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USE OF AUDIBLE SOUND FOR ON-LINE MONITORING OF GAS METAL ARC WELDING PROCESS

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In this paper sound generated during the gas-metal arc welding process was studded. Experimental analyses of the acoustic signals have shown that there are two main noise-generating mechanisms, first having impulse form is arc extinction and arc ignition; the second is the arc itself acting as an ionization sound source. The sound signal is used for assessing and monitoring of the welding process, and for prediction of welding process stability and quality. A new algorithm based on the measured welding current was established for the calculation of emitted sound during the welding process. The comparisons have shown that the calculated values are in good agreement with the measured values.

Key words: welding, welding current, noise, prediction

Čujni zvuk kao signal za izravnu kontrolu elektrolučnog procesa zavarivanja. U radu je istraživan čujni zvuk, koja se generira kod procesa elektrolučnog zavarivanja po MAG postupku. Eksperimentalna analiza zvučnog signala je pokazala, da se javljaju dva glavna mehanizma generiranja zvuka, prvi, koji ima karakter impulza, je posljedica paljenja i gašenja električnog luka (plazme); drugi je sam električni luk, koji djeluje kao ionizirajuči izvor zvuka. Zvučni signal je upotrijebljen za ocjenjivanje i nadzor procesa zavarivanja, te za ocjenjivanje kvalitete i stabilnosti procesa zavarivanja. Razvijen je novi matematički model za izračun emitiranog zvuka kod procesa zavarivanja a koji bazira na izmjerenoj struji zavarivanja. Usporedba izračunanih i izmjerenih vrijednosti zvučnog signala je pokazala veliku suglasnost.

Ključne riječi: zavarivanje, struja zavarivanja, buka, izračun

INTRODUCTION

Today the most frequently used arc welding process is the gas metal arc welding (GMAW) process. The process is suitable for automation and mobilization [1]. But, unfortunately, during GMAW there are other high intensity side effects of, such as heat, light and sound or noise. At the same welding parameters audible noise can rise at welder ear above the daily permissible level, 85 dB(A). Measurements have shown that equivalent sound pressure level can exceed even 100 dB(A) at the welder ear. On the other hand, the noise can be used for monitoring the quality of the welding process as well as for checking for anomalies in the welding process.

To maintain and direct the welding arc an experienced welder uses his senses, especially eyes and ears to combine visual and audible information [2]. The significance of sound in monitoring the arc welding processes has been known for a long time, but relatively few studies have been published in which sound waves are regarded as a source of information for monitoring the welding process.

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Erdmann and Jolly [3, 4] published the first study on acoustic waves generated during the GMAW process in 1967. They discovered that sound pressure increases with arc length and welding current. Twenty years ago, Arata et al. [5, 6] performed important measurements and concluded that the sound traveling into the sample and into the surrounding air has influence on the welding process by affecting the behavior of the molten pool. They also discovered that sound waves are synchronized with short-circuiting. Some attempts to use acoustic signals for on line monitoring of submerged arc welding were presented by Mayer in 1987 [7]. In 1990 Rostek [8] used computer-aided acoustic pattern recognition to test the monitoring capabilities of acoustic signals. In 1996 Grad et al. [9, 10] developed a monitoring method using different statistic parameters to evaluate welding process stability.

Adaptive control of welding parameters, based on audio signals only, is still unrealized in industrial environment. Some authors [6, 8, 11] believe that background noise obstructs analysis of measured signals and might be considered as one of the most important obstacles for the acoustic monitoring technique.

Grad and Kralj [9, 10], our earlier research efforts [12-14] and the present study have been focused on establishing a theoretical and experimental base to implement acoustic monitoring of the welding processes in industrial environment. By detailed analysis of each part of the acoustic signal, we tried to find the correlated sound source in time and space. Only investigations of audible sound generated during GMAW in short circuiting mode are discussed in this paper.

SOUND GENERATED DURING GAS METAL ARC WELDING PROCESS

In the GMAW process an electric arc is established between consumable wire electrodes and a melted zone on the welding material. Both are shielded by gas in the form of active CO_2 or gas mixtures containing Ar, CO_2, etc. The power source usually has constant static voltage characteristic of $U = f(I) = const.$ At constant adding velocity of consumable electrode the result is a stabile arc length. This phenomenon is known as a principle of internal self-regulation [15, 16].

The electrical circle of the welding system (power supply, cable, consumable wire, arc and welding material) consists only of the basic elements: resistance R in Ohms (Ω), inductance L in Henrys (H) and capacitance C in Farads (F). A suitable equation for describing the electrical scheme can be obtained by using the second Kirchoff's law:

$$U = RI + L\frac{dL}{dt} + \frac{R_a I}{1 + j\omega C_a R_a} \quad (1),$$

where I is the electric current in Amperes (A), U is the equivalent open-circuit voltage supply in Volts (V), R_a and C_a are the resistance and capacitance of the arc and is the angle frequency. The capacitance of the arc C_a in Eq. (1) can, owing to very small value, be neglected, and since the arc is responsible for noise generation we expressed the arc voltage U_a explicitly as

$$U_a = R_a I = U - RI - L\dot{I} = U - U_R + U_L \quad (2).$$

Morita et al. [17] and Kim et al. [23] published different phases of material transfer during the GMAW process, in short circuit mode and in dependence on the arc formation. The corresponding welding current is presented in Figure 1.

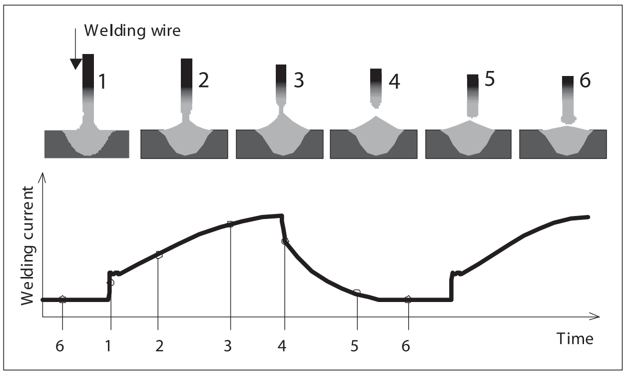

Figure 1. Description of different phases of material transfer during GMAW in short circuit mode

At points 1, 2 and 3 in Figure 1. there is no arc, whereas at points 4, 5 and 6 an arc is formed. In points 1, 2, 3 and towards point 4 a consumable electrode is in contact with the molten pool; this period of short circuit is depicted as a welding current peak.

As accompanying phenomena during the GMAW process, more different sound sources appear simultaneously and/or successively. They have different characteristics and they differ in time and form of appearance. With regards to time, there are two characteristic time intervals of noise generation. The first is the short circuit that ends with arc ignition (see points 1 to 4 in Figure 1.) and the second is the oscillations of the burning arc that ends with arc extinction (points 4 to 6 and 1 in Figure 1.).

According to the form of appearance, emitted sound can be in a form of sound impulse and in a form of so-called "turbulent" noise. The sound impulse is connected with the rapid current changes and has two origins. The first origin is a result of short-circuiting between the electrode and welding material, and arc extinction thereof, which is accompanied by partial spraying of the molten drop when it strikes the molten pool (see point 1 in Figure 1.). The second origin of sound impulse is a result of tearing off the molten drop from the welding electrode and sudden arc ignition (spark ignition) which causes a rapid increase in temperature and expansion of shielding gas around the arc, causing a strong pressure pulsation in the surrounding air, (see point 4 in Figure 1.).

The "turbulent" noise is the result of many processes and mechanisms that generate sound or have influence on sound wave propagation. Among them the oscillation of the arc, the electrode and the molten pool, as well as racking of the material's due to inner tension relaxation are the most important.

In industrial environment, sound impulse as well as "turbulent" noise are contaminated by background and reverberation noise. In any case, the sound impulse generated during the arc ignition (point 4 in Figure 1.) is the most dominant noise source during the welding process.

Among different types of sound impulses, the arc (spark) ignition generates N-shaped impulse noise or "shock waves" [19]. The core of the spark is heated up to 24 000 K, and expansion speed of the shock wave is over 1000 m/s [22]. As a consequence of rapid increase of temperature, a strong pressure oscillation appears which causes the sound impulse.

Some authors tried to find a correlation between the emitted sound pressure and the arc volume, and other studies have revealed, that amplitude of sound pressure $p(t)$ is correlated to the electrical power (UI) supplied to the arc [18, 20, 21]:

$$p(t) = C_1 \frac{d}{dt}(U_a I) \quad (3),$$

where C_1 is the factor of proportionality, which depends on the distance between microphone position and the arc, and velocity of sound in the arc.

By substituting equation (2) into equation (3) the next equation follows:

$$p(t) = C_1 \frac{d}{dt}\left[\left(U - RI - L\dot{I}\right)I\right] =$$

$$C_1\left[U\dot{I} - 2RI\dot{I} - L\left(\dot{I}^2 + I\ddot{I}\right)\right] \qquad (4),$$

Equation (4) is a transfer function between the welding current (I) as an input into the welding process and emitted sound pressure $p(t)$ as an output from the welding process. The transfer function allows us to compare the welding current with the generated sound pressure.

MEASUREMENT SETUP

Experimental set-up is shown in Figure 2. Standard industrial welding equipment was used in the experiments. As power supply an Iskra E-450 with constant static voltage characteristics was used, the consumable wire was electrode VAC 60, ϕ = 1.2 mm, and the shielding gas mixture was CORGON (82 % Ar and 18 % CO_2). Two different materials (low carbon steel and structural steel) and two different supply voltage (U_1 = 40 V and U_2 = 50 V) were used in the experiment. An A/D converter with a sampling rate of 48 kHz per channel and with 16-bit data resolution was used for data acquisition. Twenty seconds of welding process were recorded for each single environment, and stored on hard disk. The welding current was measured via a shunt resistor. A half-inch B&K, type 4134 microphone was fixed to the welding head on a distance of 0,35 m from the arc in order to maintain constant distance from the welding process. This distance is approximately equal to the distance of the welder's head from the arc, which means that the measured signal of noise can also be used for assessing the effect of welding noise on the welder.

EXPERIMENTAL RESULTS AND DISCUSSION

In Figure 3. the measured welding current (above) and sound pressure signal (below) during the GMWA process with regards to time are presented. The welding current signal consists of peaks, which are connected with short circuits. The sound signal consists of short impulses separated by long-term "turbulent" noise; see also Figure 4. There are two different sound impulses and they are in correlation with the welding current peak. The first appears in a moment of short circuit arc extinction (smaller inexpressive one) and the other appears in a moment of arc ignition (the most powerful one). The first impulse (smaller one) can be neglected in comparison to the second larger one. The larger impulse, occurring at the end of the welding current peak, can thus be assigned to the corresponding welding current peak, see Figure 3. and 4.

From sound signal analyses it follows that between two sound impulse peaks due to arc extinction and arc ignition, under the welding current peak, the sound signal consists of just low-level background noise (denoted by background noise in Figure 4.). The sound signal between two successive impulses, between two welding current peaks, consists of turbulent noise, generated mostly by pulsation of the shielding gas in the arc (denoted by "turbulent" noise in Figure 4.). It has much higher level than the background noise. This denotes that the welding sound is generated and dominated by the arc itself, as already stated by many authors [1, 20, 21]. It is also obvious that the sound impulse is prevailing, its total level is far more than 10 dB(A) higher than the turbulent arc noise, and can, thus, represents the total emitted noise.

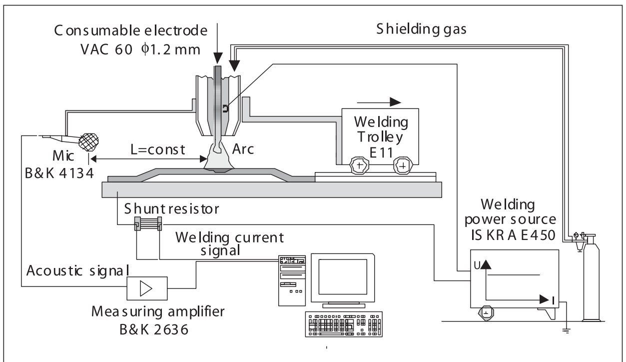

Figure 2. Experimental set-up of the GMAW process

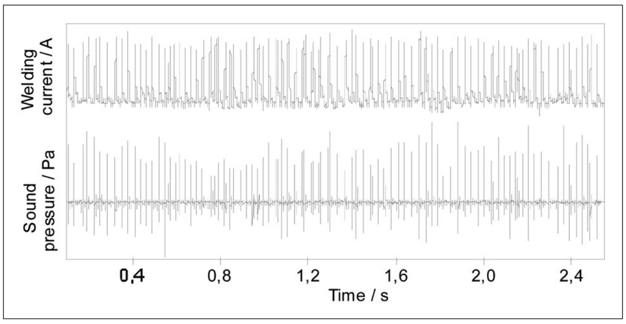

Figure 3. Welding current (above) and acoustic signal (below) during GMWA process

Amplitude of impulses can thus be used for on-line control of some parameters, as for example, sort of material, voltage supply or volume of the molten material [14], and therefore for control of welding process stability and quality.

NUMERICAL ANALYSIS

Equation (4) was used for calculation of the emitted sound pressure generated by the GMAW process. Values of the constants in Eq. (4), resistance R, inductance L and capacitance C, were determined by comparison of the calculated and measured values of the sound pressure using the least mean square (LMS) method.

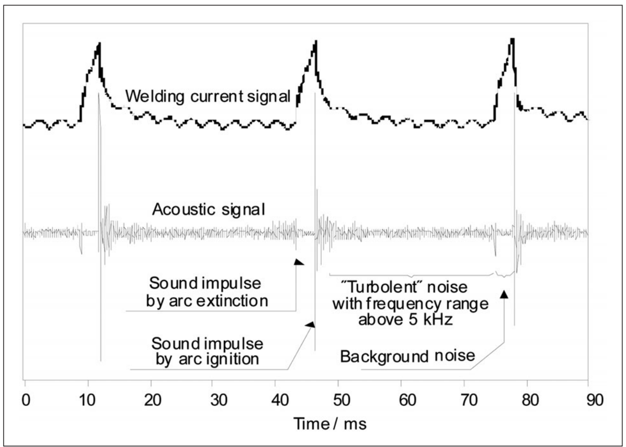

Figure 4. Three successive welding current peaks with corresponding sound impulses

The value of the constants (resistance R, inductance L and capacitance C) are changing over a longer time scale during stabile welding, due to instability in welding process, but detailed analyses have shown that these values (R, L, C), as well as the constant of proportionality C_1 in Eq. (4), can be treated as constant values for calculation of impulse sound. Using the average value of the constants, the emitted sound pressure was calculated and compared with the measured acoustic signal.

A comparison between measured and calculated values by using of Eq. (4) for four successive sound impulses is presented in Figure 5. Agreement between calculated values (thick curve) and measured values (thin curve) is quite good.

The proposed algorithm, represented by Eq. (4), can thus be used for calculation and prediction of the emitted noise during the GMAW process, and to calculate the total noise level. It can also be used for assessing the effect of the welding noise on the worker and for on-line monitoring and control of stability and quality of the welding process. Figure 6. shows a specimen of structural steel with a defect in the welding process, which is noticed in the welding current and sound pressure records. Figure 7. shows a point with the defect in the enlarged scale.

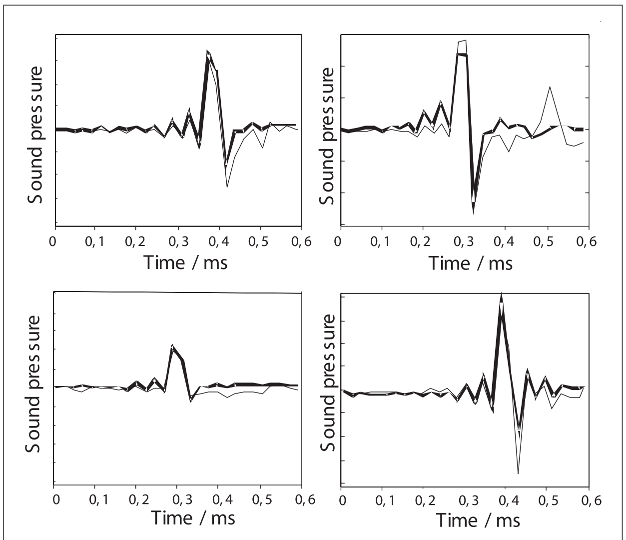

Figure 5. Comparison between measured values of four successive sound impulses (thin curve) and calculated values from welding current using Eq. (4) (thick curve)

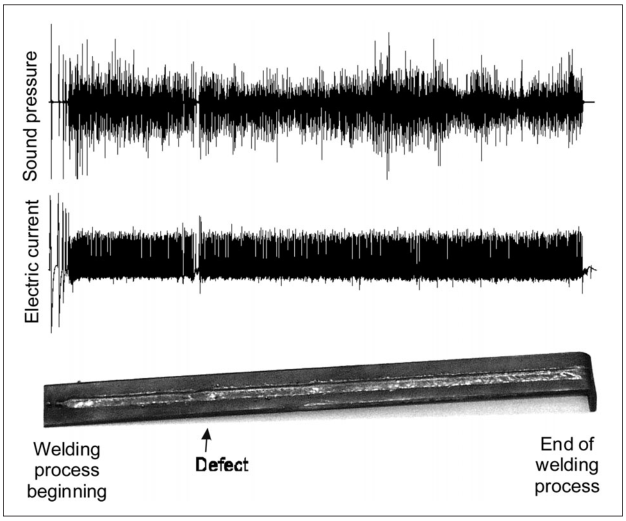

Figure 6. Specimen of structural steel with detail of the welding defect

The main advantage of the proposed algorithm, based on the current welding data, is that the calculated values are not contaminated by background and reverberation noise as is in the case of measuring noise in an industrial environment. Determination of welding noise using the proposed algorithm is thus more exact, robust and user-friendly.

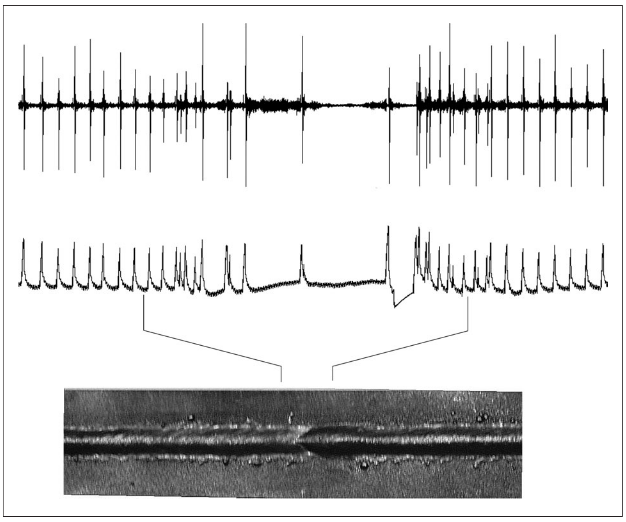

Figure 7. Enlargement of defect in welding process with the records of welding current and corresponding sound pressure

CONCLUSIONS

During the gas metal arc welding (GMAW) process noise emission is a side effect, which can rise for the welder above the daily permissible level of 80 dB(A). Therefore, theoretical and experimental analyses of the sound signal were performed in order to find the sound origin in time and space. There are two mechanisms that generate the overall noise during welding process: impulse noise and so-called "turbulent" noise. The impulse noise has its origin in short circuit arc extinction and arc ignition. The turbulent noise has different origins; the most important are: oscillation of the arc, the electrode and the molten pool, as well as racking of the material due to inner tension relaxation. The impulse noise is far more than 10 dB(A) higher then those containing the turbulent noise and so represents the dominant noise generating mechanism during the welding process.

A new algorithm for calculation of sound generated during welding process was established. The algorithm, which is based on measured welding current data, is also suitable for prediction of total emitted noise. The algorithm was verified on different welded materials (structural steel and low carbon steel). Comparisons have shown that the calculated values are in good agreement with the measured results. The main advantage of the proposed algorithm is that the calculated values are not corrupted by background noise as it is in a case of measuring of noise in industrial environment. Therefore, it is also suitable for on-line monitoring and control of welding process stability and quality.

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Note: Language lectur Terry Troy Jackson, Ljubljana, Slovenia.

Nomenclature

C	capacitance / F
C_1	factor of proportionality
I	electric current / A
L	inductance / H
p	sound pressure / Pa
R	resistance / Ω
t	time / s
U	voltage supply / V
ω	angle frequency / s^{-1}

Indexes:

$_a$	arc
$_I$	inductance
$_R$	resistance