A review of Tool Wear Compensation Methodologies in µEDM

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Abstract
The inherently persistent tool wear in µEDM and process variants has been a serious issue since it disrupts the dimensional accuracy of the fabricated micro-components. Several attempts to eliminate the issue are being made by proposing offline and online (real-time) strategies in the last two decades. Instead of compensating the worn-out portion of the tool, methods for minimizing its adverse effect on the fabricated components are proposed even before discerning several disadvantages. Most of these methods are for an intended objective, a generalization of which in terms of validity for a wide range of tool-work materials combination and parametric input settings are still required. This paper provides a thorough review which aims to connect the modern developments in tool wear compensation methodologies to possible future research. This paper focuses on tool wear compensation techniques, offline compensation method, and online tool wear compensation.

Keywords: Tool wear compensation, pulse discriminating system, real-time volume removal, VRD

Nomenclature
C Combination of a fraction of energy and fraction of molten area
erfc Complementary error function
Iₛ Average current (A)
kₜ Average thermal conductivity (Wm⁻¹K⁻¹)
q Heat flux
r Radial distance of material
R Heat flux radius (µm)
T Temperature (K)
Tₚₒₚ Pulse on time (ns)
Vₜ Average voltage (V)

Greek Letters
α Average thermal diffusivity (m²s⁻¹)
τ Dimensionless time

Abbreviations
µEDM Micro electrical discharge machining
CLU Combination of linear and uniform method
EWR Electrode wear rate
LCM Linear compensation method
MRR Material removal rate
SR Surface roughness
UWM Uniform wear method
VRD Volume removal per discharge

I. Introduction
The EDM system involves an electrode and workpiece, which are electrically conductive and immersed in a dielectric fluid. It is a controlled metal removal process in which the metal is removed using electric spark erosion. In this method, an electrical spark is used as a cutting tool to disintegrate the workpiece and create the desired shape. The workpiece is connected to the anode, and the electrode is connected to the cathode terminal. Once a voltage is supplied to the tool, the suspended particles in the dielectric fluid concentrate between the electrode and workpiece due to the magnetic field and generating a bridge for current to flow to the workpiece. Then the electrical intensive arc is produced, creating sufficient heat to melt a part of the workpiece and some of the tooling material. The high concentration of electrons and ions among the tool and workpiece made a plasma channel. A large amount of electron will flow from tool to job and ions from job to tool due to the less electrical resistance of the plasma channel. At a temperature of about (10,000 ºC – 12000 ºC), material removal occurs due to the melting of the workpiece (Patel NK, 2014). The occurrence of plasma channel raises the temperature, and the material removal takes place due to the spot vaporization of metallic particles. The melted particles are removed partly.

On the other hand, one of the input factors for electrical discharge machining is the workpiece material machinability. As, the machinability is the technological property of the workpiece material to be machined in the best conditions for
the producer; this means that the material could be machined with high material removal rate, with a low wear of the tool, with a minimum mechanical solicitation of the machining equipment, with obtaining a low roughness of the machined surface, with a convenient form of the detached chips. It is expected that during the electrical discharge machining, the electrode wear is influenced by various factors; these factors could be grouped in factors which characterize the workpiece material (the melting temperature, the vaporizing temperature, the thermal conductivity, the thermal capacity), the values of the machining electrical parameters (pulse frequency, duration of the electric pulse, duration of the pause between two successive electric pulses, mean value of the electric intensity), the characteristics of the dielectric fluid. The electrode wear could be evaluated by the change of the electrode dimensions or of the mass; in each of these case, various specific methods and instruments could be used to obtain an adequate image about the electrode wear. μEDM is an extremely significant method in micro-features fabrication with several advantages, but it also has some disadvantages. Some of them are the long machining time and poor flushing, especially while machining an in-depth profile. These issues associated with μEDM are closely related to the tool wear, which is a result of poor flushing and lengthen the process.

It is understood from above that the tool wear is a major centralized issue which influences the accuracy of product fabricated by μEDM [2, 3]. Further, several worldwide attempts made by researchers to get rid of the issue have been discussed methodically. The intended objective of the several proposed attempts is focused on highlighting the advantages and limitations associated. This review is a proposed future research plan for a more effective real-time tool wear compensation.

II. Tool wear compensation techniques

The development of tool wear is inevitable and very significant as electrode shape deterioration directly influences the profile and depth of microstructures. The electrode shape quickly varied during the machining process when for milling or drilling EDM, a microspherical tool is employed. Electrode wear increases on both sides at the end or on the side face of the electrode and is also signified as corner and front wear, consistently. Front wear creates errors in the tool span and therefore contribute to the inadequate depth of a micro-hole in μEDM mainly for drilling. The corner wear tends to round edges of the electrode and thus to result in geometrical imprecision of microstructure in μEDM milling. To resolve the electrode wear issues as well as to enhance the machining precision in EDM, apart from research examinations in μEDM, there are lots of scopes on the improvement of electrode wear compensation techniques for μEDM. However, from the last two eras, several attempts have been made to solve the electrode wear problem solely in μEDM milling.

To solve the tool, wear issues in μEDM, two compensation methods are introduced known as offline compensation method and online compensation method. The results for electrode wear problem in μEDM were primarily attempted using offline compensation, and afterward, some, efforts were taken via an online compensation method as well. Both the offline compensation method and an online compensation method is discussed in the section below.

III. Offline compensation method

The offline tool wear compensation process determined the electrode wear mainly in the form of EWR or calculated at a regular interval of time during the machining. From 1980’s the offline tool wear compensation is mainly accomplished by determining the length of the tool at a regular interval of time by several tools wear sensing approaches like the approaches which depend upon laser sensors, machine revelation method, etc. [4, 5]. The actual implementation of the downward-effort is an expected compensation which is based upon the offline electrode wear model before machining. However, such methods are still being used for variant applications in the manufacturing machine but have not established to be a modernizer in electrode wear compensation. The offline compensation simulation section determines the essential reduction of electrode length for every part of the electrode path. Such calibration is depending on the work-piece quantity to be removed and a comparison of relative volumetric wear.

3.1 Periodical improvement of the tool wears compensation

During machining, depending on the periodical analysis of electrode length, the expected compensation can be added to the improvement of tool wear compensation. Precise electrode length determination permits the validation of real electrode wear. As the machining is carried out in consecutive layers, the determination of electrode length and improvement of the expected wear compensation are generally carried out after every layer. The periodical determination achieves in disruptions of the machining tends to higher machining period. The electrode wear compensation processes are specifically uniform wear method (UWM) and the linear compensation method (LCM). In the case of LCM, the tool wear compensation is performed by feeding the tool into work-piece after it travels a certain distance beside the electrode path. The fraction of the tool feed depth to the traversing space is supposed to be steady. This type of process ensures the end wear of electrode and does not work significantly in three-dimensional composite profile machining [6].

3.2 Machine vision measurement method

In machine vision measurement method primarily, the compressed air was used to blow off the dielectric liquid droplets on the electrode, and after that, the tool was dragged up to a location where the machine vision process operated. A shadow reflection of the tool was then obtained by employing an equivalent light, and the deformation of the electrode was determined. This method is not capable of measuring the drilling deepness in specimens because the tool surface color is dark below the equivalent light resource detection line algorithm. Such algorithm noticed the length of the tool
with a dielectric fluid droplet on it and drilling the depth in specimens quickly and effectively [4]. In 1989 Kaneko et al. [4] proposed a technique to compensate the electrode wear of a revolving axisymmetrical electrode when layer by layer EDM method is used. The deformation of the electrode is expected, and the electrode path is automatically selected to compensate for the wear [4]. The compensation arrays are measured experimentally. In 1992 Kaneko [7] modified the compensation method by placing a charged couple device camera on the EDM testing machine to obtain the real profile of the electrode. The schematic of the experimental setup and the captured image of the electrode is depicted in Fig.1.

![Schematic setup and captured image](image)

(a) Schematic set-up  
(b) Captured image

*Fig.1 Schematic representation of the optical measurement method [7]*

Guo et al. [8] proposed a tool measurement section based upon a charged couple device machine vision method to manufacture micro tools. They revealed that when the calculated result of SEM was compared with the array of tool diameter, a relative measurement error of 3% was obtained. Huang [9] performed an investigation to form an original measurement system by employing a machine vision method. The investigational outcome shows an optimal precision and effectiveness for the measurement of electrode length and drilling depth under variant circumstances.

From all the efforts related to μEDM, the predictable tool wear is one of the most significant challenges, because it strictly degrades the correctness and decreases the consistency of the machining procedure. Hence various efforts have been situated to compensate for the volumetric failure caused by tool wear using either evaluation or monitorization techniques to facilitate the high accuracy machining.

### 3.3 Linear compensation method

LCM is the existing method to compensate electrode wear and to assure elevated machining in three-dimensional micro EDM milling [6, 10, and 11]. The conventional LCM though assumes a fixed electrode wear performance and generally relies on experimental models which are modified and updated through offline tool wear determination. According to the theory of LCM, an electrode wear compensation parameter is used to compensate the longitudinal electrode wear for sustaining the required machining accuracy. LCM is a process which compensates the electrode wear constantly or in a little increase along the electrode path [9, 10]. They revealed that in this method, the electrode is traversed in a downward direction, and after it traverses a certain distance, it is used to machine a 9×9mm square hole by employing a 1mm diameter electrode. The final smoothness of the hole base was between 2µm. However, the measure of compensation in the LCM is generally an experimental value which significantly depends on the considerable testing. Since this method frequently underperforms in three-dimensional hole machining [12]. Wang et al. [13] suggested in-situ pulse monitoring as an efficient and capable process for electrode wear compensation during the high accuracy EDM machining of hard 3D micro holes. Wang et al. [14] investigated the LCM principles, and then the in-situ method is formed to measure the pulse performance, and process dynamics in terms of variant electrode wear compensation situations. They revealed that the overall 18% saving of machining time is achieved while still sustaining the required dimensional and shape accuracy. Fig.2 depicts that the genuine average hole depth will be less as compared to the target value. However, the overcompensation will respond in a deeper hole cavity.

![Diagram showing correct, under, and over compensation](image)

*Fig.2 Machining depth error due to the wrong electrode wear compensation factors after a single machining layer [14]*
3.4 Uniform wear method

To overcome the restrictions of the LCM, the UWM was introduced. In UWM, the whole machining procedure is obtained by milling several thin layers one by one. To maintain the machining depth, the electrode is compensated for a length every time before the equivalent layer is machined. In 1998 Yu et al. [6] introduced the UWM, which is a ubiquitous machining approach to compensate longitudinal electrode wear in $\mu$EDM milling. Since to and fro scanning electrodes path overlapped and machining the hole boundary and interior consistently. This approach is capable of recovering the electrode profile to its actual shape after machining one layer. Moreover, the UWM is already incorporated with CAD/CAM to fabricate random three-dimensional micro holes [15]. Kruth et al. [16] introduced a predictable wear compensation approach where the electrode wear for each section of the electrode is measured by offline prediction. This compensation process is further depending upon the offline determination of volumetric relative wear and does not influence more for online wear compensation. Though EWR was employed widely in various offline electrode wear compensation approaches, however, several problems exist in measuring EWR. Initially, the EWR is extremely affected by both the material and methods which must be modified by experiments for an appropriate geometry and needs a high setup time [11]. Secondly, as the dimension of the electrode is extremely small, and erosion from the electrode is considerably less than the specimen, the determination of EWR is influenced by elevated imprecision [12]. Nguyen et al. [17] also used tool wear compensation in UWM, which gives an enhanced evaluation of wear as compared to the theoretical model. Yu et al. [3] introduced a new electrode wear compensation method, called CLU, by combining LCM with UWM to resolve the issue mentioned above. By using this approach, they considerably enhanced SR and machining performance. The investigational results show that machining efficiency like MRR, EWR, and SR has been enhanced by employing the proposed approach as compared to UWM.

3.5 The fixed length compensation method

To enhance the layer thickness of $\mu$EDM milling, which restricts the performance of UWM and LCM method Pie et al. [18] proposed a fixed length compensation method by employing cylindrical electrodes. In fixed length compensation process, an accurate theoretical model of electrode wear was produced, and the probability of obtaining huge layer thickness was confirmed. By taking compensation of the highly accurate theoretical model and huge layer thickness, a high precision and machining performance was achieved. However, as stated by Zhang et al. [19], a conic electrode end was obtained in a fixed state during the fix length compensation milling method. Because of this, an additional measure must be performed to remove those alterations which considerably enhance the problem of machining method. Moreover, Pie et al. [18] proposed the fixed length compensation process when a rotating tool traverses a fixed length between two compensation processes. The fixed length is based on the compensation precision and the layer width. Since the process was capable of restraining the effect of electrode wear on the surface accuracy, both the measurement precision and the shape precision were optimized. Due to the expected wear of tool in $\mu$EDM Pie et al. [20] further introduced an enhanced fix length compensation approach for $\mu$EDM milling of the workpiece by employing a tubular electrode. They found that the comparative error of the fabrication was controlled in 2% for most of the circumstances, and the surface variation was smaller than 4 $\mu$m.

The drawbacks of offline electrode wear compensation methods like a disturbance in machining because of the periodical determination of electrode wear and problems in measuring EWR former to machining can entirely be removed by providing an online electrode wear compensation method.

IV. Online tool wear compensation

The compensation methods discussed in the earlier sections, however, not become initiator in electrode wear compensation as they led to discontinued and unwanted machining period. To overcome the limitations of the offline tool, wear compensation method, and for the entire removal of dimensional imprecision, real-time electrode wear compensation approach is introduced. Usually, the modern real-time electrode wear compensation approach compensates tool wear by approximating and predicting the real-time volume ($V_{RT}$) eliminated from the specimen rather from the electrode. As the approach is mainly depending upon Volume removal per discharge (VRD) determined from the specimen, it is crucial to approximate the VRD precisely. This is obtained either by discharge pulse counting method or by statistical pulse discrimination method. The previous one does the electrode wear compensation by counting the number of discharges and multiplying it among the electrode wear per discharge or VRD from the electrode or specimen, respectively.

4.1 Pulse counting based

This approach is based on counting the discharges through a pulse counter and compensating on the assumptions of approximating volume removal from the electrode or specimen by employing a predetermined value of tool wear per discharge and VRD. In 2002 Bleys et al. [21] first proposed a real-time electrode wear compensation method for conventional EDM milling. They demonstrated a connection between electrode wear and the number of normal discharge, considering the pulses are isoenergetic. However, this approach cannot be used to $\mu$EDM as the pulses in $\mu$EDM are non-isoenergetic. So Bleys et al. [22] in 2004 further depicted a compensation process depends upon real-time electrode wear sensing, which could be related to unwanted profiles. The downwards motion was constrained according to the EWR determined earlier; hence, the error formed by longitudinal electrode wear was removed. Bhattacharyya et al.
[23] proposed a technique for constant online determination of electrode wear based on the economical spindle motor voltage and current calculation for the complex and irregular cutting surface milling operation. Further, the study was invented by Bissacco et al. [24,25] and enforced to µEDM milling by selecting electrode wear per discharge. However, determinations of electrode wear per discharge are extremely affected by imprecision as the removal from the electrode is very small than that of the specimen. This tends to the improvement of electrode wear compensation technique depended upon real-time determination of VRD from specimen relatively than from electrode. Related to these, Jung et al. [26] first introduced an indirect method of real-time electrode wear compensation in µEDM milling by approximating eroded specimen volume, instead of determining electrode wear. The electrode wear compensation was applied by just counting the discharges and compensating according to the VRD. Bissacco et al. [27] also carried out an equivalent type of electrode wear compensation in µEDM milling. MRD presented a reducing path with the development of the machining process and achieving stabilization after a particular depth based on the power range. Jung et al. [28] first used this approach to µEDM drilling and presented an error of larger than 11%. In all these studies mentioned above the pulses are supposed to be isoenergetic and VRD to be stable during the machining. Hoang and Yang [29] explains a real-time determination of MRR and the specimen height. They revealed that this process enhances the performance and production of the µWEDM method since the working capability of the RC circuit can be increased. Wang et al. [30] also performed an investigation on real-time pulse counting to study the influences of the irregular current flow during the removal of material and the electrode wear in the µEDM method. They found that the reverse current flow is supporting to straighten the boundaries of debris and to shape the debris entirely. Nguyen et al. [17] used a real-time examination approach to find out the number of compensation in UWM, which gives an optimal determination of wear as compared to the theoretical model. However, Yeo et al. [31] and Alligiri et al. [32] revealed that there is a significant alteration of VRD while determined at the different deepness of machining. In µEDM arc discharge constantly comes in a set of pulses with a very small-time period and small current amplitude value as depicted in Fig.3.

![Fig.3 A µEDM waveform with its classification [32]](image)

To minimize the time exhausted in determining the offline electrode wear compensation, the online wear examining method was then established by counting the number of pulses indirectly during the machining.

4.2 Pulse discrimination based
All the authors mentioned above supposed that µEDM pulses are contributing pulses. However, Bissacco et al. [27] revealed that these are non-contributing in nature. Therefore, even for similar alternative settings, the efficiency level of every pulse will not be the same, and therefore, their contribution to the removal of material will also fluctuate. Hence while determining VRD, this non-contributing nature of the pulses must be measured. For that detection of variant kinds of contributing and non-contributing pulses is extremely important. This method of determination of pulses, at last, tends to the development of complete discrimination based on electrode wear compensation process. Alligiri et al. [32] first proposed a pulse counting based online electrode wear compensation method in µEDM drilling. This method was based on complete discharge discrimination and removal of material description through the determination of debris volume of single discharge by employing a thermal model. According to the author, the approach was depended on the determination of debris volume of discharge. Fig.4 depicts the schematic of a µEDM system for real-time monitoring of tool wear compensation.
However, Aligiri et al. [32] also performed an electro thermos modeling for single discharge erosion. For every developed discharge waveform, the pulse on time, regular current during the pulse on time, and standard voltage during pulse on time are removed. Firstly, the pulse on time is employed to determine the heat source radius to deliver the boundary circumstances for the anode. The heat source radius, which signifies the development of plasma channel and generally indicated as a function of pulse on time is proposed by Patel et al. [33] in 1989, and this is expressed as:

\[ R = 0.0633 \times T_{on}^{0.7616} \]  

(1)

Here, \( R \) illustrates the heat flux radius in micrometers and \( T_{on} \) illustrates the pulse on time in nanoseconds. These alternatives are then employed to calculate the magnitude of heat flux \( (q) \) which is considered as consistently distributed \( q \) with a time-dependent magnitude as proposed by Patel et al. [33] and obtained from the following equation:

\[ q = \frac{C_{x} \times T_{on}}{\pi \times R^{2}} \]  

(2)

The dimensionless parameters such as \( \frac{a \times T_{on}}{R^{2}} , \frac{u}{R} , \frac{w}{R} , \text{ and } \theta (u, w, \tau) = \frac{k_{i} x T (r, z, t, \tau)}{q \times R} \) with the material properties of specimen are proposed to deliver a normalized temperature distribution in the vertical axis as suggested by Carslaw and Jaeger [34].

\[ \theta (0, w, \tau) = \sqrt{\frac{\tau}{\pi}} \exp \left( - \frac{w^{2}}{4T} \right) \left[ 1 - \exp \left( - \frac{1}{4T} \right) \right] + \sqrt{\frac{w^{2} + 1}{\sqrt{\tau}}} \text{ erfc} \left( \frac{\sqrt{w^{2} + 1}}{\sqrt{\tau}} \right) - w \text{ erfc} \left( \frac{e}{\sqrt{\tau}} \right) \]  

(3)

The normalized temperature distribution in terms of the horizontal axis is provided by Yeo et al. [35] in equation (4):

\[ \theta (u, o, \tau) = I_{1} - I_{2} \]  

(4)

However, the result of first integral i.e. \( I_{1} \) is proposed by Thomas et al. [36] and expressed as follow:

\[ \begin{cases} E (u), & \text{when } 0 < u < 1 \\ \frac{2}{\pi} , & \text{when } u = 1 \\ \frac{2}{\pi} \left[ E (u^{-1}) - (1 - u^{-2}) K (u^{-1}) \right] , & \text{when } u > 1 \end{cases} \]  

(5)

In this equation, \( K \) and \( E \) are the elliptical first and second kind integral correspondingly.

Moreover, the result of the second kind integral, \( I_{2} \) is provided by Beck [37] in 1981 and is expressed as follow:

\[ I_{2} = \frac{1}{\sqrt{\pi \tau}} \sum_{i=0}^{\infty} \left\{ (-1)^{i} ! \frac{1}{(2i + 1)(4i)} \sum_{j=1}^{i+1} \frac{u^{i-1}}{(j-1)!(i-j+2)} \right\} \]  

(6)

The dimensionless temperature circulation along the radial axis can be determined by joining the results of equations (5) and (6) in equation (4).

V. LITERATURE REVIEW

The details of the different types of tool wear compensation methods proposed by various investigators on \( \mu \) EDM in their investigational and systematic study are summarized and depicted in Table. 1 and Table. 2.
<table>
<thead>
<tr>
<th>SN</th>
<th>Author</th>
<th>Year</th>
<th>Type of compensation</th>
<th>Benefits/conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.</td>
<td>Kruth et al. [16]</td>
<td>2000</td>
<td>UWM</td>
<td>The largest tensile stress and the penetration depth of tensile stress reduce due to the rise in the amount of finishing stages.</td>
</tr>
<tr>
<td>3.</td>
<td>Lim et al. [38]</td>
<td>2003</td>
<td>Machine Vision</td>
<td>For the steady and significant scanning EDM, a capacitance of 1-10 nF and space control speed of 0.01-0.02 mm/s has been obtained to be more appropriate arrays.</td>
</tr>
<tr>
<td>4.</td>
<td>Pham et al. [1]</td>
<td>2004</td>
<td>Machine Vision</td>
<td>The whole machining performance was based on a complicated relationship between the variant progression alternatives, and their optimization mostly depends upon experimental processes.</td>
</tr>
<tr>
<td>5.</td>
<td>Guo et al. [8]</td>
<td>2005</td>
<td>Machine Vision</td>
<td>The array of tool diameter with a relative measurement error of 3% was obtained via a machine vision method when evaluated with the calculated result of SEM.</td>
</tr>
<tr>
<td>6.</td>
<td>Kurnia et al. [39]</td>
<td>2008</td>
<td>Machine Vision</td>
<td>The analytical prediction responses for MRR and EWR are obtained to have a difference of about 30-40% respectively from their equivalent experimental data.</td>
</tr>
<tr>
<td>7.</td>
<td>Yu et al. [3]</td>
<td>2010</td>
<td>CLU</td>
<td>The investigational results show that the machining performance and SR have been enhanced; however, the EWR has been decreased.</td>
</tr>
<tr>
<td>8.</td>
<td>Yan et al. [40]</td>
<td>2011</td>
<td>Machine Vision</td>
<td>The multi-cut development process and tool wear compensation technique can considerably enhance the machining precision and decrease the machining time for the μEDM process.</td>
</tr>
<tr>
<td>9.</td>
<td>Nguyen et al. [17]</td>
<td>2015</td>
<td>UWM</td>
<td>The UWM was used to make sure that the tooltip profile remains unaffected. Moreover, it was obtained that there was no error in deepness and breadth during grooving and a minute error in 3D holes machining.</td>
</tr>
<tr>
<td>10.</td>
<td>Zhang et al. [19]</td>
<td>2015</td>
<td>Fix Length</td>
<td>The above results depict that the relative error of the reproduction as compared to the investigational data is between 4% under the majority of machining circumstances.</td>
</tr>
<tr>
<td>11.</td>
<td>Wang et al. [13]</td>
<td>2016</td>
<td>LCM</td>
<td>The alteration of the tool path pattern is a very significant parameter which influences the behavior of this combined process, and a decrease of higher than 80% of the amount of original offline compensation method is obtained.</td>
</tr>
<tr>
<td>12.</td>
<td>Pei et al. [18]</td>
<td>2016</td>
<td></td>
<td>The investigational results revealed that the error of compensation length was between the 2 μm and the consistency of the machined plane with a deepness of 66 μm was between the 4 μm, respectively.</td>
</tr>
</tbody>
</table>
13. Wang et al. [14] 2017 LCM The overall save of machining time up to 18% has been achieved when still sustaining the required dimensional and shape accuracy.

14. Dong et al. [41] 2017 Machine Vision The tool wear standard diameter and taper angle enhanced as the current rises. While the current arrives at 3.5A, the machining constancy decreases, which shows that the high current is not optimal for large aspect ratio microcavity.

15. Pie et al. [20] 2018 Fix Length The relative error of the fabrication was controlled in 2% for the majority of circumstances, and the surface variation was smaller than 4 μm.

### TABLE II
LITERATURE REVIEW ON ONLINE TOOL WEAR COMPENSATION METHODS

<table>
<thead>
<tr>
<th>SN</th>
<th>Author</th>
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<th>Type of compensation</th>
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</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Bleys et al. [21]</td>
<td>2002</td>
<td>Pulse Counting</td>
<td>A connection between electrode wear and the number of normal discharge was established, considering the pulses are isoenergetic. However, this approach cannot be used to μEDM as the pulses in μEDM are non-isoenergetic.</td>
</tr>
<tr>
<td>2.</td>
<td>Bhattacharyya et al. [23]</td>
<td>2007</td>
<td>Pulse Counting</td>
<td>The paper depicts that it is probable to vary the cutting force signals overall as an indicator of electrode wear through the power and current signals</td>
</tr>
<tr>
<td>3.</td>
<td>Jung et al. [28]</td>
<td>2008</td>
<td>Pulse Counting</td>
<td>It has been proposed that the developed process makes 2D and 3D μEDM milling methods-fast and precise without any compound path development to compensate tool wear.</td>
</tr>
<tr>
<td>4.</td>
<td>Liao et al. [42]</td>
<td>2008</td>
<td>Pulse Discrimination</td>
<td>The formed discriminating method can be used for the design of an optimal servo control method in a μEDM associated process μEDM drilling, and it is in process.</td>
</tr>
<tr>
<td>5.</td>
<td>Yeo et al. [31]</td>
<td>2009</td>
<td>Pulse Counting</td>
<td>There is a significant alteration VRD while determined at the different deepness of machining.</td>
</tr>
<tr>
<td>6.</td>
<td>Alligiri et al. [32]</td>
<td>2010</td>
<td>Pulse Discrimination</td>
<td>The developed drilling process can compensate electrode. The depth error of drilling 900 μm micro-hole can be minimized to 4% by using this process</td>
</tr>
<tr>
<td>7.</td>
<td>Bissacco et al. [27]</td>
<td>2013</td>
<td>Pulse Counting</td>
<td>From the executed experimentation in μEDM, it has been found that the ratio within the anode wear and cathode wear decreases with a decrease in discharge time interval apart from the discharge energy contents.</td>
</tr>
<tr>
<td>8.</td>
<td>Tee et al. [43]</td>
<td>2013</td>
<td>Pulse Discrimination</td>
<td>They depict a high performance of this process by differentiating the standard pulses from harmful pulses, short circuit, and open circuit pulses based on their determination of delay period.</td>
</tr>
<tr>
<td>9.</td>
<td>Wang et al. [30]</td>
<td>2016</td>
<td>Pulse Counting</td>
<td>The reverse current flow is supporting to straighten the boundaries of debris and to shape the debris entirely.</td>
</tr>
</tbody>
</table>
VI. CONCLUSIONS

The issue of immanent tool wear, which leads to dimensional inaccuracies in the micro-parts developed by µEDM and its process variant, is introduced in this article. The tool wear compensation techniques to overcome dimensional inaccuracies is presented in the form of a thorough review. It is learned that out of the several strategies for tool wear compensation in µEDM, the real-time based, using the PD System, performs better. As it contributes to the removal of the material using the discharge pulses of different types in a strategized fraction. The PD system plays a vital role in the strategy and is found to be normalized for varied machining conditions. In this regard, a robust electro-thermal model-based tool wear compensation technique, in combination with a real-time operating PD system, could promising results in the future.

REFERENCES