Assessment of Abrasion-Assisted Material Removal in Wire EDM

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I. Menzies, P. Koshy (2)

Department of Mechanical Engineering, McMaster University, Hamilton, Canada

Abstract

Machining speed and surface integrity continue to be issues of focus in current wire EDM research. In this light, the proof-of-concept of a hybrid wire EDM process that utilizes a wire embedded with electrically non-conducting abrasives is presented. Material removal in this novel process is realized through electrical erosion that is augmented by two-body abrasion. This is shown to bring about a significant improvement in the removal rate and generate surfaces with minimal recast material, in comparison to an equivalent wire EDM process. Implementation details and process characteristics are discussed.

Keywords:

Abrasion, Wire EDM, Hybrid machining process

1 INTRODUCTION

Since its inception in the early seventies, concerted research efforts from industry and academia have elevated wire EDM (WEDM) performance to impressive levels in terms of machining speed, accuracy and machined surface integrity. These advances are primarily due to improvements relating to solid state generator technology with anti-electrolysis and pulse shaping capabilities, various wire configurations and coatings, effective flushing techniques under submerged machining conditions, and advanced adaptive control strategies [1].

Current WEDM capability with reference to maximum workpiece height and taper, machining accuracy and surface finish are largely consistent with component requirements in typical applications appropriate to the process. Significant progress notwithstanding, it is desirable to improve the metallurgical quality of the machined surface/subsurface, in order to expand the process envelope and establish new application domains. For instance, the wear behaviour and tool life of cemented carbide punches machined using WEDM have been shown [2] to be comparable to that of ground ones; nevertheless, WEDM is not employed in the manufacture of critical rotating aerospace components as yet, due to concerns with depreciated fatigue strength. Likewise, although WEDM machining speeds have increased [3] by a factor of ~30 in the last three decades, it is of interest to further enhance it with a view to maximizing productivity towards reducing cost.

The issues of machining speed and machined surface quality are interlinked in WEDM with respect to the fundamental mechanism of material removal at the scale of a single discharge. The removal of molten workpiece material is presently understood to be due to the implosion of the plasma channel, and it is estimated that indeed only about 10% of the molten material is actually removed from the parent material, due to inadequate ejection forces [4]. The rest of the material is recast upon the machined surface, and sustains microcracks due to rapid solidification and shrinkage, not only rendering the process inefficient but also appreciably affecting the integrity of the machined surface.

An improvement in the ejection efficiency would consequently bring about an increase in the removal rate and also yield a better surface quality. This is notable considering that in typical WEDM processes, a high removal rate and good surface quality are mutually exclusive, with one response obtained at the expense of the other. At the present time, aspects of gap flushing, wire design and generator technology are already at such sophisticated stages of development that future refinements can be expected to offer only incremental benefits. It is therefore imperative to develop innovative approaches to enhancing material removal efficiency.

One avenue to accomplishing this is to invoke the notion of a hybrid machining process that relates to the integration of two or more machining processes with distinct mechanisms of material removal, to exploit their synergy. The efficiency of material removal in WEDM is enhanced in the present work by incorporating abrasion of the workpiece material in the working gap, concurrent with spark erosion. The abrasive action is realized by substituting the wire commonly used in WEDM with a wire that is embedded with electrically non-conducting abrasives (Figure 1). This paper presents the proof-of-concept and operational aspects of this novel process, hereafter referred to as Abrasive Wire EDM (AWEDM).

2 ABRASION-ASSISTED WEDM

The development of hybrid machining processes is often spurred by the need to address technological limitations inherent to traditional machining processes. Several hybrid machining processes entail abrasion as one of the constituent mechanisms by which material is removed. In electrochemical grinding, the abrasive action continually removes the passivation layer in-process, facilitating electrochemical material removal; a variant of this process [5] uses an abrasive wire. Similarly, an abrasive-laden air jet directed at the melt pool created in laser milling/grooving processes has been shown [6] to enhance the material removal rate (MRR) while

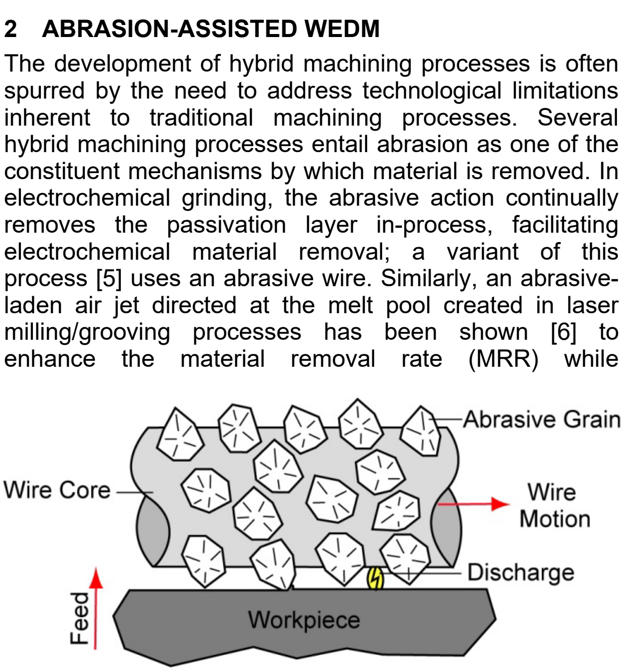

Figure 1: Schematic of AWEDM.

diminishing the heat affected zone and the roughness of the generated surface.

The concept of integrating abrasion into electrical discharge machining for processing electrically conducting hard materials seems to have been first proposed by Grodzinskii and Zubotava [7] in the early eighties. Several researchers have since developed the idea for the productive machining of advanced engineering materials that are difficult to machine, in plunge grinding [8,9] and drilling [10] configurations. This combination can be viewed in terms of the electrical spark discharges augmenting grinding performance through effective in-process dressing/declogging of the grinding wheel and thermal softening of the workpiece material [8,9]; alternatively, the abrasive action can be considered to enhance electrical erosion through in-situ removal of the molten/recast workpiece material [10].

The work reported in this paper extends the concept towards realizing a novel WEDM process. AWEDM is fundamentally different from the so-called wire electrical discharge grinding process [11], which is in fact a misnomer as the process is actually non-contact and does not involve any material removal by grinding. The emphasis in the present work is on exploring how abrasion can be utilized to improve WEDM performance.

AWEDM is realized by replacing the wire used in WEDM by a fixed-abrasive wire, and can therefore be considered to be a combination of WEDM and a wire sawing process at relatively low wire speed. The process kinematics in AWEDM (Figure 1) are similar to that of WEDM: the wire translates along its axis lateral to the machined surface while being simultaneously fed relative to the wire axis under servo control, such that a dielectric filled gap of several μm is maintained between the workpiece surface and the wire core.

As the gap width is sensed and controlled electrically, it is essential that the wire core is electrically conductive and the abrasive is electrically non-conductive. Under conditions that the abrasive protrusion height p_h is greater than the working gap width g_w (Figure 2), electrical discharges occur between the wire core and the workpiece to remove material by spark erosion, while the abrasives simultaneously abrade the workpiece. For a particular servo reference voltage setting, g_w is dependent on the dielectric strength of the working fluid in the gap; p_h is primarily determined by the size of the abrasives used in the wire.

The extent of material removal by abrasion in AWEDM is controlled by the relative magnitudes of g_w and p_h, both of which are random variables that are characterized by their distributions. At a certain location in the working gap, an active abrasive (see Figure 2) tends to remove an uncut thickness (p_h–g_w) of the workpiece material that could be molten, thermally softened or recast, depending on the time interval between the occurrence of a discharge along the path of the abrasive and the abrasive engagement.

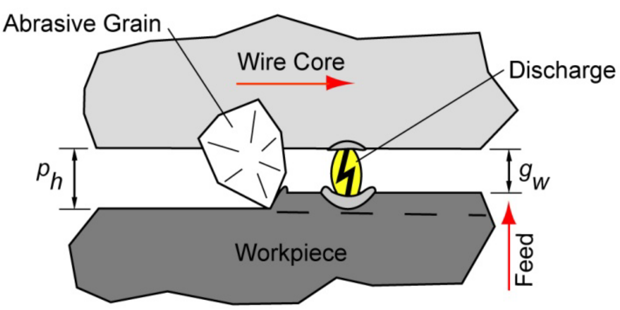

Figure 2: The interelectrode gap in AWEDM.

3 EXPERIMENTAL

The concept of AWEDM was proven on a sinker EDM using a WEDM attachment. In AWEDM, it is not practical to guide the wire using stationary dies, and supply power through electrical contacts as in conventional WEDM machine tools, due to the issue of severe abrasion of these elements. The experimental attachment therefore comprised two carbide rollers with V-shaped grooves for wire location and feed, to minimize the relative motion between the abrasive wire and the guiding surfaces, thus alleviating the problem of abrasive wear leading to premature failure. Electrical power was conveyed to the wire through the attachment.

The wire used in the AWEDM experiments was a commercially available diamond wire meant for precision wire sawing applications in the semiconductor industry (Figure 3). The wire was 180 μm in diameter, and comprised a high tensile strength steel core, with synthetic diamond abrasives of a nominal diameter of 50 μm retained in an electroplated nickel layer. The rationale for the choice of this wire is discussed later.

The objective of the experimental work was to identify the mechanism of material removal in AWEDM, and to compare its performance against an equivalent WEDM process, with respect to the MRR and the recast layer. Corresponding WEDM experiments were hence run with the same wire as was used in the AWEDM experiments, but with no abrasives.

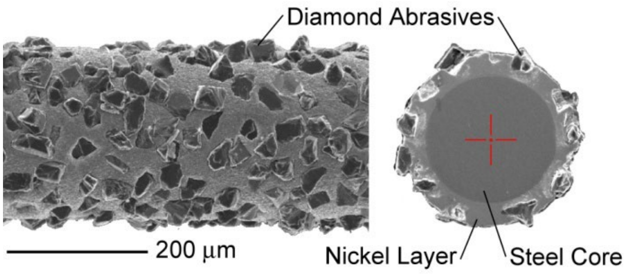

Figure 3: Surface and section of diamond wire.

The experiments were conducted with the average working voltage U and the discharge current i_e as the variables. The pulse on-time, pulse off-time and open circuit voltage were held constant at 4.9 μs, 100 μs and 180 V, respectively. The values above were determined from extensive preliminary experimentation, with a view to realizing a stable process that incurs no wire breakage. Experiments involved a synthetic dielectric fluid with flushing applied coaxial to the wire at a pressure of 1 bar, with the workpiece completely submerged. The wire tension and axial speed were maintained constant at 6.8 N and 5.5 m/min, respectively.

Experiments entailed annealed SAE 1018 steel workpieces in the form of plates of thickness 1.2 mm, and were for a duration of 5 minutes each. Assessment of the process response variability indicated the responses to be repeatable within 5%. Supplementary trials were also run on a nickel alloy to assess the reduction in the recast material. Attempts at measuring the normal force in AWEDM using a piezoelectric dynamometer were not successful on account of the forces being low compared to the external forces arising from the dielectric fluid flow. The normal machining force was therefore estimated by considering force equilibrium with reference to the wire bow and wire tension.

4 RESULTS AND DISCUSSION

Successful operation of the AWEDM process depends on the appropriate choice of the electrical parameters and the abrasive wire that would facilitate material removal by both spark erosion and abrasion. The performance of this process was hence studied with respect to the average working voltage *U* and the discharge current i_e. The *U* parameter controls the gap width; a decrease in the gap width would increase the relative proportion of material removal due to abrasion, by increasing the abrasive engagement with the workpiece. Varying i_e alters the extent of material removal by spark erosion.

Initial AWEDM experiments indicated the range of electrical parameters that could be effectively employed with the abrasive wire to be severely limited by wire failure. Detailed examination of the cross-section of failed wires attributed this to process-induced embrittlement of the steel core, with its hardness having increased from 54 HRC to 64 HRC, which approaches the maximum hardness for steel. Based on preliminary experiments that focussed on averting wire failure, the appropriate ranges for the *U* and i_e parameters were determined to be 108–162 V and 1.2–8.0 A, respectively.

Over the range of parameters above, experiments were conducted using a wire with no abrasives to: (i) obtain the MRR due to WEDM alone for comparison with AWEDM, and (ii) to determine the nominal gap width, estimated as half the difference between the machined kerf width and the wire diameter. These experiments indicated the WEDM removal rate and the gap width to be in the ranges of 0.02–0.10 mm^2/min and 8–20 μm, respectively. The removal rates obtained are orders of magnitude lower in comparison to those typically obtained [3] in WEDM of steel (hence the use of thin plate workpieces to facilitate cutting speed measurements). This is due to the present process employing a steel wire with a nickel outer layer under considerably low peak current and duty factor, with a dielectric oil as the working fluid under low flushing pressures. Nonetheless, for a proof-of-concept study, these values can be deemed to constitute an acceptable baseline.

The protrusion height distribution of the abrasives on the diamond wire was characterized using white light interferometry, after sputtering the wire with a thin layer of gold to avoid problems with reflection of light from the diamond grains. The distribution shown in Figure 4 would indicate that the wire is suitable to realise abrasion simultaneous with spark erosion, as the gap width was determined to be in the range of 8–20 μm.

Figure 5 presents the percentage increase in the MRR with respect to *U* and i_e parameters, and the corresponding normal force developed in the process in the form of a contour plot. It can be seen that the

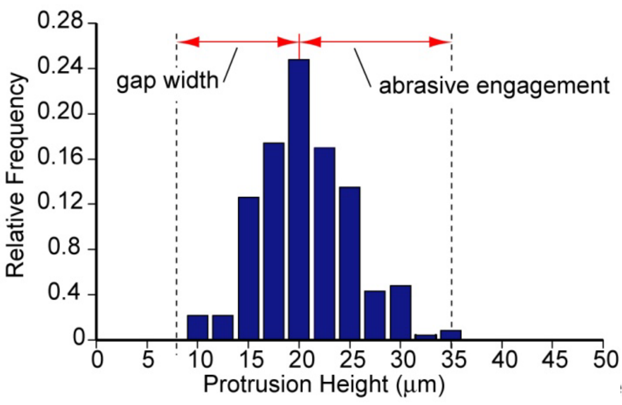

Figure 4: Protrusion height distribution of abrasive wire.

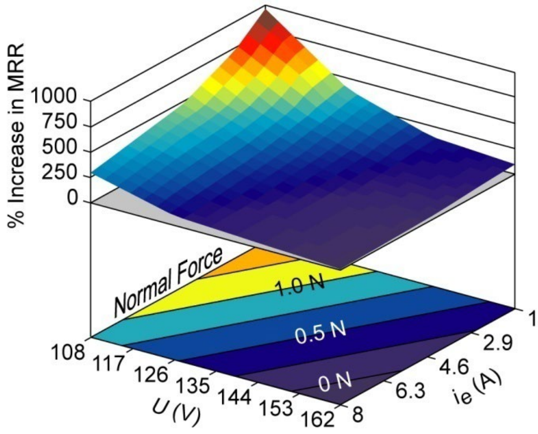

Figure 5: MRR and normal force in AWEDM.

enhancement in the MRR is significant, with the maximum value being an order of magnitude higher, typical of such hybrid processes [8-10]. The trends are such that the increase in MRR becomes higher with decreasing *U* and i_e. This indicates that the enhancement in MRR is a consequence of the increase in the component of material removal due to two-body abrasion. The steepest gradient in the change in MRR can further be observed to be in line with the gradient in the normal force, which signifies the role of abrasion in increasing the removal rate. The rate of increase in the MRR with a reduction in i_e is further seen to be higher with decreasing *U*. This is evidently due to the exponential increase in the number of active abrasives with decreasing gap width, on account of the normal distribution of protrusion height (Figure 4). At lower values of *U* and i_e, the process approaches a wire sawing operation, with increasing wire bow that is detrimental to machining accuracy. Further increase in the MRR could be obtained at higher wire speeds.

The debris collected during AWEDM presents further evidence on the role of abrasion. Debris collected at a voltage of 162 V and a current of 8 A (Figure 6a) comprises mostly spherical particles characteristic of EDM. The corresponding percentage increase in MRR and the normal force can therefore be observed (Figure 5) to approach zero. Debris collected at a lower voltage of 108 V and the same current (Figure 6b), however, can be seen to predominantly include particles that denote abrasion, which is responsible for the ~300% increase in the MRR and a normal force of ~1 N (Figure 5). The abraded particles do not exhibit a lamellar structure that signifies intense shear, typical of chips generated in grinding, which suggests that the material removed by abrasion was by then thermally softened by the electrical discharges.

Figure 7a shows the topography of the surface machined using WEDM at a voltage and current of 108 V and 8 A, having a roughness of 2 μm R_a. The surface is isotropic with several microcracks (shown by arrows), typical of spark eroded surfaces. The corresponding AWEDM surface (Figure 7b) with a roughness of 0.9 μm R_a has a

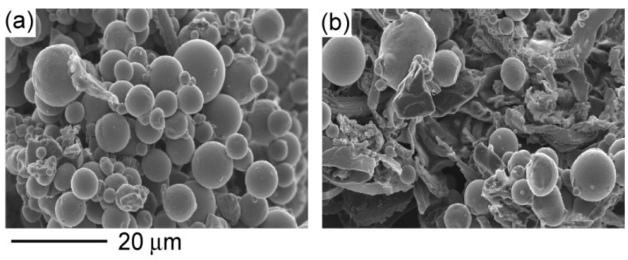

Figure 6: Debris obtained from AWEDM.

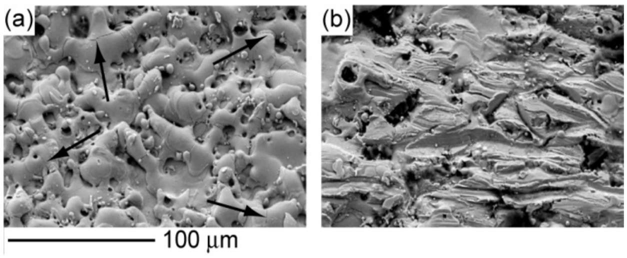

Figure 7: Machined surfaces from: (a) WEDM, (b) AWEDM.

defined lay as a result of material removal by abrasion.

Limited experiments were also conducted on a nickel 600 alloy to compare the extent of the recast layer in WEDM and AWEDM, as the machining of recast-free surfaces is of interest in the aerospace industry. Figure 8a shows the recast layer generated in WEDM to be continuous and of a thickness of ~5 μm. For identical electrical parameters, the recast layer is largely absent in AWEDM, with only insignificant recast evident in isolated pockets, as indicated by arrows in Figure 8b.

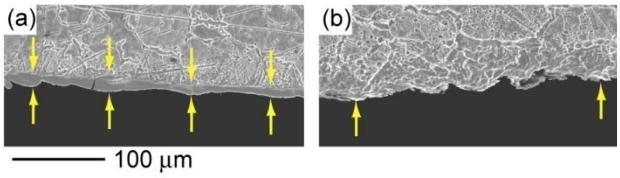

Figure 8: Sectional view of surfaces machined using: (a) WEDM, (b) AWEDM.

Diamond wire was used in this work as it is commercially available. Experiments conducted to examine the performance of the diamond wire over repeated use indicated wire performance to degrade to a level close to that of a wire with no abrasives, after just the first few passes. This is conceivably due to the graphitization of diamond abrasives under high temperatures in the presence of iron as a catalyst [12]; this implies that diamond is unsuitable for implementing AWEDM, not just from an economic perspective, but also from a technological point of view. The process is best implemented using wires embedded with considerably cheaper aluminum oxide abrasive, which unlike diamond is not susceptible to chemical wear. This however requires significant research effort towards wire design and development, as wires with aluminum oxide abrasives are currently not produced commercially.

An important issue from the machine tool standpoint is the design of wire/power feed devices appropriate for AWEDM. One plausible approach is a wire with abrasives only over a partial sector of the wire, such that the section free of abrasives can be utilized for wire location and power supply, without abrading the wire guides and electrical contacts. This however makes the process somewhat involved as the workpiece would have to be oriented such that the instantaneous feed direction is normal to the sector of the wire with the abrasives. The wire could further be of a non-circular cross-section for the purposes of wire location and feed. Electrical power may also be conveyed to the abrasive wire through couplings that employ low melting temperature alloys or consumable brushes.

5 CONCLUSIONS

Proof-of-concept experimental work presented in this paper has validated the feasibility of an order of magnitude increase in WEDM removal rates, by replacing the conventional wire with a fixed abrasive wire, which introduces abrasion in the working gap. Machined surfaces were further shown to entail negligible recast material. Although the bulk of this work pertained to the machining of steel, AWEDM could be advantageous in the processing of metal matrix composites such as polycrystalline diamond that are difficult to WEDM. The process seems better suited for roughing sequences considering that the force due to abrasion would negatively influence machining accuracy, and is hence ideally implemented in a twin-wire machine tool. Although it was expedient to use a diamond wire in this work, wire bonded with aluminum oxide abrasives would be of a better performance and lower cost. Practical exploitation of the concept calls for extensive effort in developing wires that have good sparking and grain retention characteristics. Further work could also explore the viability of electrical discharges assisting wire sawing of electrically conducting hard/brittle materials, in such terms as enhancing cutting rates through controlled thermal shock-induced fracture.

6 ACKNOWLEDGMENTS

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