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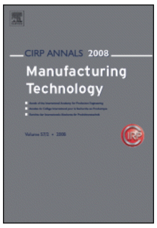

Applications of acoustic mapping in electrical discharge machining

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Abstract: The spatial distribution of discharges in electrical discharge machining (EDM) comprises valuable process information, which is not accurately obtained from electrical signals that are utilized extensively for process monitoring and control. This research hence explored the application of acoustic emission (AE) to map the discharges, in consideration of the acoustic time lag. In particular, the work refers to realistic process conditions, wherein AE from successive discharges cause repeated signal interference, which is detrimental to reliable time lag estimation. The applications of this capability for the respective identification of electrode length and workpiece height in fast-hole EDM and wire EDM are presented.

Keywords: Electrical discharge machining (EDM), Monitoring, Acoustic emission

1. Introduction

The conception and development of sophisticated online monitoring schemes continues to be a staple in further enhancing the performance of electrical discharge machining (EDM) processes. Presently, the information used to control EDM predominantly involves indices reflecting the state of the process that are derived from the voltage/current waveforms. This paper presents the proof-of-concept of the application of acoustic emission (AE) from the electrical discharges towards mapping their locations, which constitutes an important additional dimension in advancing intelligent adaptive control of EDM.

For instance, while the incidence of unfavourable arcing may in itself be identified from the electrical signals, the location at which arcing is manifest is not accurately obtained therefrom. Such information is indeed valuable as it enables the prospect of invoking such strategies as adaptive flushing to effectively annul arcing, towards enhancing process productivity and ensuring product quality. Likewise, considering that a stable EDM process is characterized by the constant and uniform excursion of the discharge location over and across the entire machining gap, the variance in the discharge locations may be considered [1] to be a control parameter that signifies process stability.

There have previously been a few attempts at mapping discharges in EDM using various means. Kunieda et al. [1] proposed routing the electrical energy to the tool electrode through 2 or 3 branches, depending on the problem being one-dimensional (wire EDM) or two-dimensional (planar sink EDM), so as to estimate the discharge location with reference to the ratio of the discharge currents channelled through them. As this method entails the electrical resistance between the spark location and the point of measurement, it is applicable only when the electrode is sufficiently large and is made of such materials as graphite with a relatively high electrical resistivity; furthermore, the fact that this method is effective only for fairly long pulse on-times discounts its application in wire EDM. In order to circumvent these limitations, Han et al. [2] subsequently proposed discharge location identification by considering the potential difference as opposed to the current between the branches. They showed that the accuracy with which a discharge is located is higher when the voltage towards the end rather than the beginning of the pulse is taken into account, as the corresponding noise is fairly lower; this notwithstanding, the location accuracy was on the order of 10 mm.

Qiang et al. [3] presented a non-contact method with a location accuracy similar to that above, which relies on a comparison of the relative intensities of the electromagnetic signal from the discharge, measured using Hall sensors. This method is somewhat limited by the need for a magnetic field concentrator to compensate for the exponential signal attenuation, and the computational overhead associated with the processing of high-frequency electromagnetic signals that need be acquired at rates as high as 30 MHz per channel. Okada et al. [4] obtained sub-millimetre accuracy while mapping the discharge distribution in wire EDM using direct high-speed digital imaging of the machining gap using a specially-configured experimental set-up; such an arrangement is however not practical in a manufacturing environment.

Conceptually similar in principle to the present work, Ydreskog and Novak [5], and Muto et al [6] reported on the feasibility of locating discharges by considering the time lag associated with the discharge-induced AE, in reference to the speed of sound in the material through which the acoustic wave propagates. Using AE sensors with a resonant frequency of 20 MHz, Muto et al [6] showed that discharges could be located to within 0.3 mm in steel workpieces. While this technique is viable for single, isolated discharges, repeated superposition of acoustic waves from a train of discharges that pertain in practical process conditions severely convolutes and obscures the acoustic signal, thereby precluding reliable estimation of time lags.

The present research focussed on solving this issue by considering the evolution of the frequency content of the AE from the discharges. On development of the capability for locating discharges under realistic process conditions, the applications of the technology is demonstrated in solving two industrially-relevant problems relating to the assessment of electrode length and workpiece height in fast-hole EDM and wire EDM, respectively.

2. Experimental

This work involved two stages: (i) single discharge experiments conducted to characterize the speed of propagation of AE in the wire/electrode material, and (ii) application experiments that utilized this speed information for discharge mapping. The fast-hole and wire EDM operations were appropriately simulated on a sink EDM machine tool. AE signals were acquired at a sampling frequency of 10 MHz, using commercial sensors with a fairly uniform sensitivity in the range of 100 kHz to 900 kHz. The corresponding discharge current signals were collected with a Hall sensor. Fast-hole EDM experiments referred to pulse on- and off-times of 12 µs each, and a discharge voltage and current of 80 V and 13 A, respectively, which are typical for the 0.3 mm diameter electrode used. Experiments referring to workpiece height identification in wire EDM involved a stationary wire, and featured a pulse on-time of 1.12 µs, a pulse off-time of 10 µs, and a discharge voltage and current of 80 V and 10 A, respectively, in order to avert failure of the 0.25 mm diameter wire used.

3. Results and discussion

Fig. 1 shows AE emanating from a single discharge on a wire, acquired using 2 sensors at either end, along with the corresponding current signal for reference. Although the electromagnetic interference (EMI) picked up by the AE sensors and superimposed on the AE signals is essentially noise, it can be seen to offer a useful datum signifying the instance of the discharge, by virtue of it aligning with features in the current spike. The actual discharge location being offset and closer to sensor 1 is clearly brought out by the onset of the AE signal from sensor 1 preceding that from sensor 2. The difference in the acoustic paths between the sensors and the point of discharge is further denoted by the relatively lower magnitude of the signal from sensor 2, consequent to the attenuation in the AE signal.

Such prospects aside, several critical issues need be addressed before these characteristic observations may be usefully applied for the spatial mapping of discharges in EDM. Firstly, discharges

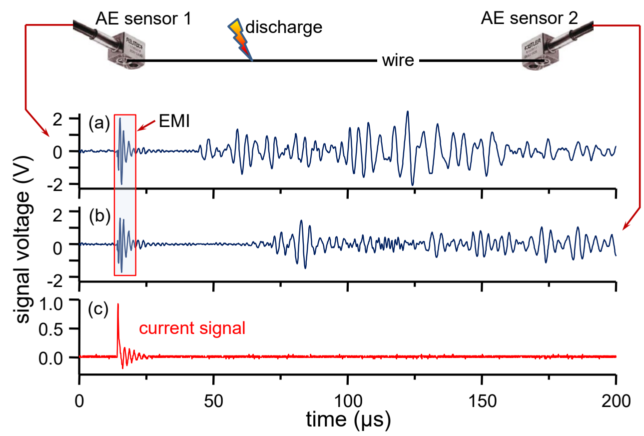

Fig. 1. Signals from: (a) & (b) AE, and (c) current sensors.

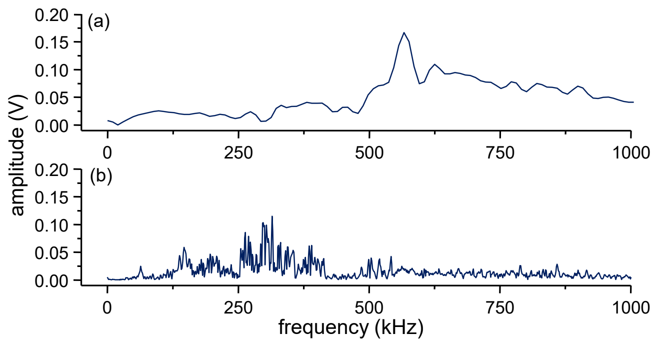

Fig. 2. Frequency spectra of: (a) EMI, and (b) AE signals.

repeated at a known location indicated issues with identifying the onset of the acoustic wave in terms of predefined threshold crossings or the first peak in the AE signal, as these do not provide a repeatable datum with respect to which the time lag may be precisely determined. For offset discharges (such as in Fig. 1), the disparity in the signal magnitudes further renders the application of techniques such as cross-correlation to be ineffectual, as they rely on the correspondence between the two signals. Secondly, noting that the AE from a single discharge is active for a period of time in excess of 150 µs (Fig. 1), which is longer than typical pulse off-times employed in EDM, AE from successive discharges brings about repeated self-interference in the signal, which leaves time lag estimation to be acutely problematic. Increasing the pulse off-time at regular intervals may be considered to address this issue, but for this incurring a penalty on the machining rate.

An insight into formulating a reliable frame of reference for the onset of an AE wave in the presence of interference from overlapping AE packets and EMI may be gained by an examination of the frequency content of the AE signal, and its evolution over time. A Fast Fourier Transform of the EMI (Fig. 2a) and AE (Fig. 2b) components indicates the frequency spectrum of the latter to be largely confined to the 200−400 kHz interval with a maximum amplitude in the vicinity of 300 kHz, while the EMI is essentially manifest at frequencies upwards of 500 kHz. Variations in the frequency content of the AE over time may be obtained using a Short Time Fourier Transform (STFT) of the signal. A typical spectrogram shown in Fig. 3 depicts the EMI to be discernible at approximately 25 µs, with the acoustic wave commencing shortly thereafter and eventually attaining the maximum intensity at about 80 µs.

An investigation involving a multitude of AE signals indicated this peak in the spectrogram to constitute a consistent reference on the acoustic wave, from which to estimate the time lag with respect to the spike in either the current or the EMI. Identification of the peak in the spectrogram may be facilitated by considering a specific frequency, say 300 kHz, which refers to the maximum amplitude in the frequency spectrum of the AE signal (Fig. 2b). The average of 20 time lags each measured thus at known locations are depicted in Fig. 4, for two different wire types. The inverse of the slopes of these characteristics refer to

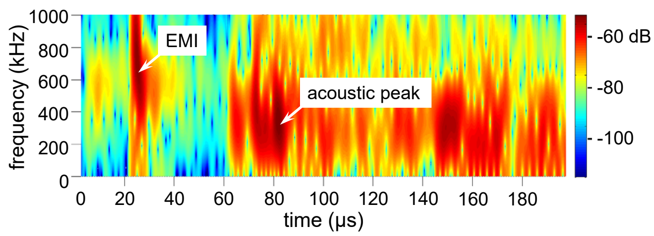

Fig. 3. Spectrogram of a typical AE signal.

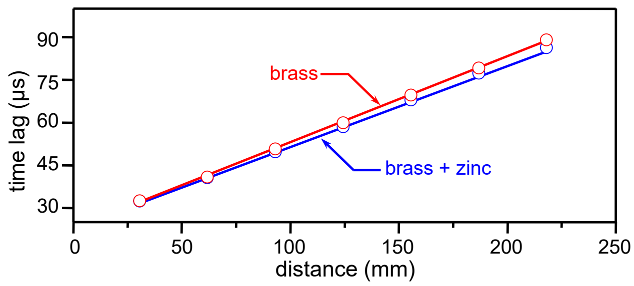

Fig. 4. Speed of sound calibration for brass and zinc-coated brass wires.

the speed of sound in the corresponding wires: 3299.4 m/s for brass and 3452.2 m/s for zinc-coated brass. The latter is higher due to the faster speed of sound in the zinc constituent [7]. In decreasing order of velocity, propagation of AE entails longitudinal, shear and surface (Rayleigh) wave modes, which for a thin wire/electrode may be consolidated to correspond to an equivalent velocity. It is to be noted that the calibrated speed of 3299.4 m/s for brass is lower than its equivalent velocity of 3480 m/s [7], on account of the peak in the spectrogram (Fig. 3) that serves as the reference point for the estimation of time lag being downstream from the actual onset of the acoustic wave.

The ability to discern the exact onset of the AE wave is further limited by the sensor bandwidth, and of the three wave modes alluded to previously, the AE sensor used in the present work is mostly sensitive to the longitudinal and Rayleigh modes. Aspects above are signified by the non-zero intercept in the linear characteristics in Fig. 4. Nevertheless, as a substantial advance over the state of the art [5,6], the present work shows that it is indeed expedient to rely on a relative measure as opposed to the absolute speed of sound, with the favourable implication that discharge mapping may be realized by using commercial sensors rather than those that are purpose-built to conform to a markedly expansive bandwidth.

Experiments to calibrate for the relative speed of the acoustic wave (Fig. 4) entailed single discharges with no interference from subsequent discharges, by setting the pulse off-time to be much higher (1000 μs) than the time for which the acoustic wave from the discharge is active (~200 μs). This is however not the case in practice, and hence the efficacy of the application of the fiducial reference developed in this work to instances wherein successive discharges significantly convolute the AE signal was investigated. Fig. 5a shows the AE signal corresponding to two discharges struck 12.9 μs apart, which depicts the EMI features to be distinctive while the AE signatures are largely confounded.

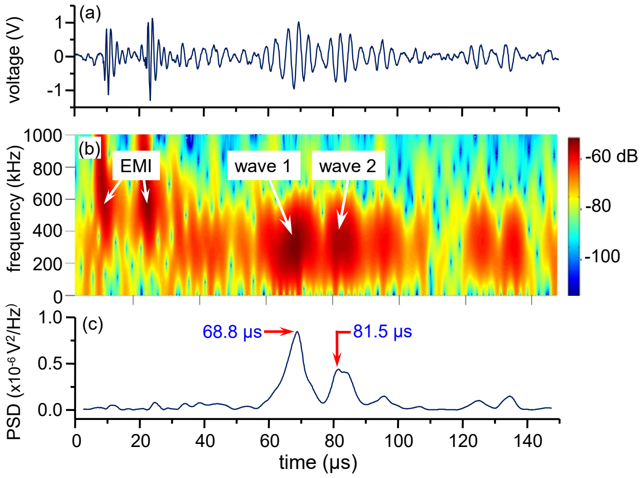

Fig. 5. (a) AE signal from 2 discharges 12.9 μs apart; (b) the corresponding spectrogram, and (c) power spectral density at a frequency of 300 kHz.

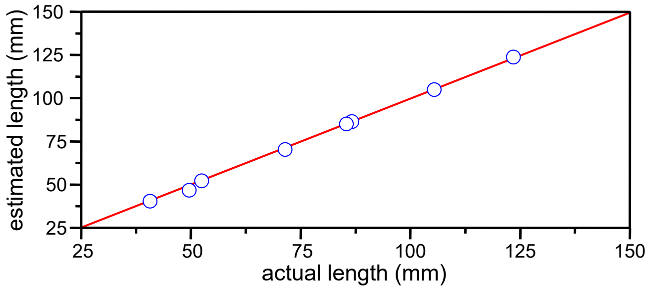

Fig. 6. A comparison of actual and estimated electrode lengths.

The two acoustic waves are but well resolved in the spectrogram (Fig. 5b), and the consecutive peaks in the corresponding power spectral density (Fig. 5c) that refers to a frequency of 300 kHz indicates the time difference to be 12.7 μs. The ensuing error of 0.2 μs in the time lag corresponds to a location inaccuracy of just 0.07 mm in reference to the calibrated speed of sound of 3299.4 m/s, which is indeed insignificant for all practical intents.

The remarkable result above led to substantiating the application of discharge location for the in-process assessment of the electrode length in fast-hole EDM, which in practice is rendered especially challenging by the relatively severe electrode wear in this process. This is of critical import in terms of detecting hole breakout with a view to reducing cycle time, particularly that this process typically entails the drilling of a large number of holes. Furthermore, this can avert instances of back-strike, which refers to inadvertent drilling into the back wall of an internal cavity that can result in the scrapping of the component altogether. Fig. 6 presents evidence to this capability wherein the electrode length estimated using a single sensor as the average of 20 measurements each to be in excellent conformance with the actual electrode length, with a location accuracy on the order of 1 mm.

Application of this scheme in wire EDM that refers to relatively rapid discharges necessitates the application of two AE sensors. For a representative window of AE shown in Fig. 7a, the spectrogram indicated a peak at 161.9 μs. Inspection of the corresponding current signal window (Fig. 7b) indicates 10 current spikes upstream of this instant in time that could each well have potentially been the source of this particular acoustic train. The actual current spike among these may be uniquely identified by considering AE simultaneously acquired using a second sensor located at a known distance from the first sensor,

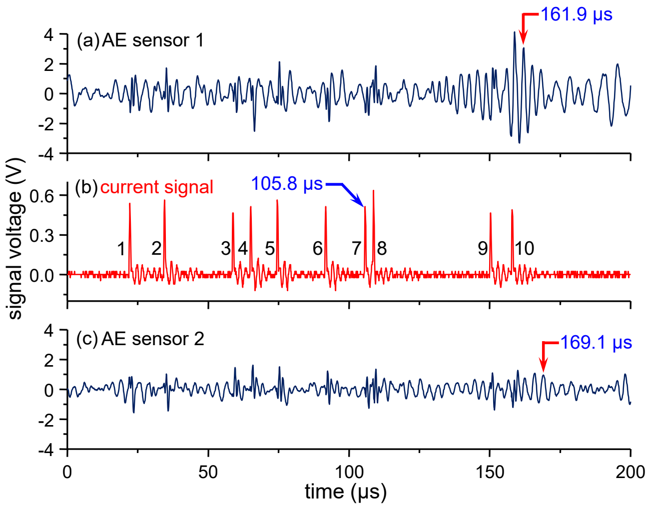

Fig. 7. Estimation of time lag in AE signals from: (a) sensor 1, and (c) sensor 2, respective to the: (b) current signal.

Table 1. Identification of the correct current pulse.

Current spike	x_1 (mm)	x_2 (mm)	$x_1 + x_2$ (mm)
5	216.92	240.67	457.59
6	159.18	183.93	343.11
7	112.99	136.74	249.73
8	103.09	126.84	229.93

preferably on the other side of the machining zone.

In this instance, the peak in the spectrogram corresponding to the signal from the second sensor (Fig. 7c) referred to a time of 169.1 μs. The AE segment under consideration was hence identified to correspond to current spike 7, as this minimizes the error between the calculated sum of the distances from the discharge location to sensor 1 (x_1) and sensor 2 (x_2), and the total known distance (250 mm in this case) between the sensors (see Table 1 which shows the distances for just 4 of the likely spikes). That the AE trains emanate from the same discharge may further be ensured by comparing the relative difference in their amplitudes due to distance-related attenuation, with the corresponding level of attenuation characterized during the calibration stage.

Recognizing that the envelope of discharge locations accomplished thus refers to the workpiece height in wire EDM, this technology may be employed for its online identification. This is instrumental in maximizing the cutting speed and minimizing the risk of wire failure when machining components of a variable height, by continuing to operate the process at the optimal power density. A real-time map of the discharge locations further serves to characterize the stability of the process, as well as provide a reliable assessment of the extent and efficacy of gap flushing along the machining zone, especially for thick workpieces. Previous attempts towards identification of workpiece height such as [8] that considers the dynamic relationship between gap voltage, sparking frequency and table feed rate are limited by the extensive level of effort involved in calibrating the many model parameters. The present work, on the other hand, entails just a single calibration for the relative speed of sound in the wire material, which is seldom changed in general.

The proof-of-concept of the application of AE discharge mapping for workpiece height identification in wire EDM is shown in Fig. 8 for heights of 23, 50 and 90 mm. The histograms refer to the distribution of estimated locations (~750 samples each) that refer to an error of less than 1 mm between the estimated and actual distances between the two sensors. The blue backdrop indicates the actual height and position of the workpieces for a comparison. The edges of the workpiece can be seen to align with the distances at which the cumulative distribution of the estimated heights (broken lines) markedly changes slope. Although the bulk of the estimated locations are within the physical confines of the workpiece, there are relatively few instances outside of it, conceivably due to the inordinate level of convolution in the AE signals. Future work along the lines of the use of additional redundant AE sensors, as well as data processing techniques such as wavelets in place of STFT may be considered to further improve upon this.

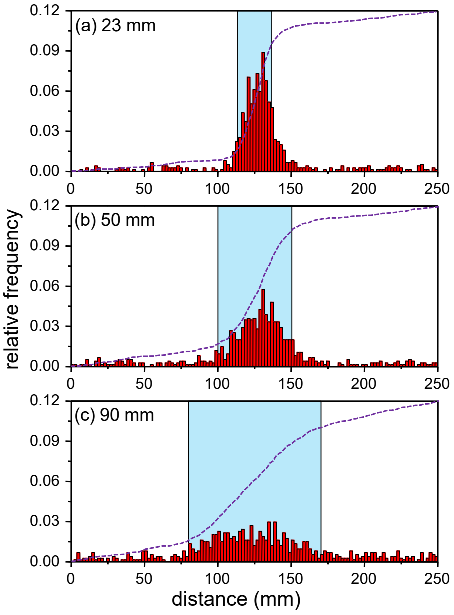

Fig. 8. A comparison of actual and estimated workpiece heights.

4. Conclusions

Although the concept of applying AE for locating discharges in EDM was first proposed more than two decades ago, difficulties associated with handling the superposition of wave trains from successive discharges have hitherto hindered its development. The research presented in this paper addressed this matter by examining the time evolution of the frequency content of the AE signal, and establishing the maximum intensity in the spectrogram of the AE signal as the frame of reference for determining the acoustic time lag. The proof-of-concept of the applications of AE discharge mapping for the respective identification of electrode length and workpiece height in fast-hole EDM and wire EDM presented in this paper highlight its significant potential. Additional work in terms of acquisition and processing of AE signals is warranted to further develop this technology towards its real-time implementation, as well as its extension to sink EDM. In practice, AE arising from friction due to relative motion between the wire/electrode and the guiding elements would further need to be isolated.

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