A REVIEW OF ULTRASONIC ASSISTED ELECTROLYTIC IN-PROCESS DRESSING (UA-ELID)

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Abstract: This paper presents previous research work of researchers on electrolytic in-process dressing and its ultrasonic-assisted system variant. This paper also contains information about the ELID system and applications of ultrasonic-assisted ELID. This technique enables continuous dressing of wheels made using metallic bond in the grinding process itself while retaining sharp grits from the super abrasive wheels. An ultrasonic-assisted setup requires an ultrasonic power generator, piezoelectric transducer (PZT), horn assembly. An ultrasonic generator generates ultrasonic pulses, which are supplied to the piezoelectric transducer. The piezoelectric transducer then converts electrical energy to mechanical energy and vibrates either in longitudinal mode or in transverse mode. The horn system then amplifies these vibrations, and amplified vibration is supplied to the grinding tool. The relevance of research papers referred to regarding setup development of ultrasonic-assisted electrolytic in-process dressing, effect of process parameters and modeling of the ultrasonic-assisted ELID process is described in this paper.

Keywords: ELID, PZT, Ultrasonic assisted, Mathematical modeling, the Oxide layer

1. INTRODUCTION

Electrolytic in-process dressing (ELID) is a traditional dressing method employed for the uninterrupted truing of abrasive wheels. In 1990, Japanese research scholars Ohmori and Nakagawa, for the first time, developed ELID grinding for creating excellent topographic surfaces on hard and brittle materials. Then onwards, many scholars used this method for creating mirror like surfaces by employing very fine grain metallic bonded wheels [2]. Ohmori [2] stated that ELID grinding contains a basic setup which contains a power supply, an electrode as either cathode or anode, a metallic-bonded abrasive wheel, and an alkaline electrolytic-grinding fluid.

Nowadays, many researchers are interested in ELID grinding for its intelligent method of self-dressing of the grinding wheel. Many researchers have reported their findings regarding exploring the mechanism and application of the process, though comparatively less work has been reported so far to...
create a smart machine tool, especially for ultrasonic-assisted ELID grinding. A newly developed technique of ELID is instrumental in resolving the limitations of traditional grinding for hard and brittle materials. This technique offers continuous sharpening of wheels made using metallic bond in the grinding process itself while retaining sharp grits from the super abrasive wheels. The schematic of the ELID process is illustrated in figure 1 above.

The continuous sharpening of the wheel involves the basics of the electrolysis process. Here electrical energy gets converted into chemical energy. Due to electrical energy, the dissolution of ions arises in the electrolytic solution, and the cations and anions in the solution travel towards cathode and anode, respectively. This will trigger a chemical reaction at the anode, which results in the formation of metal oxide. This oxide layer will either dissolve in an electrolyte or quickly wear out during grinding allowing new grit protrusion.

2. UA-ELID PROCESS

ELID works on the principle of electrochemistry. After the pre-dressing, the bonding material, which acts as an anode, gets dissolved, and the oxide layer of the bonding material is generated on the wheel surface. This layer acts as an insulating covering. This is the reason because of which the increase in oxide layer thickness decreases the electrical conductivity of the abrasive wheel surface and thus the electrolysis current reduces. The oxide layer will be effortlessly machined during the grinding process. As a result of this, the increment in current takes place which in turn accelerates the anodic dissolution. This makes ELID process as self-regulating and a dynamic equilibrium process [31]. The repetition of this cycle enables the process to achieve stable grinding.

Ultrasonic vibrations are generated by providing electrical power to piezoelectric plates. These plates are used in the vibrator. With the help of the excitation of different piezoelectric plates by high-frequency electrical signals, the vibrator was resonated. The transformation of electrical energy into mechanical vibration is done through the piezoelectric transducer (PZT). As the amplitude of oscillation generated at the surface of PZT was incapable to achieve a sufficient cutting rate, the tool-horn assembly is proposed to intensify the amplitude of vibration. Figure 2 illustrates bi-modal vibration produced by PZT systems, i.e., longitudinal vibration mode and transverse vibration mode [17].

In longitudinal mode the vibrations generated are in line with the axial (Z) direction, and in transverse type, vibrations produced are in the plane orthogonal to the axis. For generating longitudinal vibrations, single bunch of circular piezoelectric plates is required as illustrated in figure 2 (a). After the application of a voltage which is having a sine wave like structure to the transducer, the piezoelectric plates start broadening and shrinking, so that the vibrator is reverberated and the tooltip which is adhered to the tail end of the horn pulsates longitudinally along its axis. “The amplitude of vibration depends on the applied voltage, the property of piezoelectric material, and the arbor structures. The pulsation amplitude is boosted by the horns such that its maxima developed at the tooltip. As shown in figure 2 (b), if two semicircular shaped piezoelectric plates are situated on the PZT and two sinusoidal voltages with 180° phase difference are applied to the piezoelectric plates, the two piezoelectric plates will broaden and shrink alternately, finally causing the tool adhered to the end of the horn to vibrate in the transverse mode in the XY plane” [17].
Concerning ultrasonic horn design, Y. Choi et al. [23] have designed a tool horn length of 130.8 mm using FEM analysis. They have also found that the maximum amplitude of vibration can be obtained at an ultrasonic frequency of 20 kHz [23,42]. For fabricating the ultrasonic unit, A. Zahedi et al. [42] have selected lightweight, reasonable strength, large processability, and large sonic efficacy, aluminum alloy 7075 for the fabrication of the ultrasonic module. The intended model consists of two parts: i) booster-sonotrode, which establishes the association among the transducer and the workpiece, and ii) the housing, which retains the vibrating system on the grinding machine spindle. Figure 3 illustrates a diagrammatic representation of the ultrasonic system. It is advantageous to have a pulsation mode in the center plane of the booster so that the casing will be separated from the oscillating sequence (transducer, booster, workpiece). At the same time the maxima of oscillation should be positioned at the top of the workpiece [42].

![Diagramatic representation of the ultrasonic system with elements.]

**3. EXPERIMENTATION**

This chapter covers various materials, experimental conditions used during experimentations, and the effect of various process parameters in ELID and UA-ELID processes.

**3.1 Materials in experimentations**

Different materials like workpiece material, grinding wheel material, grinding wheel grit sizes, electrolyte, concentration, and operational situations are tabulated in Table 1 below.

| Workpiece Material | Grinding Wheel Material | Wheel Diameter (mm) | Grit Sizes (#) | Electrolyte | Concentration | Experimental Conditions |
|---------------------|-------------------------|---------------------|----------------|-------------|---------------|-------------------------|
| Reaction Bonded Silicon Nitride (RBSN) [1] | Synthetic Diamond  | 75 [4,24,31, 41] | 400 [1] | CIMTERIA L HD 90 [1] | 15:1 [1,24] | Voltage (V) 60 [2,3,4,5,7,11,31, 37,38,39,40], 70 [36,80 [7], 90 [3,16,28,32,34, 38,39], 100 [7,24] |
Silicon infiltrated Reaction Bonded Silicon Nitride (SRBSN) [1, 2] 150 [3, 26] 325 [2, 4, 29] 37 [2, 3, 39, 40]

Sintered Silicon Nitride (Si₃N₄) [2, 5] 200 [2, 5, 38] 600 [2] 1:20 [4, 5, 24, 31, 41] 1:50 [2, 4, 5, 31] 3,4 0.3 [24, 0.5 [38], 1[32, 38, 40], 2[7, 38, 40], 3, 4 [38], 5[11, 36, 39], 7[11], 9 [11, 37], 10 [2, 4, 5, 28], 13 [37], 16 [3], 20 [39], 24 [3]

Peak Current (A) Pulse on time (µs) Ultrasonic frequency (kHz) Axial Ultrasonic Amplitude (mm) Tool-w/p Gap (mm) Pre-dressing (min.) Feed rate (mm/min)

BK 7 glass [4, 7, 24, 28, 2 9, 41] Copper bonded Diamond 305 [11, 37] 1200 [24, 29, 40, 41] TRIM 229 [11, 37] Ultrasonic frequency (kHz) 20 [23], 20.6 [42], 28 [14], 35 [16], 100 [31] Axial Ultrasonic Amplitude (mm) 0.008 [14] 0.0082 [16] 0.02-0.025 [42] Tool-w/p Gap (mm) 0.1-0.3 [34, 37], 0.25 [41] 0.4 [31] Pre-dressing (min.) 5 [40] 10-15 [3, 34] 20 [41] 61.87 [37]

Silicon Wafers [5, 29] Cobalt Cast Iron Compound Diamond 23 [14] 2000 [2] TRIM C270 [11, 19, 33] 50:1 [40]

Zirconia bronze bonded Diamond 25 [16] 4000 [2, 4, 7, 11, 24, 29, 39] TJMX-V [31, 34, 38]

Sapphire [11] CBN [32, 38] 205 [25] 170 [3] Kyodo Oil [40] 0.3, 0.6, 0.9, 1.2 [42]

Ti6Al4V [23] Tungsten bonded CBN [26, 40] 211 [33] 280 [16, 31]

Carbon steel [25] D151C118 Diamond wheel [42] 60 [34] 1000 [33] 20000 [36]

SiC [33] GaN [36] 2.5 [40] 50:1 [40]

3.2 Effect of process parameters

Process parameters are key variables on which the functioning of the process relies as explained in section 2 of this paper. The impact of different operational variables like wheel velocity, depth of cut, feed velocity, oxide layer thickness, inter-electrode gap, selection of cathode and anode, vibration frequency and amplitude and mode of oscillation is studied by different researchers [16, 22, 32, 38, 42].
1) Wheel velocity
As the abrasive wheel speed increases, the surface roughness decreases as shown in figure 4 (a) this is because higher the wheel speed lesser the time of engagement of the abrasives with the workpiece and as the engagement time is less, there is a less chance of cutting of oxide layer by chips. The linear behaviour of oxide layer enhances the uniform surface topography [16].

2) Depth of cut
The increase in depth of cut raises the surface roughness because of the indentation fracture mechanics. Depth of grinding increases the extrusion resistance offered by the workpiece. This resistance between the wheel and the workpiece can expand the cracks thus the surface becomes highly nonuniform and thus the quality of the surface decreases as shown in figure 4 (b) [16].

3) Feed velocity
Feed velocity is the rate at which abrasive wheel is moving in the axial direction. Again, rise in the feed velocity rises the surface roughness as the rate of extrusion resistance increases and the fundamental of indentation fracture mechanics applies. The influence of feed velocity on surface roughness is shown in figure 4 (c) [16].

4) Oxide layer thickness
Oxide layer plays an essential role in generating the surface quality. Oxide layer acts as an insulating covering so, increase in oxide layer depth decreases the electrolysis current and vice a versa. Formation of oxide layer lowers down the actual depth of cut of abrasives. Therefore, rise in the electrolytic control current reduces the oxide layer thickness and in turn raises the actual depth of cut of abrasive particles. Furthermore, this leads to the rise of undeformed chip thickness of abrasive particles and thus the surface roughness and waviness rise as illustrated in figure 4 (d) [38].

![Figure 4. Graphs of effect of various process parameters.](image-url)
5) Inter-electrode gap
Inter-electrode gap is a gap maintained between abrasive wheel and a workpiece surface. The rise in this gap increases the electrode potential due to which the tendency of electric spark discharge rises. This phenomenon develops the corroded pits on the workpiece surface as a result of which the surface quality decreases as shown in figure 4 (e) [16,38]

6) Selection of cathode and anode
The importance of electrode is explained in section 2 of this paper. Figure 4 (f) shows the effect of selection of tool as a cathode and anode on normal grinding force. As discussed earlier, if dressing current increases then there will be reduction in the oxide layer thickness due to which actual grinding depth rises. Also, with the reduction in layer thickness, no. of protruding grains increases and this results in the rise of grinding force. Normal grinding force in ELID with workpiece as cathode is less than that of ELID with tool as cathode [32].

7) Vibration frequency and amplitude
Energy ratio decreases with the combined effect of increase in ultrasonic pulsation frequency and the amplitude which is also illustrated in figure 5. The decrease in the grinding energy ratio inherently increases the surface quality [42].

![Figure 5. Impact of oscillation frequency and amplitude on the energy ratio. [42]](image1)

8) Mode of oscillation
Vibrations can be applied in two modes i.e., longitudinal vibrations (orthogonal to the grinding direction) and transverse vibrations (along the grinding direction) figure 6 illustrates these vibrations schematically. Amplitude of vibration is less in longitudinal mode than the transverse mode also, longitudinal deepens the valley height whereas transverse reduces the peak height. This is the reason why longitudinal vibrations increases the surface roughness and transverse vibrations smoothen the surface roughness [22,42].

![Figure 6. Schematic of the effect of oscillation modes. [42]](image2)
4. MATHEMATICAL MODELING

In this chapter, various mathematical models regarding oxide layer formation and surface quality prediction in ELID as well as UA-ELID are explained.

4.1 Oxide layer formation

An oxide film is formed by the electrolysis process as explained in chapter III of this paper. The formation of an oxide film significantly contributes in improving the topography of the surface in ELID grinding. When the oxide film is too dense, the work surface has remote possibility of being machined by an abrasive wheel surface which consists of pointed abrasives. When the oxide layer is too lean, the metal bond is eroded quickly and the grinding wheel fade out at higher rate. Therefore, the depth of the oxide layer affects the operational state instantly. Many researchers worked on developing the mathematical model of oxide layer thickness formation [12,14,19].

X. Jia et al. [14] have studied and formulated the mathematical model of oxide layer thickness in UA-ELID multiplicate grinding. In addition to electrolysis and Faraday’s law, they have incorporated the effect of ultrasonic vibrations and removal of the oxide layer due to crack propagation. Worn out grains are being squeezed out by workpiece particles. This squeezing cause regional softening of the oxide layer and surface fractures got enhanced by residual stress of permanent distortion. The unit grinding force on single grain \( F_p \) can be expressed as per Eq. (1) and the average normal force per grain \( F_{ng} \) can be expressed in Eq. (2).

\[
F_p = \frac{6\lambda a_p v_w}{\pi \cos \beta N m (v_s+v_w)} \phi \sqrt{1 + \left(\frac{2A_0 \pi f}{v_s+v_w} \cos \left(\frac{2\pi f}{v_s+v_w} x + \varphi_0\right)\right)^2} dx
\]

\[
F_{ng} = F_p \left(\frac{a_v}{v_s}\right)^2 a_p \frac{2}{D} \sin \beta \tan \beta
\]

Where “\( \lambda \) is a constant related to material, \( a_p \) is plastic deformation per unit grain, \( v_w \) is workpiece feed speed, \( v_s \) is the velocity of grinding wheel, \( \beta \) is the half conical angle of a single grain, \( N_m \) is grain number of unit area, \( A_0 \) is the amplitude of ultrasonic vibration, \( f \) is the frequency of ultrasonic vibrations, \( \varphi_0 \) is initial phase angle and \( a \) is the distance between continuous cutting edges” [14].

“When \( F_{ng} > \) holding force for a single grain, the macroscopic cracks are created on the contact interface between oxide layer and grains. By the principle of indentation fracture, the volume of the oxide layer fall of per grain (\( \alpha \) can be written” [14] as Eq. (3) and thus the thickness of the oxide layer (\( h \)) at any time (\( t \)) can be expressed in Eq. (4).

\[
\alpha = \alpha_0 \left(\frac{F_{ng}}{\eta A U S_c \alpha_1 R_c} \right)^{\frac{9}{8}} \left(\frac{K_c}{H}\right)^{\frac{1}{8}} \left(\frac{E}{H}\right)^{\frac{3}{4}} \frac{v_s}{2} \]

\[
h = \sqrt{\frac{\eta A U S_c \alpha_1 R_c t}{2\left(1-\frac{\pi}{6}\right)}} \rho_p \rho F R^2 DB + \frac{\rho_4 \rho_2 \sigma^2}{4 \rho_2 \sigma^2} (t \leq t_0)
\]

\[
h = \sqrt{\frac{\eta A U S_c \alpha_1 R_c t}{2\left(1-\frac{\pi}{6}\right)}} \rho_p \rho F R^2 DB + \frac{\rho_4 \rho_2 \sigma^2}{4 \rho_2 \sigma^2} - \frac{\rho_4 \rho_2 \sigma^2}{2\rho_y} \left(\frac{6\eta}{\pi \rho_4 \rho_2 \sigma^2} \right) \left(\frac{v_s+v_w}{a_v a_1}\right) \alpha_2 R_c (t-t_0) (t > t_0)
\]

Where, “\( \eta \) is current efficiency, \( A \) is atomic mass, \( U \) is effective voltage, \( S_c \) is cathode active area, \( \alpha_1 \) is the wrap angle of layer formation area, \( R_c \) is duty ratio, \( t \) is time, \( k \) is the volume ratio of grain, \( \rho_p \) is the resistivity of an oxide layer, \( \rho \) is the density of the oxide layer, \( n \) is no. of valence electrons, F is
Faraday’s constant, D is the diameter of the grinding wheel, B is outside diameter width of the grinding wheel, σ is electrode gap, \(d_g\) is the diameter of diamond grain, \(\alpha_2\) is the wrap angle of the grinding area and \(t_0\) is the time when the oxide layer just begins to shed” [14].

4.2 Surface quality prediction

UA-ELID process is generally used for the mirror-like surface finish of brittle materials. Bo Zhao et al. [16] have analyzed the interrelationship between abrasives and workpiece surface by using kinematic mechanics. Impact of ultrasonic vibration on single abrasive grain of grinding wheel, the effect of oscillations on two adjoining abrasive grains and effect of ELID process parameters has been cumulatively studied. They have finally developed the predictive mathematical model of surface roughness in ultrasonic-aided ELID internal grinding as shown in Eq. (6). The true grinding depth \(a_p\) can be modeled as shown in Eq. (5).

\[
a_p' = a_p - \frac{\eta_2 M D U A_c}{2 \pi F \rho A_a (\rho_e h_e + \rho_f h)} \tag{5}
\]

Where “\(a_p\) is the nominal grinding depth, \(\eta_2\) is the current efficiency, \(M\) is the molecular weight of the metal bond, \(D\) is the duty ratio, \(U\) is the electrode voltage, \(A_c\) is the effective cathode area, \(z\) is the valence of metallic element, \(F\) is the Faraday’s constant, \(\rho\) is the density of metal bond, \(A_a\) is the effective conducting area at the anode, \(\rho_e\) is the electrolyte resistivity, \(h_e\) is the inter-electrode gap, \(\rho_f\) is the resistivity of the oxide layer and \(h\) is the thickness of the oxide film” [16].

After adding the effect of ultrasonic vibrations and the effect of ELID parameters, finally, Bo Zhao et al. [16] have developed the mathematical model of surface roughness \(R_z\) for internal UA-ELID as shown in Eq. (6).

\[
R_z = \sqrt{2} \cdot \frac{\pi}{6 V_g} \cdot \frac{\eta_1 f a \cdot d_{avg}}{f s A A^2 V_s} \cdot \sqrt{a_p' \cdot \left(\frac{R_w - R_s}{R_w - R_s}ight) \cdot \left\{\frac{R_w}{V_s - V_w} \cdot \left(\frac{A_p}{V_s - V_w} + \left[\frac{R_w f a}{V_s - V_w} + 2 A \pi f}\right)^2 \right\}^2} \tag{6}
\]

Where, “\(V_g\) is the volume fraction of grains, \(\eta_1, \zeta_1, \zeta_2, \zeta_3\) are the correlation coefficients and indexes for considering the effect of adjacent grits on the workpiece surface, \(f_a\) is the axial feed velocity, \(d_{avg}\) is the average diameter of the abrasive particle, \(f\) is the frequency of ultrasonic vibrations, \(A\) is the amplitude of ultrasonic vibrations, \(V_s\) is the velocity of the grinding wheel, \(R_w\) is the radius of the workpiece, \(R_s\) is the radius of the grinding wheel and \(V_w\) is the velocity of the workpiece” [16].

Bo Zhao et al. [16] have also found that values of surface roughness predicted using the above model of surface quality they had developed were in good agreement with the actual surface roughness values by the experiments.

5. APPLICATIONS

5.1 Fine grinding of bearing components

In the bearing industry, it is foremost essential to enhance the surface quality of roller surfaces, which assists in decreasing disturbances and fluctuations during the functioning. SiC is usually used as the material of bearing rollers, however, by the virtue of its large hardness, it is hard to obtain a mirror-like surface by machining. For obtaining remarkable bearing quality, the surface of a roller is required to be ground, lapped, and then polished with a conventional finishing method, which increases time as well as cost. With the ELID grinding of Sic rollers, we can achieve surface roughness of 30-70 nm depending on load [33].
“The surface roughness of the bearing raceway is considered as a critical parameter of transmission accuracy. A relatively rough surface indicates the possibility of deeper damage since rough surface on the raceway can be correlated to subsurface damage, while a relatively fine surface will exert an adverse effect on the fatigue life of the finished ball bearing. Therefore, it is desired that the surface roughness on the raceway is constant in an acceptable range. With the grinding time extended from 2 to 30 min, the surface roughness on the raceway was kept stable between 0.43 and 0.53 μm constantly at the feed rate from 0.0012 to 0.006 mm/min” [34]. The section-wise raceway profile is shown in figure 7 [34]. They also concluded that the ELID groove grinding combined with intermediate truing has a considerable scope of application in accurate fabrication of bearing raceway.

5.2 Grinding and thinning of Silicon Wafers
Silicon wafers are largely employed in integrated circuits. In order to achieve high quality and low cost, J. Liu et al. [35] have used the ELID finishing of silicon wafers. They found that the surface roughness of about 1.85 nm and subsurface crack of less than 1 μm was achieved [35]. During the thinning of silicon wafers by ELID, unstable forces were observed [6]. So, M. Islam et al. [6] have newly developed Injection Electrode assisted ELID and have effectively thinned down silicon wafers from “750 μm to 70 μm” [35]. Also, they have observed a high surface quality of about 6 nm.

5.3 Light Emitting Diodes (LED)
The use of hard and brittle materials in the light-emitting diodes has been increased in several years. Silicon carbide (SiC), gallium nitride (GaN), and sapphire (α – Al₂O₃) are used as support material for LEDs. These materials are complicated to machine by virtue of mechanical properties they possess also these materials are chemically stable so, difficult to erode as well. H. Lee et al. [36] have used the sequential process of ELID and chemical mechanical polishing (CMP) to fine machining of these materials. They have observed surface roughness (Rₐ) for SiC 0.4 nm, for sapphire wafer 0.8 nm and GaN 1 nm [36].

5.4 Optical Components
Micro-optical components play an important role in applications like fiber optics, optical storage systems, and portable information devices. Surface finishing of micro components needs smaller grinding wheels, small grinding velocity, and adequate wheel-workpiece stiffness. Mirror surface finish of optical components as shown in figure 8 is desirable. With ELID grinding, microlens can be finished with great quality as ELID grinding wheels have high wheel-workpiece stiffness. Most of the optical components require Si wafers with high finish [3,10]

5.5 Micro hole machining
In many industrial fields there is an ample demand of the micro hole machining of advanced ceramics. Manufacturing of micro hole in hard and brittle materials has problems such as abrasive wheel is prone to wear more and loaded due to low grinding velocities. The process is slightly unstable also removing of grinding chips is difficult and precision as well as surface quality of machined holes are not excellent.
C. Zhang et al. [40] have used ELID – II system for micro-hole machining and have found that grinding forces reduced and micro-hole entrance and exit didn’t have crack marks [40]. Micro holes of 250 µm were finished on ceramic materials [26].

6. Conclusions

This paper gives the gist of literature referred for the ELID and UA-ELID processes. After the study of literature, the following are concluded

i. UA-ELID enhances the quality of the surface than the normal ELID process. Also, UA-ELID works in ductile regime hence is more suitable for nano composite ceramics than ELID.

ii. Longitudinal vibrations reduce the surface topography whereas transverse vibrations increase the quality of the surface.

iii. Recommended values of electric current, voltage and inter-electrode gap are 0.5-1A, 60-90V and 0.1-0.3 mm respectively. If current is less than 0.5A, then corrosion pits are developed on the surface due to electric spark and if current is greater than 1A, then it reduces the depth of oxide layer thus actual grinding depth increases which in turn reduces the surface quality.

iv. Many researchers had worked in the mathematical modeling of oxide layer thickness formation while some researchers had worked in developing surface quality prediction models for both ELID and UA-ELID. These models were used again by some researchers for developing precision controlling and online monitoring systems.

v. While much of the work has been done for ELID – I & ELID – II systems, less work has been reported in ELID – III & ELID – IV systems. So, the authors take this opportunity to highlight this area for further developments in this area.

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