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Real-time evaluation of gap flushing in electrical discharge machining

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Abstract: This paper reports on acoustic emission (AE) from electrical discharge machining (EDM) in the context of gap flushing, and demonstrates its sensitivity to gap contamination from both metallic debris and gas bubbles. AE is further shown to relate to the local medium (liquid or gas bubble) through which individual discharges occur, and hence comprise unique and valuable process information on the effectiveness with which material is removed at the scale of a single discharge. This enabling technology is readily implemented for the in-process quantification, monitoring and optimization of flushing, and may constitute the basis for flushing-related adaptive control of EDM.

Keywords: Electrical discharge machining (EDM), monitoring, flushing.

1. Introduction

Of the many factors that determine process stability and productivity in electrical discharge machining (EDM), the role of flushing cannot be overstated. Given the small inter-electrode gap width and the often-complex machining geometry, indices such as the pressure and flow rate of the dielectric fluid do not necessarily reflect the actual extent of useful dielectric flow through the working gap. It is hence of interest to develop monitoring techniques that quantify gap flushing in EDM.

Jeswani [1] proposed an optical method for the on-line measurement of gap contamination that relies on the absorption of a light beam as it passes through a sample of the dielectric fluid. Frei et al. [2] suggested an indirect approach wherein the gap state was assessed with reference to the average ignition time delay, which for a given electrical field intensity, was found to be related to the volume concentration of particulate contaminants in the fluid. These techniques did not consider gas bubbles in the inter-electrode gap that affect the process significantly. Imai et al. [3], on the other hand, did investigate the effect of gas bubbles, considering that the transmission of ultrasonic waves through a liquid decreases monotonically with an increase in the volume fraction of gas in it. This technique is but unfortunately insensitive to the presence of metallic debris in the gap, the role of which is not insignificant in EDM. Furthermore, this method is limited by the need to synchronize and stream the ultrasonic waves through the gap during the pulse off-time, for it to not interfere with or be influenced by the process.

Despite its predominant influence in EDM, there is presently a lack of a technology for the in-process monitoring and quantification of gap flushing, which is practicable enough for easy integration into commercial machine tools. This is of particular importance, given that flushing need be maintained within limits that correspond to the optimal debris concentration, in order to maximize machining performance. In this context, this research explored the feasibility of the application of acoustic emission (AE) from EDM for assessing gap flushing. AE has long been well developed for the monitoring of most machining processes. For some inexplicable reason, AE in reference to EDM has however received little attention, except for the recent application of AE in the mapping of discharge location [4], and for detecting workpiece fracture during EDM of brittle materials [5,6]. This is rather surprising considering that experienced EDM operators do often "listen" to the process to gain a sense of process stability, notwithstanding that AE from EDM is manifest in a frequency band that is well above the audible spectrum [4].

This paper initially presents results that demonstrate the efficacy of AE for the real-time quantification, monitoring and optimization of gap flushing. This is followed by a discussion on the nature of AE in EDM, as it relates to fundamental process mechanisms pertinent to flushing.

2. Experimental

Experiments entailed a rotating copper disk electrode with a nominal diameter of 154 mm and a thickness of 6.35 mm, which was used to machine a mild steel plate workpiece of thickness 3.2 mm and width 25.4 mm (Fig. 1). The disk was trued in-place to essentially eliminate the radial run-out, towards ensuring a stable process. Use of a rotating disk electrode enabled quantifiable and consistent dielectric flushing along and across the machining gap. Based on the technology recommendations from the machine tool manufacturer that maximizes the removal rate in consideration of the machining area and the electrode/workpiece material combination used, experiments involved an electrode-positive polarity, a gap voltage of 75 V, a pulse current of 4.4 A, a pulse on-time of 154 µs and a pulse off-time of 37 µs, unless indicated otherwise.

AE was captured using a commercial sensor with a fairly uniform frequency response in the range of 100–900 kHz. The voltage was subject to a 450 kHz low-pass filter to discard the components arising from electromagnetic interference [4]. The signal was accordingly acquired at a sampling frequency of 5 MHz, and was amplified at a gain chosen to not saturate the amplifier. Simultaneous to the acquisition of AE, current and voltage waveforms were also recorded. The AE signal was characterized in terms of its frequency content, as well as the root mean square (RMS) value computed using a time constant of 200 ms.

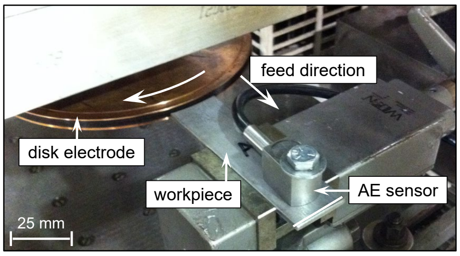

Fig. 1. Experimental configuration.

3. Results and Discussion

3.1 Application

Results of experiments conducted at different electrode peripheral speeds to vary the level of gap flushing are shown in Fig. 2. The material removal rate (MRR) was measured for a machining time of 10 min. Similar to the calculation of RMS AE, a time constant of 200 ms was used to compute the RMS current. The RMS values represent an average of 5 measurements, each of 1 second duration; the variability in the RMS index was less than 5% of the respective mean value.

The maximum in the MRR characteristic (Fig. 2a) is a consequence of the optimal debris concentration that relates to the most effective mode of material removal. At very low levels of flushing, accumulation of machining debris in the gap results in short circuits and localized arc discharges that compromise the stability of the process, resulting in a low MRR. As the level of gap flushing improves, spark discharges with a finite time delay that refer to more effective material removal tend to predominate, which enhances the MRR. At peripheral electrode speeds higher than the optimal value, the MRR exhibits a decreasing trend as a certain level of gap contamination is essential for the breakdown of the dielectric fluid to initiate discharges.

From reviewing the relative trends in Fig. 2, it is immediately evident that the AE RMS (Fig. 2b) scales with the MRR, and exhibits an excellent correspondence in terms of the optimal peripheral speed. Such a correlation was non-existent in the RMS current (Fig. 2c); investigations indicated no systematic correspondence with the ignition time delay either. In terms of gap flushing, this highlights the potential of AE in complementing the electrical signals that are exclusively used at the present time for the monitoring and control of modern EDM machine tools.

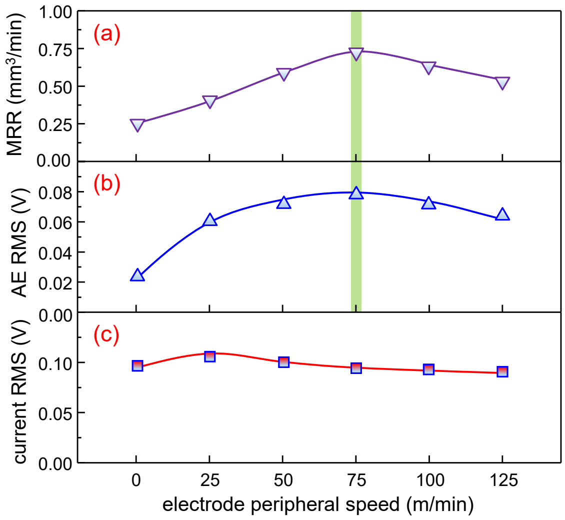

Fig. 2. Effect of electrode peripheral speed on: (a) MRR, (b) AE RMS, and (c) current RMS.

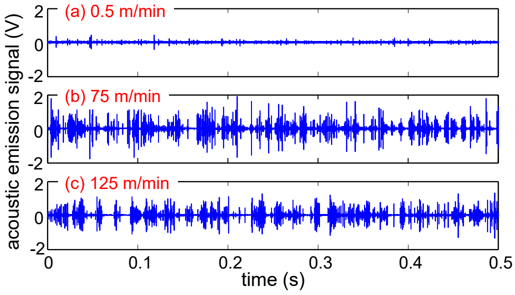

Fig. 3. Raw AE signals corresponding to various peripheral speeds.

Fig. 3 presents time domain samples of the raw AE for three electrode peripheral speeds. Acoustic events are few and feeble at a low speed of 0.5 m/min (Fig. 3a). At the optimal speed of 75 m/min (Fig. 3b), there is significant AE comprising a multitude of bursts. At a speed of 125 m/min which is higher than optimal (Fig. 3c), not only are the amplitudes of the AE bursts relatively smaller, there are also several pockets of time that are evidently devoid of any AE activity. This is an indication of the difficulty in initiating and sustaining discharges in the dielectric fluid that is being perturbed by the rapid flow.

With a view to augmenting the tests presented above, an enclosed space around the machining gap was artificially contaminated with iron powder of a nominal size of 30 µm to simulate typical EDM debris. Fig. 4a refers to the baseline AE frequency spectrum when the electrode peripheral speed was 7.2 m/min, with the gap relatively free of any contamination. Introduction of the iron powder in the vicinity of the gap can be seen to precipitate a notable reduction in the magnitudes of the AE signal across the entire frequency band (Fig. 4b). The fluid in the gap regaining a part of its dielectric strength after 2 minutes of machining using the rotating electrode is indicated by the corresponding increase in the acoustic activity (Fig. 4c). This increment does not however bring it up to par with the level seen in Fig. 4a, due to the general increase in the contamination of the dielectric fluid at large. This demonstrates the responsiveness of the simple AE technique, and its advantage over the intricate ultrasonic wave transmission technique proposed in [3], which is insensitive to the presence of metallic debris in the gap.

Having investigated the effect of flushing and gap contamination on the AE signal, it was of interest to examine the related effect of varying the active frontal machining area at a constant discharge current (Fig. 5; when indicated, error bars denote ±1 standard deviation throughout this paper). It is indeed intriguing to note that at the optimal electrode peripheral speed of 75 m/min, the RMS AE characteristic exhibits a maximum at a current density of 10 A/cm^2, which is a rule of thumb widely adopted in sink EDM practice [7]. Fig. 5 also shows the optimal value of current density to be dictated by the level of flushing in the gap. At an electrode peripheral speed of 14 m/min that is lower than optimal, the associated machining area ought to be

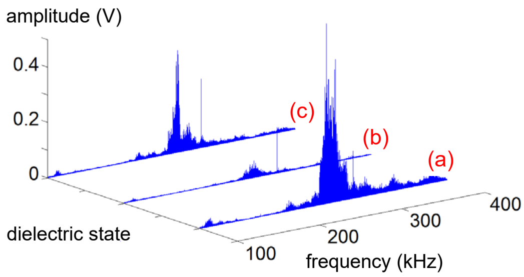

Fig. 4. Effect of gap contamination on the frequency spectrum of the AE signal.

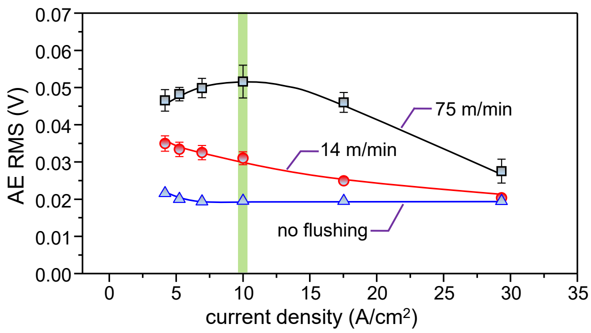

Fig. 5. Role of current density and gap flushing on the RMS AE.

correspondingly higher to appropriately disperse the discharges further apart in space, so as to secure effective material removal.

In the experiments presented thus far, the extent of gap flushing was altered by varying the electrode peripheral speed, which relates to a process like electrical discharge milling, but not to a sink or a wire EDM process. In consideration of this, the efficacy of AE in assessing external jet flushing was also investigated. The enhancement in flushing effectiveness with increasing supply pressure of the dielectric brings about an increase in the AE magnitude (Fig. 6). The results presented in this sub-section decisively validate the application of AE for monitoring flushing.

3.2 Mechanism

To gain an insight into the mechanism underlying AE in EDM, it was of interest to first determine its origin. To this end, AE was acquired when the gap was either dry or filled with oil. Dry EDM referred to little if any AE activity (Fig. 7a), whereas AE bursts were conspicuous when the gap was filled with a liquid (Fig. 7b). This aligns with the observation in [8] that while a force as high as 75 N was measured for a single discharge in a liquid dielectric, the corresponding force in a gaseous dielectric was negligibly small. Evidence of material melting on the machined surface in dry EDM indicated AE to be not borne from any thermal effect on the workpiece. The occurrence of AE bursts in the liquid dielectric suggested the possibility of the acoustic activity to be related to the gas bubble arising from the vaporization of the dielectric fluid at the discharge location.

Investigating into this further, examination of the current signal juxtaposed with the AE indicated not all discharges to manifest an AE burst. Fig. 8 shows a typical snapshot, wherein barely half the number of discharges have corresponding AE bursts. Even in the instances they do occur, significant variability is evident in the maximum amplitude and duration of the bursts, despite the current spikes being largely uniform. Similarly, experiments indicated no correlation between the occurrence of the AE bursts and the ignition time delay.

Given that dry EDM referred to no AE (Fig. 7a) and that much of the gap space in conventional EDM is occupied by gas bubbles

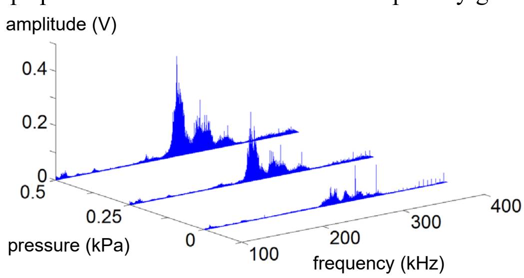

Fig. 6. Effect of dielectric pressure on the frequency spectrum of the AE signal.

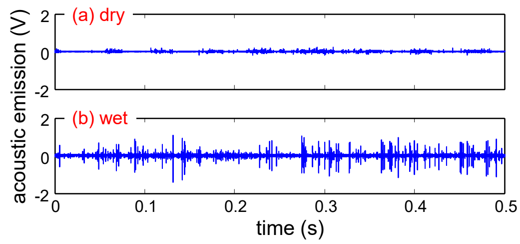

Fig. 7. Effect of dielectric environment on the raw AE signal.

[3,9–12], the absence of an AE burst was suspected to be related to the corresponding discharge being struck through a gas bubble from a previous discharge, as opposed to being initiated through the liquid phase. This line of thought of associating acoustic bursts with the local medium through which discharges occur was motivated by the paper [8] from Kunieda et al. who reported on the reaction force of discharges in EDM. In the event of two consecutive discharges in a liquid dielectric, the force associated with the second discharge was found by them to be considerably lower, due to the latter discharge having occurred through the gas bubble from the first discharge.

In addition to a significantly smaller force, a discharge occurring through a gas bubble is as well characterized by a reduction in material removal. Imai et al. [3] found the MRR to decrease two-fold within the very first second of initiating machining, during which time 30–50% of the gap was already filled with gas bubbles. This is supported by the report of Takeuchi and Kunieda [10] who indicated the size distribution of debris from successive discharges in a liquid dielectric to be in-between that from a series of single discharges in liquid and air. Likewise, Yoshida and Kunieda [11] found craters generated in dry EDM to be of a larger diameter-to-depth ratio compared to those generated in a liquid. The larger diameter was attributed to the relatively negligible resistance to the expansion of the plasma channel owing to the lower inertia and viscosity of the surrounding air, and the shallower craters to the consequent reduction in the heat flux.

Consolidating the knowledge above from [3,8,10,11], if the occurrence of AE bursts is related to the medium (liquid or gas bubble) through which a discharge occurs, it should be expected to reflect the efficacy with which material is removed in that particular discharge. Given that AE does indeed scale with the MRR (Fig. 2) and the machining area (Fig. 5) in the context of flushing, it was hence hypothesized that the manifestation of a significant acoustic burst is tied to the initiation of a discharge through the liquid medium that is more effective in removing material, relative to discharges realized through gas bubbles or at the bubble-liquid interface. Experiments were designed to verify this hypothesis by examining the effect of increasing the electrode peripheral speed and the pulse off-time. Should the hypothesis be true, the ratio of the number of acoustic bursts to the number of discharges should increase due to the resultant decrease in the volume fraction of gas in the machining gap. In testing the hypothesis, AE

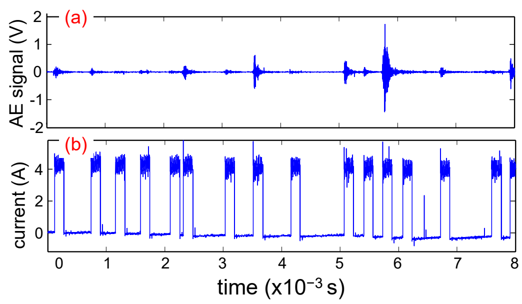

Fig. 8. Sample current pulses and corresponding acoustic activity.

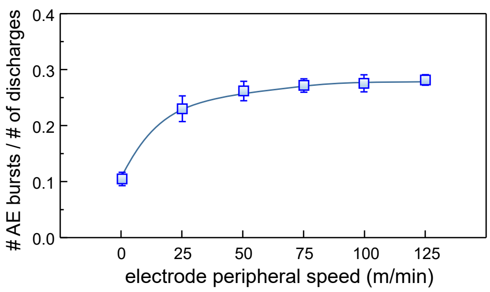

Fig. 9. Effect of electrode speed on the ratio of the number of AE bursts to the number of discharges.

was deemed to have constituted an active burst when the voltage exceeded a threshold of 0.05 V.

Fig. 9 shows this ratio to indeed increase roughly three-fold with an increase in the electrode peripheral speed, which should facilitate the transport of gas bubbles off the gap, thereby promoting discharge initiation through the liquid. Unlike the RMS AE in Fig. 2b that exhibits a maximum, this ratio does not decrease once the peripheral speed exceeds 75 m/min, as the number of discharges per unit time in itself is on a decrease in this regime, due to the rapid fluid flow interfering with the discharge initiation process. It is interesting to note that even at the optimal peripheral speed wherein the MRR is maximized, less than one in three discharges is actively involved in the effective removal of material. The proposed hypothesis was further corroborated by the increase in the number of AE bursts per discharge with an increase in the pulse off-time (Fig. 10), as this decreases the likelihood of discharges occurring through a bubble as well. Similarly, artificially introducing gas bubbles into the working gap as machining was in progress led to a substantial decrease in the AE activity (Fig. 11).

The experiments above establish that the AE bursts refer to discharges initiated through the liquid that are more effective in removing material, relative to those realized through a remnant gas bubble. This aspect is of considerable practical significance, as the volume fraction of gas in the working gap that has a great influence on the MRR is not reflected in electrical indices such as the average gap voltage [3] that is generally used as a reference parameter for servo control. The medium through which discharges are realized is not as readily reflected in the current or voltage waveforms either [12], due to the inherent variability. This further substantiates the rationale and efficacy of the application of AE towards addressing the long-standing industrial need for the real-time monitoring and quantification of gap flushing in EDM.

4. Conclusions

The proof-of-concept of the enabling application of AE for the monitoring and quantification of gap flushing in EDM has been presented. AE is sensitive to gap contamination arising from both metallic and gaseous debris. As the RMS AE scales with the rate

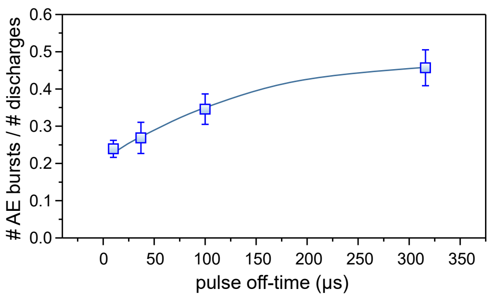

Fig. 10. Effect of pulse off-time on the ratio of the number of AE bursts to the number of discharges.

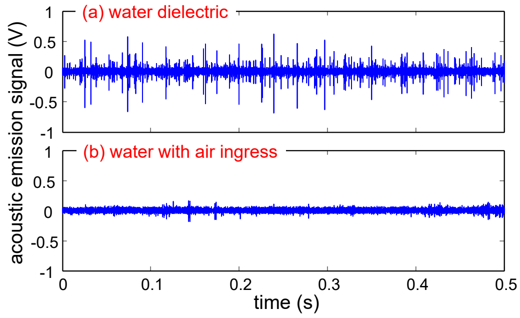

Fig. 11. Effect of artificial air ingress into the gap on the AE signal.

of material removal when flushing is varied, it is useful in determining the optimal level of gap flushing. AE is further shown to encapsulate unique and valuable process information pertaining to the effectiveness with which material is removed at the level of individual discharges, which is either not present in, or is not as readily extracted from the electrical waveforms. AE in EDM relates to the dynamics of gas bubbles in the working gap, and has been found to constitute a burst when a discharge is initiated in the liquid medium, as opposed to through a gas bubble from one of the previous discharges. Given the critical importance of flushing on the stability and productivity of EDM processes, there is significant potential for AE to complement the electrical signals that are exclusively used at the present time for the monitoring and control of EDM machine tools. This work signifies opportunities offered by AE technology in not just advancing the adaptive control of EDM in consideration of gap flushing, but also in terms of gaining fundamental insights into EDM process mechanisms.

Acknowledgement

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