J. PREZELJ, M. ČUDINA

ISSN 0543-5846
METABK 50(1) 37-40 (2011)
UDC – UDK 534-7:621.791=111

A SOUND PRESSURE FIELD DURING THE QUENCHING OF A STEEL SPECIMEN IN DIFFERENT WATER SOLUTIONS

Received – Prispjelo: 2009-11-16
Accepted – Prihvaćeno: 2010-04-20
Preliminary note – Prethodno priopćenje

The purpose of controlling the quenching process of an orange-hot steel workpiece is to ensure its required surface hardness. A sound in a cooling liquid generated by the quenching process was experimentally analyzed. It contains sufficient information about the ongoing process for its quantification, and it can be used in real time. Traditionally, the quenching and the resultant hardening can be controlled by selecting different process parameters, like, for example the characteristics of the cooling liquid, the velocity of the cooling liquid flow, its temperature, the temperature of the work-piece, and many others. The possibility of controlling the quenching process by using acoustic cavitation is considered in this article.

Key words: acoustic cavitation, quenching, steel hardening; ultrasound

Upotreba zvuka za monitoring i kontrolu kaljenja čeličnog uzorka u različitim vodenim rastopinama. Svrha nadzora procesa kaljenja užarenog čeličnog uzorka je omogućiti zahtijevanu površinsku tvrdoću. Eksperimentalno je bio analiziran zvuk koji se generira u rashladnoj tekućini za vrijeme procesa kaljenja. Utvrđeno je bilo da generirani zvuk sadrži mnogo informacija o samom procesu kaljenja, koje se mogu koristiti za njegovu kvantifikaciju u realnom vremenu. Tradicionalno se je proces kaljenja i posljedično otvrđivanja površine kontroliralo sa izborom različitih parametara procesa kaljenja, kao što su na primjer karakteristike rashladne tekućine, brzina protoka rashladnog sredstva, njegove temperature, temperature uzorka i tako dalje. U tom radu je bila istraživana mogućnost kontrole procesa kaljenja čeličnog uzorka u realnom vremenu sa upotrebom akustičke kavitacije.

Ključne riječi: akustička kavitacija, kaljenje, kaljenje (otvrdnjavanje) čelika, ultrazvuk

INTRODUCTION

The production of machine parts usually ends with some kind of a heat treatment. A proper heat treatment, like quenching, provides increased surface hardness, which improves wear resistance. The quenching process must be fast to achieve the required hardness, but not too fast to prevent surface damage. Monitoring of the quenching process in real time, and an appropriate control can improve the quality of the production. During the quenching process different stages of heat transfer occur (Figure 1). The appearance of the individual stage depends on the process parameters and on the properties of the work-piece. The quenching of a steel work-piece always starts from temperatures over 800 °C (austenitizing temperature). At the beginning of the immersion, the cooling liquid is vaporized and a stable film of vapour is formed around the work-piece, keeping its surface dry, (the film boiling or vapour blanket stage). The vapour film collapses chaotically and causes an uneven heat removal from the surface, [1]. A nucleate boiling occurs where the surface cools down below the Leidenfrost temperature and the cooling liquid wets the surface. The convective heat transfer stage is followed by the nucleate boiling stage, [1, 2]. All three stages can coexist simultaneously on different surfaces of the work-piece, and even on different areas of the same surface. A distribution of these three cooling stages determines the heat transfer from the work-piece into the

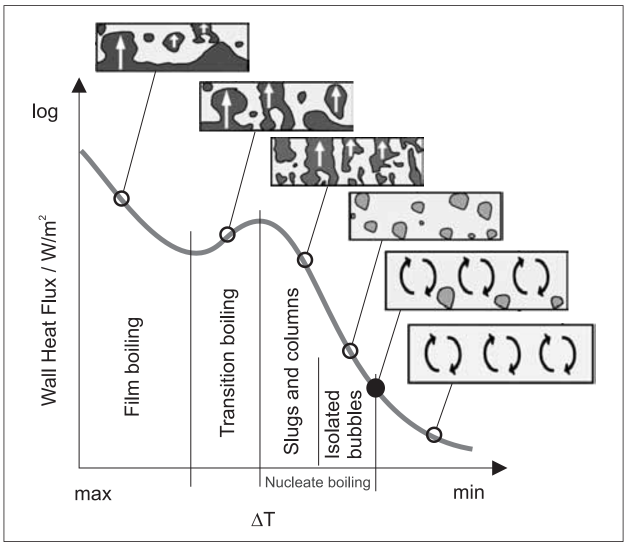

Figure 1 Nukiyama boiling curve and different stages of boiling (heat transfer)

J. Prezelj, M. Čudina, University of Ljubljana, Faculty of Mechanical Engineering, 1000 Ljubljana, Slovenija

cooling liquid. The measurement of the heat transfer in real time is essential for the control of the quenching process in real time.

Stoebener, developed an ultrasound system for recording the wetting behaviour of work-pieces submerged in quenching oil, [3]. Osborne examined the behaviour of a hot wire submerged into water. He found that sound pressure amplitude depends on different thermal flows, and that the acoustic spectra depend on wire thickness and materials, [4]. Misch [5] examined the sound emitted at sudden heating of the hot wire with simultaneous bubbles formation. Tomšič [6] examined sounds generated in boiling water next to the hot wire, under different thermal conditions. Based on the presented studies [3, 4, 5, and 6], a sound was identified as an appropriate signal for the observation of the quenching process.

It is known that an acoustic cavitation affects the heat transfer from the superheated surface into the cooling liquid [7, 8]. Therefore, the possibility of using the acoustic cavitation for controlling the quenching process of the orange-hot work-piece made of steel was investigated.

Traditionally, bubbles are formed only by thermal cavitation during the nucleate stage of boiling. A motility of bubbles is necessary to achieve an effective heat transfer. Acoustic cavitation increases the number of bubbles, affects their size, and increases their motility [9]. It was found out that the density of acoustic cavitation bubbles plays a critical role in enhancing the heat transfer. The enhancement of heat transfer by acoustic cavitation is stronger in the last convection regime than in boiling heat transfer regimes. It is because when convection occurs without acoustic cavitation, no bubbles are present to bring the cold fluid to the hot specimen surface by their motility, [7].

EXPERIMENTAL PROCEDURE

Cold specimens were heated up to the austenitizing temperature of 850 °C. An individual specimen was removed from the furnace with heated pliers and inserted into the measuring point inside the quenching medium. The time interval between the specimen removal from the furnace and its placing at the measuring point was as short as possible and never exceeded 2 seconds.

Specimens were made from chromium molybdenum low alloy steel with a medium content of carbon (42CrMo4). This steel is characterized by good hardenability. Specimens had cylindrical shape with 18 mm in diameter and 20 mm in length. Quenching was performed with different polymeric water solutions: 0 %, 5 %, and 15 % of *Aquatensid-BW*. An ultrasonic cleaning channel was used as a quenching container. The electric power of ultrasonic transducers in the ultrasonic cleaning channel was 800 W. A hydrophone B&K type 8103 was immersed into the ultrasonic cleaning channel filled with the cooling liquid. It was connected to the preamplifier B&K type 2636. Acoustic signals were directly recorded with 24 bit resolution and with 100 kHz sampling rate. LabVIEW software environment was used for the recording and analysis of acoustic signals. The duration of recordings was adapted to the intensity and to the duration of quenching. It lasted from few seconds up to two minutes.

ACOUSTIC SIGNAL ANALYSIS

All recorded acoustic signals exhibit similar properties, but they also significantly differ from each other. They all start with an abrupt amplitude increase. Then the amplitude decreases towards a background level. A decreasing rate strongly depends on the type of the cooling liquid.

A typical acoustic signal is presented in Figure 2. The amplitude ratio between the maximum level at the start of the quenching and the background noise level at the end of the quenching is sufficient to identify the different stages of the quenching process.

1. At the first contact between the orange-hot specimen and a cooling liquid a vapour film forms around the specimen. The formation and oscillation of this vapour film generates sound with high amplitude in a broad frequency range. As the specimen surface gradually cools down the oscillations of the vapour film also slows down, and the amplitude steadily decreases.
2. When the vapour film breaks apart, the temperature of the specimen surface is still much higher from the boiling temperature of the cooling liquid. Where the cooling liquid contacts the specimen surface, sound is generated. The amplitude of the acoustic signal therefore slightly increases during this, so-called, žtransition boiling.'
3. After the vapour film completely disintegrates, the cooling liquid gets in contact with the hot specimen surface. A heat transfer increases be-

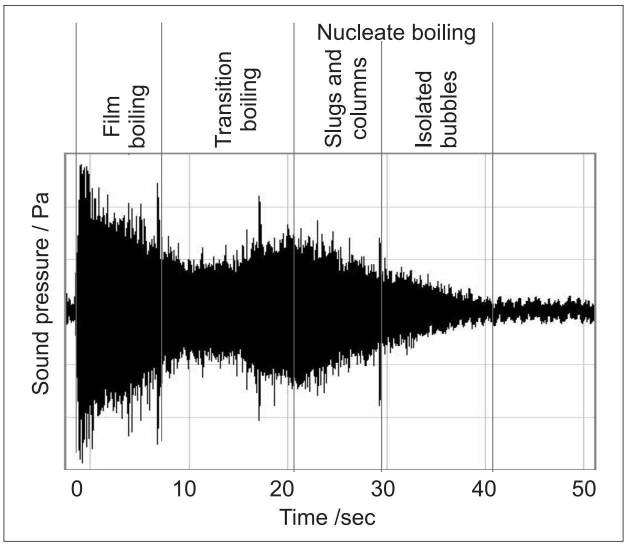

Figure 2 Typical sound pressure signal of quenching in water

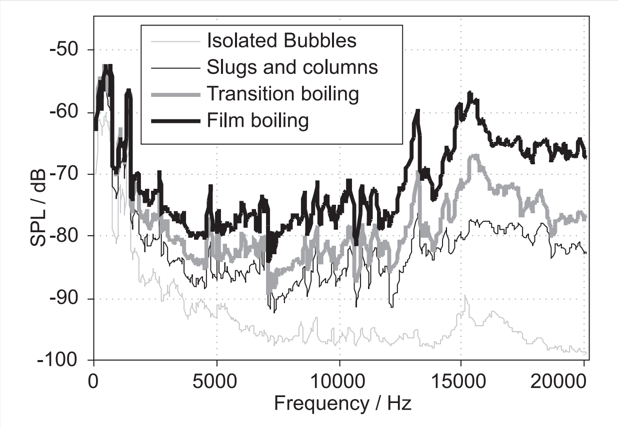

Figure 3 Frequency spectra of typical sound pressure signals in different stages of quenching with pure water

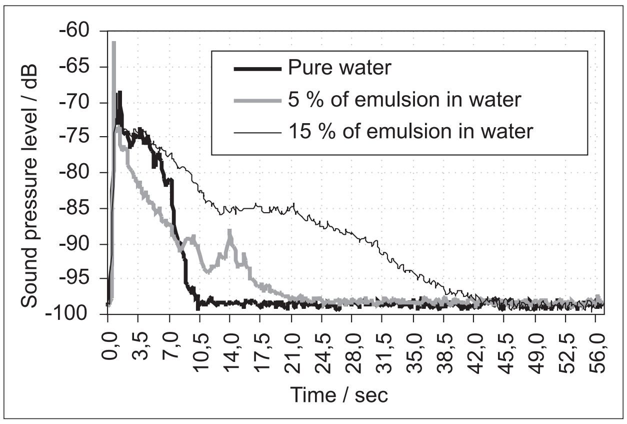

Figure 4 Time chart of acoustic signal in frequency range from 15 kHz to 20 kHz for different cooling solutions

cause the surface is wetted. The cooling liquid is locally vaporized. Bubbles are formed around the cavitations' nucleus. When the transition boiling and the nucleate boiling appear, the emission of vapour bubbles becomes smoother. In some experiments, the amplitude of the acoustic signal in the low frequency range had almost constant amplitude during this quenching stage.

4. Throughout the entire quenching process, individual sound pressure impulses can occur. A relaxation of internal tensions and/or residual stresses in the specimen causes some of these impulses, which can be easily heard.

The acoustic signal has different frequency spectra at different quenching stages. They are presented in Figure 3. During all stages a low frequency noise below 1000 Hz is present. In frequency range above 15 kHz, the signal to noise ratio increases to over 30 dB. The acoustic signal in this frequency range is correlated to bubble oscillations. Time charts of the acoustic signal, in frequency range above 15 kHz for different cooling liquids are presented in Figure 4. They clearly indicate that the quenching in pure water is the fastest. The whole process during the experiment ended in 9 seconds. The quenching with 15% emulsion is much slower, and lasted nearly 50 seconds. Time charts confirm that the quenching phenomena can be observed by the acoustic signal. Amplitude of the acoustic signal in a high frequency range (Figure 4) follows to the course of the Nukiyama boiling curve from the beginning of quenching process when the temperature difference between the specimen and quenching-medium is the highest, to the end of process, when the temperature difference is almost zero. Time chart of sound level corresponds to the measured results of temperature change with time for similar tests, [10].

QUENCHING IN ULTRASOUND

A strong ultrasonic field was used to generate the acoustic cavitation. Acoustic cavitation has a significant influence on the bubble behaviour. Bubbles are formed faster and they faster detach from the surface of the quenched specimen. A strong ultrasonic field has different effect on quenching process in different stages of the quenching [7]. A sound pressure level of ultrasonic field, for generation of acoustic cavitation, is much higher then a sound pressure level of noise, generated by the quenching. Therefore, it was impossible to detect noise of quenching during the generation of acoustic cavitation. Ultrasonic sound field, which was intended for tearing down the vapour film around the specimen surface, collapsed in the moment when orange-hot specimen was inserted into the cooling liquid. Ultrasonic sound field re-establish after the process of quenching finished. Vapour formations oscillate and generate sound in one hand. On the other hand, if they are subjected to strong sound waves they obviously act like sound absorbers.

Quenching in water with a flow velocity of 0,2 m/s is presented in Figure 5. The formation of the vapour film can be observed on the bottom side of the specimen in the form of a bubble. Additional small bubbles are attached to the surface of the specimen. Quenching in water with a flow velocity of 0,2 m/s and with an estab-

Figure 5 Quenching in flowing water

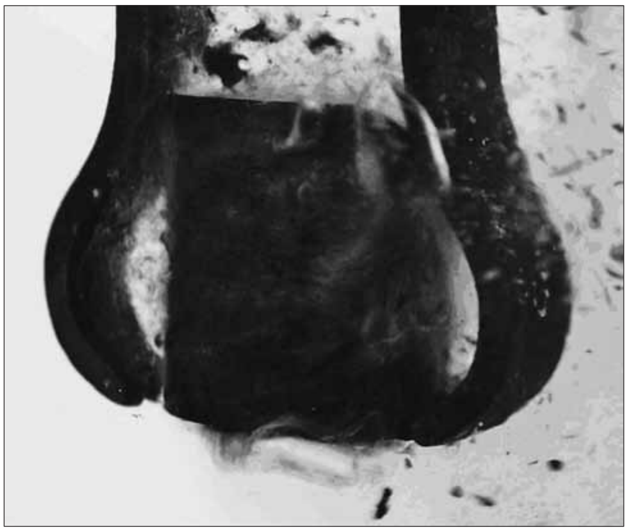

Figure 6 Quenching in flowing water and with acoustic cavitation.

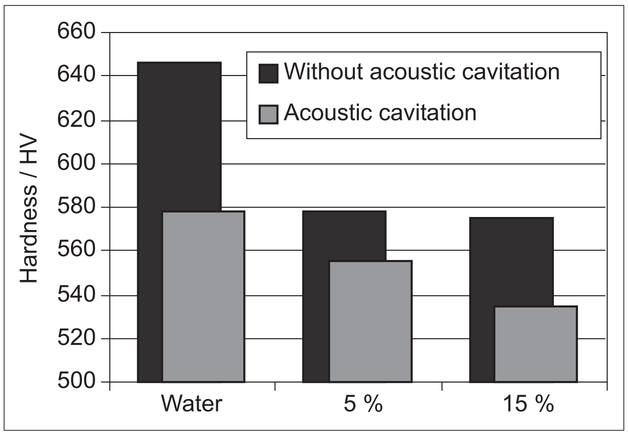

Figure 7 Hardness, achieved with and without acoustic cavitation

lished acoustic cavitation is presented in Figure 6. A strong ultrasonic field disintegrates a vapour film and small bubbles are detached from the surfaces.

Acoustic cavitation has significant influence on the heat transfer from the orange-hot specimen to the cooling liquid, and consequently on the achieved hardness of the specimen surface. Averaged values of the specimen hardness are presented in Figure 7 for different quenching parameters. The highest value of hardness is achieved with quenching in pure water without acoustic cavitation. Quenching in 5 % and 15 % solutions of emulsion without acoustic cavitation, produces lower values. However, the effect of acoustic cavitation on the final value of hardness is significant. According to Young *et al*. [7], the heat transfer is enhanced during the natural convection and during the pool boiling. The ultrasonic field does not accelerate the heat transfer in the very early stage of the quenching, when the process of the hardening is most active. On the contrary, it seems that the ultrasonic field accelerates the formation of vapour film in the early stage of quenching. The presence of a strong ultrasonic field reduces the hardening process. Similar results of the hardening process are achieved if a polymeric solution is used, or if water is used together with strong ultrasonic field.

CONCLUSIONS

Two aspects of using sound pressure in a heat treatment of material are described in this paper. Sound pressure signals generated by a quenching of the orange-hot specimen in different cooling liquids were recorded with a hydrophone. An analysis of recorded acoustic signals shows that it can be used for monitoring the quenching process in real time. A significant change in the signal shape corresponds to a formation of a vapour film on the specimen surface, and to the appearance of the nucleate boiling. An acoustic signal can be used to determine the stage of the quenching and the type of the boiling. Therefore, the acoustic signal can be used as a tool for monitoring, controlling and optimising the quenching and hardening process. The possibility of applying the acoustic cavitation during the quenching and hardening process was also tested. Results show that the acoustic cavitation significantly affects the heat transfer from orange-hot specimen surface into the cooling liquid in the early stage of quenching. The ultrasonic field can be therefore used as a method for controlling the hardening process.

REFERENCES

[1] H. M. Tensi: Theory and Technology of Quenching, Springer-Verlag, Berlin, 1992

[2] H. Auracher: Some Remarks on the Nukiyama Curve, JSME-TED Newsletter, 42 (2003), 1-6

[3] D. Stoebener, G. Goch: Wet-state Ultrasonic Measurements of Cylindrical Workpiece during Immersion Cooling, Materialwisenschaft und Werkstofftechnik, 37 (2006) 1, 69 - 75

[4] M. F. Osborne: The Acoustical Concomitants of Cavitation and Boiling Produced by a Hot Wire, Journal of Acoustical Society of America, 19 (1947), 21-29.

[5] F. H. Misch: Acoustical Measurement of Incipient Boiling, PhD thesis, University of Berkeley, 1963

[6] M. Tomšič: Acoustic Phenomena in Boiling, PhD thesis, University of Ljubljana, 1983

[7] H. Y. Kim, et al.: Enhancement of Natural Convection and Pool Boiling Heat Transfer via Ultrasonic Vibration, International Journal of Heat and Mass Transfer 47 (2004) 2831–2840

[8] D. W. Zhou: A Novel Concept for Boiling Heat Transfer Enhancement, Journal of Mechanical Engineering, 51 (2005) 366-37

[9] T. G. Leighton: The Acoustic Bubble, Academic Press, San Diego, 2001

[10] L. Pedišic, et al.: Effects of Concentration Water Miscible Metalworking Fluids on Cooling Rate, Goriva i maziva, 47(6), 2008, 437-462.

Note: Proofreading by English native speaker: Robert McKenzie, The Slovenia Times - Domus d.o.o.