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AN ANALYSIS OF ELECTROLYTIC IN-PROCESS DRESSING (ELID) GRINDING

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Abstract

In this article, introduces and reviews abrasive processes assisted by electrolytic in-process dressing (ELID) technique. This in situ dressing method is used for metal-bond wheels and is relatively new. As illustrated by the examples given below, the introduction of this technique has been highly successful when fine grain wheels were efficiently used to obtain very low surface roughness, and when hard ceramics had to be machined using a very small grain cutting depth in order to avoid failure by cracking.

The basic system, principles, and characteristics of ELID abrasion mechanisms are introduced first. The success and wide application of ELID principles to ceramic grinding are explained. Fourteen applications of the ELID principle to modern abrasive processes are documented to illustrate the scope of application.

Keywords: Electrolytic in-process dressing (ELID), electrode, grinding abrasive, ceramic materials, biomedical materials.

Introduction

Electrolytic in-process dressing (ELID) grinding was first proposed by the Japanese researcher Hitoshi Ohmori back in 1990. The most important feature is that no special machine is required. Power sources from conventional electro-discharge or electro-chemical machines can be used for ELID, as well as ordinary grinding machines. The basic arrangement of the ELID system for surface grinding is shown in Fig. 1. The essential elements of the ELID system are a metal bonded grinding wheel, a power source, and a high pH electrolytic coolant. The metal-bonded wheel is connected to the positive terminal of a power supply with a smooth brush contact, while the fixed electrode is connected to the negative pole. The electrode is made out of copper and must cover at least one sixth of the wheel's active surface and a width that is two millimeters wider than the wheel rim thickness. The gap between the wheel and the active surface of the electrode is 0.1–0.3 millimeters and can be adjusted by mechanical means. The grinding wheel is dressed as a consequence of the electrolysis phenomenon that occurs between the wheel and the electrode, when direct current (dc) is passed through a suitable grinding fluid that acts as an electrolyte.

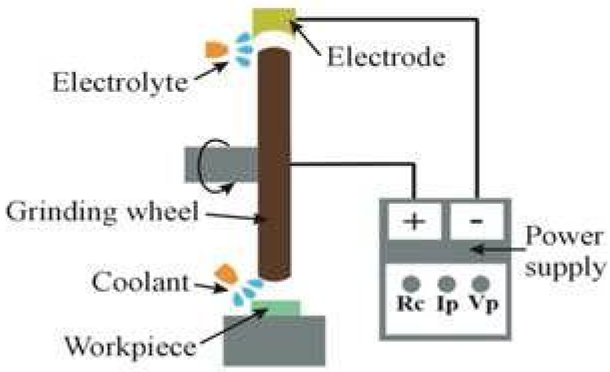

Figure 1. Basic arrangement for ELID grinding.

Literature review

Basic principles. Electrolytic in-process dressing (ELID) grinding is a process that employs a metal-bonded super abrasive wheel together with an in-process dressing by means of an electrolytic action. The electrolytic process continuously exposes new sharp abrasive grains by dissolving the metallic bond around the super abrasive grains, in order to maintain a high material removal rate and to obtain a constant surface roughness.

A key issue in ELID is, according to Chen and Li, to balance the rate of removal of the metal bond by electrolysis and the rate of wear of the super abrasive particles. While the super abrasive wear rate is directly related to grinding force, grinding conditions, and work piece mechanical properties, the removal rate of the metal bond depends on ELID parameters such as voltage, current, and the gap between the electrodes.

The rate of dissolution of the bond metal is highest at the metal diamond interface particles. In other words: the tendency of electrolytic dissolution is to expose the diamond particles. Consequently, the metal dissolution rate increases with concentration of the diamond particles.

For a fixed gap and applied voltage, the current density does not change much with concentration of diamond particles. Hence, in order to maintain a constant rate of metal removal, the applied electric field should be lower for a higher diamond concentration and, vice versa, the applied electric field should be higher for a lower concentration of particles. This electric field concentration effect is greatly reduced when the diamond particle is half-exposed. The field sharply decreases from its highest value near the diamond-metal boundary, to a small value at a distance of the order of the diamond particle size. In a conventional grinding operation, the tool face is smooth and has no protrusion of diamond particles after truing. Mechanical dressing opens up the tool face by abrasion with a dressing stone, which exposes the grits on the leading side while they remain supported on the trailing side.

Laser and electro-discharge dressing opens up the tool face by thermal damage, producing craters, micro cracks, and grooves. This degrades the diamonds because diamond undergoes a graphitization alteration at approximately 700°C. During electro-chemical dressing operations grits are exposed by dissolving the surrounding metal bonds.

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The stages of ELID grinding are depicted in Fig. 2 and presented below:

1) *Truing* is carried out to reduce the initial eccentricity below the average grain size of the wheel and to improve wheel straightness, especially when a new wheel is first used or re-installed. Precision truing of a micro grain wheel is carried out to achieve a runout of less than 2–4 microns. In Fig. 9.5, details of the truing method are presented. A special electrical discharge (ED) truing wheel, made out of high temperature bronze-tungsten carbide alloy and insulated from its central shaft, is mounted on a three-jaw chuck, and connected to a negative pole. Both wheels rotate at rather low speeds and the ED-truing wheel reciprocates with the machine tool's saddle. Little or no coolant is supplied to prevent electrolysis and to obtain high truing precision. After truing, a pre-dressing operation is required prior to grinding.

2) *Pre-dressing* of the wheel by electrolytic means aims to increase protrusion of the abrasive grains. The procedure is performed at low speed and takes about 10–30 minutes.

3) *Grinding* is performed simultaneously with continuous in process dressing by electrolytic means.

4) *Stabilized* wheel condition during ELID grinding.

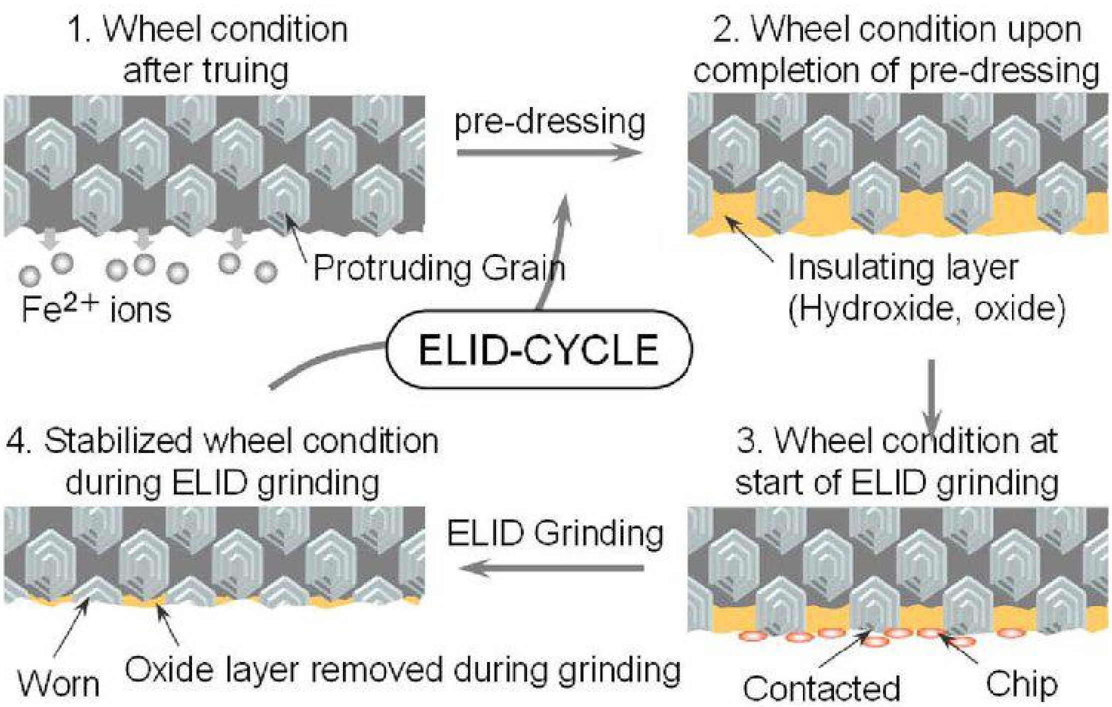

Figure 2. Stages of ELID grinding.

Research methodology

Grinding wheels for ELID applications. The grinding wheels utilized for ELID-assisted abrasive processes have two main characteristics. They contain fine and very fine super abrasive grains, and they are made with electrically conductive bond. Usually, the combination of ultrafine super abrasive grains and metal bond makes the wheels prone to rapid dulling and very difficult to dress, unless special techniques, as is ELID, are employed to maintain their cutting ability throughout the process. Therefore, the grinding wheels for ELID applications include cast iron bonded and cast iron fiber-bonded wheels, with diamond or cubic boron nitride (CBN) super abrasives.

Cast Iron Bonded Diamond. These wheels are manufactured by mixing diamond abrasive, cast iron powders or fibers, and a small amount of carbonyl iron powder. The compound is shaped to the desired form under pressure of 6–8 ton/cm2, and then sintered in an atmosphere of ammonia. These wheels are unsuitable for continuous grinding for long periods of time, particularly for metals.

This is because of the following:

1. A tough metal-bonded wheel is difficult to dress, so efficient and stable grinding cannot be achieved.
2. High material removal rate wears the abrasive and requires frequent redressing.
3. The wheel becomes embedded with swarf during grinding of steels and other metals.

Cast Iron Fiber-bonded Diamond. These wheels provide high grinding ratio and high material removal rates.

Cubic Boron Nitride (CBN). Tough metal-bonded CBN wheels can be dressed during the grinding process using the ELID technique. This process can be used to control abrasive protrusion before and during the grinding of ceramics.

ELID grinding of ceramics. In recent years, a number of publications confirm the merits of ELID grinding for common brittle materials, but also for BK-7 glass, silicon, and fused silica using fine-mesh superabrasive wheels.[5] Many of these publications report that the ELID system provides the ability to obtain spectacularly fine finishes on brittle material surfaces, down to the nanometer scale of 4 to 6 nanometers, after grinding operations. For some applications, this completely eliminates the need for loose abrasive lapping and/or polishing operations. ELID grinding has also been applied to the fabrication of large optical components, 150 to 250 millimeters in diameter. The data also suggest that ELID grinding can be successfully applied to very thin deposited substrates. Applications of ceramics are found in tool manufacture, automotive, aerospace, electrical and electronics industries, communications, fiber optics, and medicine.

The properties of ceramic materials, as for all materials, depend on the types of atoms, the types of bonding between the atoms, and the way the atoms are packed together, also known as the atomic scale structure. Most ceramics are compounds of two or more elements. The atoms in ceramic materials are held together by a chemical bond. The two most common chemical bonds for ceramic materials are covalent and ionic, which are much stronger than metallic chemical bonds. That is why metals are ductile and ceramics are brittle. The atomic structure primarily affects the chemical, physical, thermal, electrical, magnetic, and optical properties. The microstructure also affects the properties but has its major effect on mechanical properties and on the rate of chemical reaction. For ceramics, the microstructure can be entirely glassy (glasses), entirely crystalline, or a combination of crystalline and glassy. In the last case, the glassy phase usually surrounds small crystals, bonding them together. The most important characteristics of ceramic materials are high hardness, resistance to high compressive force, resistance to high temperature, brittleness, chemical inertness, electrical insulation properties, superior electrical properties, high magnetic permeability, special optic and conductive properties, etc.

The interest in advanced structural ceramics has increased significantly in recent years due to their unique physical characteristics and due to significant improvements in their mechanical properties and reliability. Despite these advantages, the use of structural ceramics in various applications has not increased as rapidly as one might have expected, partly due to high machining cost. The cost of grinding ceramics may account for up to 75% of the component cost compared to 5–15% for many metallic components.

The primary cost drivers in the grinding of ceramics are:

- Low efficiency machining operations due to the low removal rate.
- Highly expensive super abrasive wheel wear rate.
- Long wheel dressing times.

A conventional grinding process applied to ceramic materials often results in surface fracture damage, nullifying the benefits of advanced ceramic processing methods.These defects are sensitive to grinding parameters and can significantly reduce the strength and reliability of the finished components. It is, therefore, very important to reduce the depth of grain penetration to very small values so that the grain force is below the critical level for structural damage. The critical value of grain penetration depth for a hard ceramic is typically less than 0.2 microns. This small value of grain penetration depth is made possible using the ELID grinding technique with very fine grain wheels.

Although ELID grinding is good for work piece accuracy, it is not necessarily beneficial to work piece strength as the discussion of the effects of removal rates demonstrates. Stock removal rate increases with the increasing number of passes, higher stock removal rates are obtained with a stiffer machine tool in the first few passes. For grinding wheels of a similar bond type, a larger stock removal rate is obtained for the wheels of larger grit sizes. Cast iron bonded wheels used during the ELID grinding allows a larger stock removal rate, yet a lower grinding force, than a vitrified bond grinding wheel used in a conventional grinding process. Machine stiffness has little effect on residual strength of ground silicon under multi pass grinding conditions; this can be attributed to the effect of the actual wheel depth of cut on work piece strength. As the number of passes increases, the actual depth of cut approaches the set depth of cut, which means that regardless of machine tool stiffness, grinding force does not necessarily alter work piece strength in a stable grinding process. In addition, more compressive residual stress can be induced with a dull grinding wheel, with a grinding wheel of a larger grit size, or with a wheel, that has a stiff and strong bond material. However, a larger grinding wheel grit size causes a greater depth of damage in the surface of the ground work piece. As the number of passes increase, the normal grinding force also increases. This increase of force is steep initially and slows as the number of passes increases, a phenomenon more evident for a high stiffness machine tool. Due to machine tool deflection, the normal grinding force is initially smaller with lower machine stiffness. Eventually, the normal force approaches a limit value, regardless of the machine stiffness characteristics. To avoid damage to the work piece, it is necessary to limit the grain penetration depth, which is more directly dependent on the removal rate than on the grinding force. A little studied, yet controversial, aspect of the ceramic grinding process is the pulverization phenomenon that takes place in the surface layer of a ceramic work piece during grinding. Surface pulverization makes ceramic grains in the surface much smaller than those in the bulk, and gives the ground surface a smoother appearance.

Analysis and results

Significant reduction in grinding force has been reported with the application of ELID to work pieces ground both in the longitudinal and transverse directions.

ELID Grinding. Protruding grains abrade the work piece. As a result, the grains and the oxide layer wear down. The wear of the oxide layer increases the electrical conductivity of the wheel. As a result, the electrical current in the circuit increases, leading to an intensification of the electrolysis. Consequently, protrusion of the abrasive grains increases and, during a short period, the thickness of the oxide layer recovers. The described electrical behavior is nonlinear due to the formation of this insulating oxide layer. The oxide layer has a beneficial lubricating role in the grinding process. The process of wear and recovery of the oxide layer follows in a rather stable manner during the entire ELID grinding operation.

Other In-process Dressing Technologies. Nakagawa and Suzuki investigated various techniques of in-process dressing. The effects of in-process dressing using a dressing stick were studied. The wheel is dressed at the beginning of each stroke. Higher material removal rates were reported. An application of this procedure to side-grinding is difficult. However, use of a dressing stick accelerates wear of the super abrasive grains. The technique of electro-chemical dressing was introduced by Mc.Geough in 1974. An electro-conductive metal-bond wheel forms the anode and a fixed graphite stick forms the cathode. The dressing process takes place by electrolysis. Welch, et al., employed sodium chloride electrolyte. However, sodium chloride is corrosive and harmful to the machine tool.

Another dressing technique is based on the principle of electrical discharge machining (EDM). The conductive grinding wheel is energized with a pulsed current. The flow of ions creates hydrogen bubbles in the coolant, creating an increasing electric potential. When the potential becomes critical, a spark is generated that melts and erodes the material that clogs the wheel. This procedure does not continuously provide protruding abrasive grains, and is considered unsuitable for ultra-fine grinding of materials, especially with micro grain size grinding wheels.

Other nonconventional machining processes based on electrochemical metal removal are electro-chemical machining, electro-chemical grinding, electro-chemical polishing, etc.

Conclusions

During the last decade, a number of publications have demonstrated the merits of ELID for abrasive grinding of brittle materials such as common advanced ceramic materials, BK-7 glass and fused silica, ceramic coatings, and hard steels, as well. Materials have been ground in various shapes and sizes: plane, cylindrical external and internal, and spherical and aspherical lens. For some applications ELID grinding eliminated polishing and/or lapping operations.

ELID grinding provides the ability to produce extremely fine finishes on brittle material surfaces, with surface roughness on the nanometer scale (4 to 6 nm). Yet, coarse grit size wheels (JIS #325 and coarser) show only slight, if any, difference in the final roughness when ELID is applied compared with conventional grinding. However, for finer wheels (JIS #4000 and finer) ELID gives finer surface roughness compared with conventional grinding. ELID grinding is more stable than conventional grinding allowing high removal rates over a longer period. Material removal rates between 250 mm3/min and 8000 mm3/min were reported, with specific stock removal rates between 25 and 800 mm3·mm-1/min.

Cast-iron bond wheels utilization resulted in both a larger stock removal rate and a lower grinding force than vitrified bond grinding wheels.

ELID grinding can be completed in brittle-fracture mode for coarse wheels and in a ductile mode for finer wheels (JIS #4000 to #20,000, FEPA #1200 and finer). By carefully selecting the grinding parameters and controlling the process, ceramic materials can be ground predominantly in a ductile mode resulting in relatively smooth grooves on the surface.

Ductile mode grinding can be implemented even on a conventional grinder by controlling the wheel topography. ELID grinding can be implemented even on low-rigidity machine-tools and for low-rigidity work pieces.

Cutting speed and feed-rate were proven to have little effect on work piece surface final roughness.

Grinding forces are lower during ELID grinding than during conventional grinding. Grinding force was found to be relatively constant and reduced in value after the first ELID stage was completed. Fine ELID grinding induces compressive surface stress of about 150–400 MPa. The depth of the compressive layer produced during ELID grinding may be half that of the one produced during honing. For example, 10 μm depth was produced after ELID fine grinding compared with 15–20 μm produced after honing.

Hardened bearing steels can be ultra-precisely ground to produce an optical quality surface characterized by 10 nm *Ra* or less. The final surface roughness is enhanced by the burnishing action of the worn grits.

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