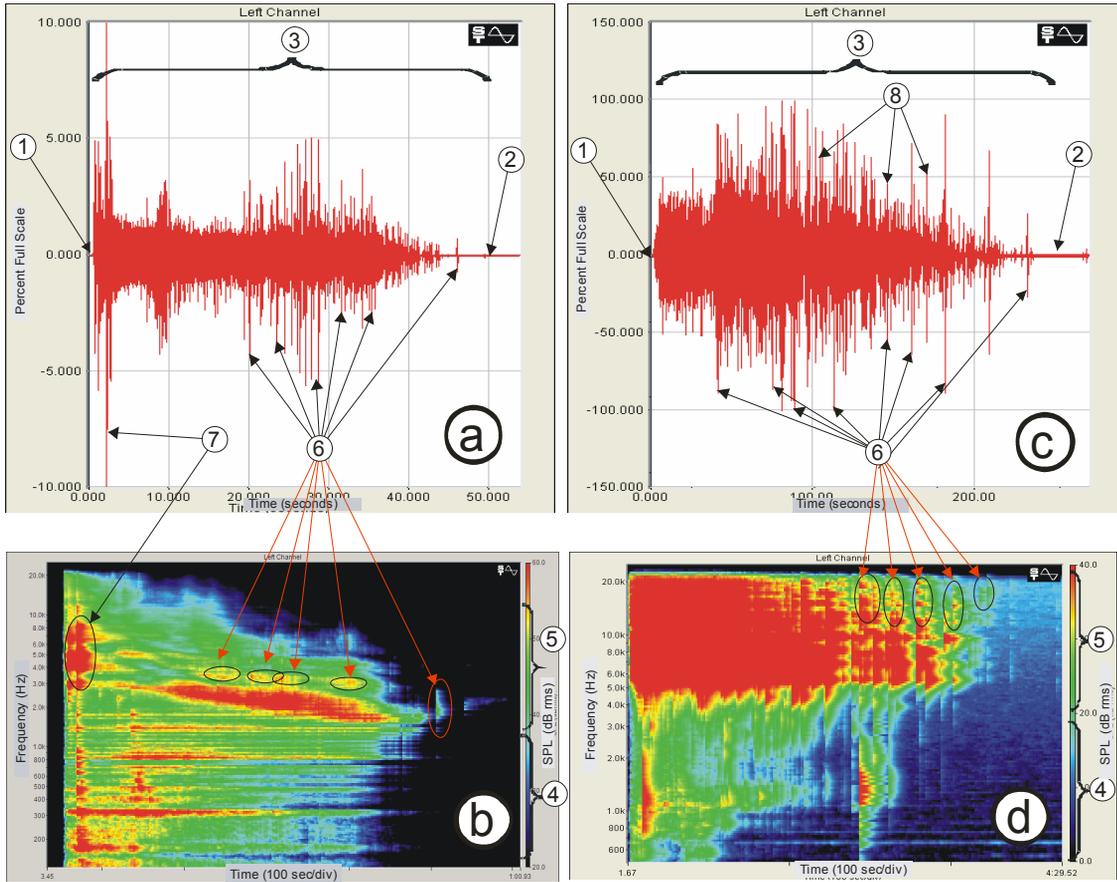
after quenching in pure water   after quenching in"Olmakal Rapid 90" oil

Fig. 6.   *Acoustic signal obtained in quenching of a ϕ 45 mm specimen of in pure water and "Olmakal Rapid 90" oil*

The spectrogram of the quenching process shows the presence of low frequencies at the beginning of the process, i.e. in the first 10 seconds, when water is used as the quenching medium. Intense sound pulses occur due to the formation and decay of the vapour film and some other mechanisms, i.e. vapour film oscillation, cracking of the sample, etc. Their frequencies are gradually reduced due to the cooling rate decrease.

The analysis of the sound spectrum obtained during quenching comprises the emitted sound pressure level. It provides detailed information on individual events in the quenching medium used. Figure 6 shows two records of sound pressure level signals detected with the hydrophone and shown in the spectrogram, giving the frequency of events during nucleate boiling. Although the signal of the ϕ 45 mm specimen

quenched in pure water (Figs. 6 a and b) and the one quenched in the "Olmakal Rapid 90" oil (Figs. 6 c and d) differ considerably, the following may be concluded:

- The beginning of quenching is described by the signals of various frequencies which differ in their amplitude from the environmental noise (Fig. 6 a and b, point 1);
- The end of quenching is described by the signal of an intensity comparable to that of the environmental noise, which means that the number and intensity of the signals with regard to the frequency and their intensity reduces. (Fig. 6 a and c, point 2);
- The process is the duration between the beginning and the end of quenching where the average cooling rate can be established (Fig. 6 a and c, area 3);

- Spectrograms of sound signals, obtained with the hydrophone, were analysed. Two characteristic areas can be determined:
  - an area of lower frequencies, i.e. up 1 kHz in water quenching, and up to 2 kHz in oil quenching, where only the amplitude changes (Fig. 6 b and d, area 4), and
  - an area of higher frequencies, i.e. up to 18 kHz in water quenching, and up to 20 kHz in oil quenching, where the signal frequency varies as well (Fig. 6 b and d, area 5).
- Individual peaks of higher sound intensity given by a voltage signal of higher frequencies (up to 6 kHz in water quenching, and up to 14 kHz in oil quenching), due to surface oxidation and oxide scale cracking at the surface (Fig. 6 a and c, point 6), are identified. In sound emission, there are also short-time peaks of high intensity with frequencies of up to 12 kHz in water quenching, as a result of a too high cooling rate (Fig. 6 a and b, area 7).
- The individual peaks of high intensity with

A – free convection   B – nucleate boiling   **a)**
C – transition boiling   D – film boiling

b)
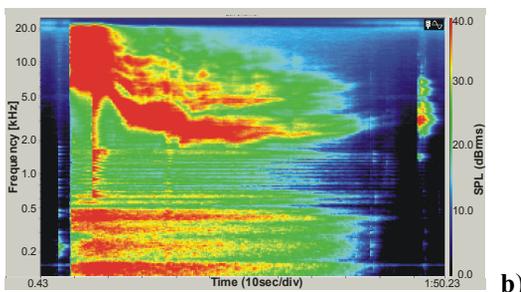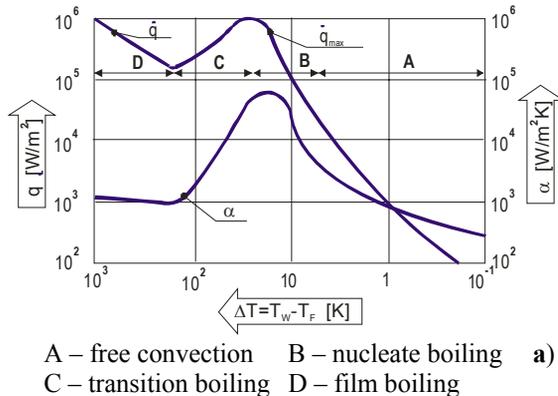
Fig. 7. Comparison between Nukiyama boiling curve (a) and spectrogram during cooling (b) at specimen of ϕ 53.5 mm quenched in 10% polymeric water solution

lower frequencies are a result of steam bubbles escaping from a drillhole of 4 mm in diameter at the upper specimen plane, which are particularly distinct in oil quenching (Fig. 6 and c, d, area 8).

Generally, it can be concluded that from the detected sound emission, characteristic changes at the specimen/quenching-medium interface during quenching could be determined.

2.2 Comparison of Spectrograms

A comparison of the spectrograms obtained in the quenching of the specimens of different forms but equal mass in different quenching media, indicates an important spectrogram characteristics shown with differentiation in sound intensity. The differences stated in sound emission intensity during quenching distinctively depend on the type of the quenching medium used (Fig. 7b). As the specimen-surface wetting occurs simultaneously at different sections of the specimen surface during quenching, all phases of Nukiyama boiling curve between the beginning and the end of the cooling can be differentiated. The Nukiyama curve in Fig. 7a shows a heat flow in quenching as a function of the temperature difference between a workpiece temperature T_W and a quenching-fluid temperature T_F. Comparing individual time frames shows that higher intensity of heat flow causes high intensity of emitted sound and on the other hand, heat flow decrease reduces sound emission.

2.3 Temperature Measurement

Figure 8 shows cooling curves at the surface of all five quenching media for ϕ 45 mm specimen. The temperature was measured at the surface and in the core, but only the surface temperature was taken into account for the purpose of describing the interface phenomena.

Water quenching is more intense, i.e. cooling from the quenching temperature to the water boiling point takes only a few seconds (43 s at the surface and 47 s in the core), whereas cooling to a temperature of 40 °C at the surface takes 87 s.

Oil quenching is slower, i.e. cooling from the quenching temperature to a temperature of

100 °C takes much more (279 s at the surface and 290 s in the core) whereas cooling to 50 °C at the surface takes 470 s.
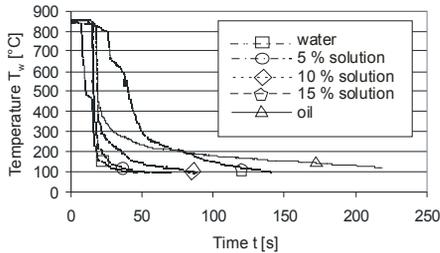
Fig. 8. *Temperature variation 2 mm below the surface of specimen of 45 mm in diameter during quenching in different quenching media*

The time variation of the temperature as well as small temperature differences between the surface and the core are anticipated. They are attributed to a small specimen size. At the same time the small temperature difference indicates soft hardness variation from the surface to the core in the specimen centre.

2.3 Measurement of Residual Stresses

Measurement of residual stresses was carried out with a Hole Drilling Strain Gauge method specified in ASTM standard [ASTM Int., E 837-01, 1995 and ASTM Int., E 837-08, 2008] and with equipment produced by Vishay Meassurement Group Inc. It was evaluated using the program package RESTRESS [9; 11, 14]. A resistance measuring rosette was mounted at the lower edge of the cylindrical specimen. Strain measurement is carried out in three directions taking into account the position of a three-legged resistance-measuring rosette, which permits a subsequent calculation of principal strains and residual stresses. The method makes it possible to determine directions of the principal residual stresses with reference to the position of the individual legs in the coordinate system. Figure 9 shows calculated variations of the principal residual stresses in the thin surface layer of the cylindrical type B specimens in the radial direction, by quenching the specimen in the 5% polymeric solution (a) and after oil quenching (b). The through-depth stress variation varies to the

highest value, then it decreases with a small gradient, at a greater depth. The highest principal stress σ_{RSmax} and the lowest one σ_{RSmin} are shown. At the specimen surface, where the specimen is quenched in oil, residual stresses show a tensile character with the highest value of 169 MPa in a depth of 0.1 mm whereas a minimum compressive stress is achieved in a depth of 0.8 mm. The specimen quenched in 5% polymeric solution showed the highest values of the compressive character of 234 MPa in a depth of 0.7 mm, whereas the minimum residual stresses also show the compressive character. From a comparison of the residual stresses and their through-depth variations, it can be inferred that:

- in quenching in a less intense quenching medium than the 5% polymeric water solution, i.e. in oil, the residual stresses show a tensile character,
- in quenching in a more intense quenching medium than oil, i.e. in the 5% polymeric water solution, the variation of residual stresses in the more favourable compressive zone shows much higher absolute values than in quenching in oil;
- a specimen quenched in pure water will show predominantly compressive residual stresses of higher absolute values than in quenching in the 5 % solution;
- the specimens quenched in the 10%, 15%, and higher concentrations of polymeric water solution show variations of residual stresses which, because of an increased influence of stresses due to microstructural changes, pass over to the tensile zone.
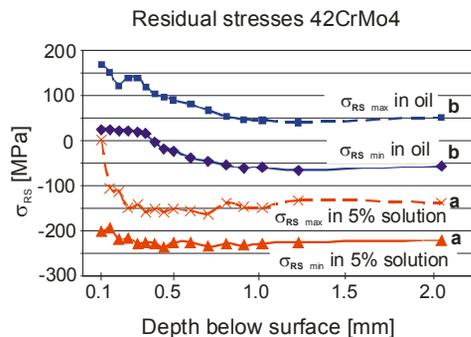
Fig. 9. *Residual-stress variation in surface layer of specimen type B in radial direction a) after quenching in 5% polymeric solution; b) after quenching in "Olmakal Rapid 90" oil*

Table 4. *Resume of microhardness profile [$HV_{0.1}$]*

Measuring area	Specimen quenched in 5% polymeric water solution			Specimen quenched "Olmakal Rapid 90" oil		
	Max.	Average	Min.	Max.	Average	Min.
Outer cylinder - LEFT	581	478	407	413	310	219
Outer cylinder - RIGHT	591	539	491	401	362	290
Longitudinal cross section - MIDDLE	571	466	353	613	429	353
Top face	742	650	533	507	275	162
Transversal cross section - MIDDLE	742	572	363	613	444	330
Bottom face	876	693	439	591	405	214

2.4 Microhardness Measurement

In order to obtain more information about the influence of the quenching process, the microhardness by HV was measured on both faces of cylindrical specimen (top and bottom), in transversal cross section, in the mid-height of the specimen. It was measured in the axial direction, on both sides (left and right), and also in the longitudinal cross section through the axis of the specimen. A load of 1 daN was used to obtain more accurate measuring results of microhardness variation presented. The results of hardness measurement in longitudinal direction on specimen type B quenched in 5% polymeric water solution and "Olmakal Rapid 90" oil are shown in Fig. 10, and the results in transversal direction in Fig. 11.

- The average microhardness values measured on the surface in longitudinal direction are considerably higher when quenching in 5% polymeric water solution than when quenching in oil. However, there are still huge deviations of hardness measured values from the min. value of 407 $HV_{0.1}$ to the max of 591 $HV_{0.1}$ of the specimen quenched in 5% polymeric water solution, and from min value of 219 $HV_{0.1}$ to max value of 413 $HV_{0.1}$ of the specimen quenched in oil (Table 4). The deviations of the measured values on the specimen quenched in 5% polymeric water solution are minor in comparison with the values of the specimen quenched in oil. On the other hand, the course of the values of the sample quenched in oil is from the highest on the bottom face, which was first in contact with the quenching media, to the lowest on the top face. The course of deviations of the values for other specimens is almost uniform around average value.

- The average microhardness values measured on the surface in transverse direction are also considerably higher when quenching in 5% polymeric solution than when quenching in oil. The deviations of the measured values of hardness for the specimen quenched in 5% polymeric solution are not very significant. The maximal value of 876 $HV_{0.1}$ appears on the bottom face close to the centre, while the minimal value of 439 $HV_{0.1}$ is also close to the centre. The course of the measured hardness on the top face is very similar to the bottom face, only the deviations are not so intensive from the min. value of 533 $HV_{0.1}$ to max value of 742 $HV_{0.1}$. The maximal deviations of the values between min and max appear in the inner region with the diameter equal to approx. ½ of the outer diameter of the specimen. The major deviations of the measured values range a little higher than the min. value of 162 $HV_{0.1}$ to max value of 507 $HV_{0.1}$. The course of values for the specimen quenched in 5% polymeric water solution differ considerably from those measured on the specimen quenched in oil, and deviations around average value are present on the whole of the specimen surface.

- The difference between average value of measured microhardness for the specimen quenched in 5% polymeric water solution and the one quenched in oil is not so significant. The characteristic shown for the:
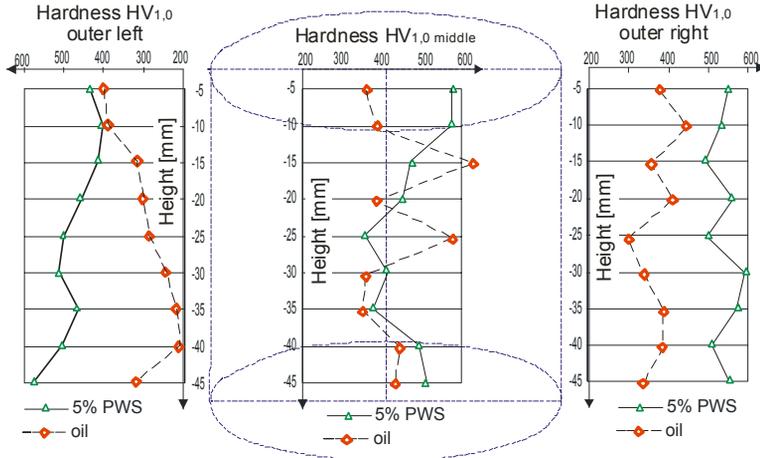
Fig. 10. *Microhardness deviations in axial direction on the specimens' surface areas and in the longitudinal cross-section after quenching in 5% polymeric water solution and in "Olmakal Rapid 90" oil*

- specimen quenched in 5% polymeric water solution shows minor deviations throughout the height of the specimen which reaches the max. value on the top face and the min value on the region on the middle of the height of the specimen. The hardness measured for the specimen quenched in oil displays extreme deviations throughout the height of the specimen and reaches at certain points an even higher value (613 $HV_{0.1}$) than for the specimen quenched in 5% polymeric water solution.

- The deviation of microhardness reflects certain statistical principles and meets expectations to a certain extent. However, the values reach their maximum close to the center and not at the edge of the specimen when quenching in both quenching agents.

The results related to the deviations of hardness at the cylindrical-specimen surface or over the central part of the specimen in the longitudinal and transverse directions indicate differences in hardness deviations due to irregular quenching along the specimen.

2 CONCLUSIONS

The paper treats the results of steel quenching in different quenching media obtained from the sound signals captured with the hydrophone. The analysis of sound emission offers a new approach to processing, evaluation and optimization of the quenching process. The
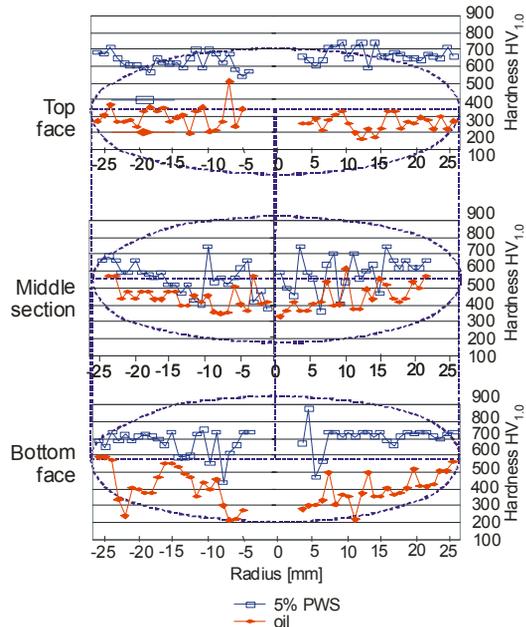
Fig. 11. *Microhardness deviations in radial direction on the specimens' surface areas and in the middle cross-section after quenching*

sound-pressure signals described with the voltage-signal amplitude were detected with the hydrophone and shown in the diagrams as a time-dependent amplitude. The analysis results confirm that there are important differences in the amplitude and frequency of the detected signals,

which is indicated by the formation and decay of the vapour film at the specimen surface as well the occurrence of nucleate boiling at the specimen/quenching-medium interface during quenching. The sound emission occurring during quenching is found predominantly in the audible range of the spectrum; therefore, detecting of emission is efficient since the phenomena at the interface can be monitored. The phenomena at the interface play an important role in the heat removal from the workpiece, which means that quenching effects with deviations in hardness and residual stresses in the cylindrical specimens can also be detected. The investigation conducted shows that the proposed experimental system for detecting sound emission and temperature at the specimen enables obtaining useful information from a voltage signal, although the phenomena during quenching are fast. The method proposed shows efficient monitoring of sound emission at the interface by means of evaluating the amplitude values and frequencies of the detected signals and provides useful information on the quenching process.

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