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Review of Sustainability Issues in Non-traditional Machining Processes

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Review of Sustainability Issues in Non-traditional Machining Processes


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Abstract

Non-traditional machining processes (such as EDM and ECM) provide alternatives or sometimes the only alternative in generating highly complex 3-D features in very difficult-to-machine materials. This paper reviews recently published work on sustainability issues related to these processes. For example in Electrochemical machining (ECM) the effect of sludge generation and selection of dielectric in Electrodischarge machining (EDM) need to be investigated from the sustainability point of view. All processes need to be studied not only for resulting productivity and accuracy but also their environmental impact during product generation and usage. This paper addresses process mechanisms, surface integrity, sensing and control and sustainability issues of EDM, ECM, USM and AFM processes at macro, micro and nano-scales.

Keywords: ECM, EDM, sustainability

1. Introduction

Manufacturing which converts raw materials into useful and saleable products is one of the biggest consumer of both renewal and non-renewable materials and a large portion of produced energy. The waste generated during manufacturing adversely affects the environment [1]. The sustainable manufacturing aims at optimizing efficiency but at the same time minimizing environmental effect with social equality [2]. The Brundtland Commission of the United Nations defines sustainable development as “Sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs.”

A better understanding and characterization of energy consumption of a manufacturing system has been termed as the first step towards attaining sustainable manufacturing [3]. Adopting sustainable manufacturing practices offers machining companies a cost-effective path to improve the three pillars of sustainability, i.e. social, environmental...
and economic performance [4]. Sustainability in manufacturing can be achieved at three levels, namely, the product level, the system level and the process level [5].

Following activities have been identified as important for achieving sustainable manufacturing [6]:

- Using renewable materials
- Using recycled, non-hazardous and fewer materials in inputs
- Modifying the process to use less resources and reduce the waste generated
- Lowering the product weight by reducing the packaging and improving logistics for the product
- Working with stakeholders and customers to reduce the environmental impact of distribution
- Increasing the life of product, making it easy to repair and reuse
- Designing the product in such a way that it is reusable, remanufacturable, recyclable and biodegradable.

2. Sustainable manufacturing:

The 6R concept in sustainable manufacturing includes i.e. reduce, reuse, recover, redesign, remanufacture and recycle, instead of the traditional 3R concept (reduce, reuse, recycle) aims at developing a closed loop multiple life cycle paradigm. This 6R concept has been defined as follows in [4]:

- Reduce the raw material and resources used and the waste generated in the process
- Reuse the product or its components for the subsequent life cycles after the first life cycle of the product
- Recycle the waste generated into new materials or products
- Recover products and components after the first life cycle for reusing them in subsequent life cycles
- Remanufacture the used products to restore them to their original state or useable state
- Redesign the product to simplify the future post use processes

To determine sustainability levels following measures have been developed and are reproduced here from [4]:

- Quality of machined product through machined surface integrity
- Costs of machining process and their possible reductions
- Resources and energy consumption
- Waste production and their disposal costs
- Environmental performance
- Health and safety performance
- Competitiveness, skill level and public image

Recently issues related to sustainability and energy efficiency in unit processes such as turning, milling and electrical discharge machining (EDM) have been discussed and reported [1,7-11]. This paper presents a review of sustainability and energy consumption issues in unconventional machining processes such as EDM, electrochemical machining (ECM) and ultrasonic machining (USM).

3. Electrochemical machining

Electrochemical machining (ECM) is a non-traditional machining process in which material is removed by the mechanism of localized anodic dissolution [12-15]. A D.C. voltage (10-25 volts) is applied across the inter-electrode gap between pre-shaped cathode tool and an anode workpiece. The electrolyte (e.g. NaCl aqueous solution) flows at high speed (10-60 m/s) through the inter-electrode gap (0.1-0.6 mm). The current density is usually 20 to 200 Amperes per cm square. The anodic dissolution rate, which is governed by Faraday’s laws of electrolysis, depends on the electrochemical properties of the metal, electrolyte properties and electric current/voltage supplied. ECM generates an approximate mirror image of the tool on the workpiece. Advantages of ECM over other traditional machining processes (e.g. turning and milling) include its applicability regardless of material hardness, no tool wear, comparable high material removal rate, smooth and bright surface, and the production of components of complex geometry with stress-free and crack-free surfaces. Therefore, ECM has been applied in many industrial applications including turbine blades, engine castings, bearing cages, gears, dies and molds and surgical implants. A recently conducted study of technological and economical comparison of roughing operation of titanium and nickel based blisks by milling, EDM and ECM shows depending on the geometry, ECM is comparable in machining titanium alloy. EDM has been found to be a better alternative for smaller batch sizes whereas ECM is more suitable for large
scale production. The research and technological development activities in ECM process, its variants and related hybrid processes are continuing to address its emerging applications. Pulse electrochemical machining (PECM) is a variation of ECM where a pulsed power is used instead of DC current. PECM leads to higher machining accuracy, better process stability and suitability for control. These advantages are due to the improved electrolyte flow conditions in the inter-electrode gap, enhanced localization of anodic dissolution, and small and stable gaps found in PECM. When applied for micromachining PECM is referred as pulse electrochemical micromachining (PECMM). ECM process mechanism has been used in developing a pulse/pulse reverse approach to electro-polishing and thorough-mask electro-etching with applications to automotive planetary gears, fluid control valves, medical stents and superconducting radio-frequency cavities. As mentioned earlier ECM applications include aerospace, biomedical, deburring, energy, deep hole machining for automotive applications, and tribology.

3.1. Sustainability and Safety Issues in ECM

The anodic electrochemical dissolution in ECM process generates a large amount of solid, liquid and gaseous by-products. In ECM, 1 lb of material removal may result in 200-300 lbs of sludge. A large plant may generate about 400 cubic meters per week of sludge containing close to 10 tons of solid waste. The sludge may contain metal ions, acids, nitrate, oils and even traces of heavy metals ions (e.g. hexavalent chromium). Additionally, electrolyte splashing, skin and eye contamination and irritation and toxic vapors pose occupational health dangers.

Environmental Conscious Manufacturing aims at reducing waste generation at the front end (i.e. source) to save energy and make processes sustainable. In ECM practice, the goal has been to reduce or eliminate environmentally harmful waste at source rather than employing traditional end-of-pipe sludge treatments and disposal operations. ECM has a unique problem called” memory effect” unlike any other machining process. In ECM, anodic dissolution takes place wherever significant voltage and therefore current is available. This results in stray machining. Thus the initial unevenness of a work piece is not totally removed in the final product. This phenomenon is called memory effect. Hence, in industrial practice, large initial stocks are used to off-set the memory effect of the initial unevenness on the final shape. The large stock leads to excessive amount of sludge. An attempt has been reported to minimize the amount of generated sludge by predicting the minimum machining allowance and improving the degree of localized dissolution.

Theoretical modeling, simulation and experimental work indicated that 35% reduction in material to be removed can be obtained by using Pulse-ECM with 1-3 ms and a duty factor of 50% with passivating electrolyte sodium nitrate [16].

Other related issues are generation of hydrogen gas because of electrochemical reactions. Usually special exhaust systems are installed to remove it from working areas. Electrolyte such as sodium chloride, sodium nitride and acids (hydro-chloride and hydro-sulfuric) splashing is another concern for operator safety. Generally, the exposure to electrolyte splashing is avoided by interlocking the ECM chamber door with the electrolyte supply system.

It is known that an exposure to chromates via inhalation, ingestion, and eye/skin contact has an adverse effect on liver, kidney and skin. Exposure to Nitrate and nitrite may also adversely affect thyroid gland, hemoglobin in blood and nitrosamines. Use of protective gear, good ventilation and appropriate equipment enclosures help in reducing the overall exposure.

Recently a new ECM technology called Recycling ECM has been reported. This technology uses Pulse-ECM concept for recovering copper, alloy steel and nickel alloy in solid, metallic form devoid of hydroxides, without intermediate electrolyte processing [17].

3.2. Electro discharge machining

Electro Discharge Machining (EDM) is a non-contact electro-thermal machining process. Precise machining can be done on primarily on electrically conductive using this unconventional machining process. EDM is used to drill circular and non-circular holes, generate profiles and make complex shaped dies of both macro and micro sizes. Both the micro EDM and the micro EDM are extensively used for making dies. Recently a related process, electro machining at the nano scale has also been reported.
EDM is a thermo-electric machining process in which the material removed or eroded from the work piece due to the energy from a series of electric discharges generated between the tool electrode and the work piece electrode immersed in a dielectric medium. The electric discharges or sparks produced at the gap remove the work as well as tool material by melting and evaporation. The dielectric medium acts as a deionizing medium between the electrode and the work piece, thus providing the optimal conditions for spark generation and also flushes the debris formed in the spark gap. The erosion mechanism in EDM is a very complex phenomenon and involves many physical processes. Therefore, the exact physical phenomenon taking place in the spark gap (gap between the electrode and work piece) continues to be a topic of research [18-21].

As EDM is a thermal process taking place at a very high temperature and involves work and tool material alloys and dielectric oil (hydrocarbon in die-sinking EDM process), a potential for many hazards outcomes exists. Such possibilities include hazardous smoke, vapor (depending the dielectric flash point), and aerosols, decomposed products and heavy metals, electromagnetic radiation, irregular and sharp-edged debris, and fire.

As die-sinking EDM the dielectric fluid is hydrocarbon oil as opposed to deionized water in Wire-EDM, it generates more fumes and aerosols than Wire-EDM. Depending on the workpiece and tool material, EDM may also be surrounding air by micro size particles of various metals and alloys such as chromium, nickel, tungsten carbide and titanium carbide.

Therefore, many protective measures need to be implemented for the health and safety of EDM operators. Specifically, use of only dielectric which does not cause skin irritation, is not toxic, does not emit smoke, has a high flash point and does not chemically (e.g. corrosion) react with parts of EDM equipment. Industry accepted techniques and standards of using appropriate exhaust systems, proper filtering and disposal systems for dielectrics, proper shielding of equipment to avoid or reduce the electromagnetic radiation and safety training for EDM operators are additional measures which must be incorporated [7,11].

For sustainability purposes the dielectric oil properties are important to be considered and their preferable levels and effect on sustainability need to be determined. The following measures are commonly used for assessing sustainability of dielectrics [7,11]:

- **Flash Point**: The higher the flash point the better for safety consideration
- **Pour Point**: Dielectric with low pour point is preferable than that of high pour point for efficiency and operational time purposes
- **Vapourability**: Oil with low vapourability is better for faster evaporation and better efficiency
- **Evaporation rate**: Dielectric with slow evaporation rate is desirable especially in EDM
- **Oxidation stability**: Dielectric with high oxidation stability is desirable which gives fewer tendencies to react with oxygen and less degradation as well as longer service life. The need of high oxidation stability increases as operating temperature increases
- **Viscosity**: The level of dielectric’s viscosity is not constant for all application, but low viscosity helps providing easier pump and enhanced flushing characteristics
- **Acid Number**: Oil with low level of acid is preferable for corrosion and cost consideration
- **Color**: Dielectric color has no such great effect
- **Odor**: There is no standard measure for odor but generally a dielectric oil with minimum odor is preferable to reducing reduce health related consequences as a factor of sustainability

Therefore, for sustainability, safety, and performance considerations, experiments and research have shown that the EDM fluid characterized with high oxidation resistance/stability, minimum to no odor, low viscosity, low specific gravity, minimum health effect, and better aging stability (economic reason) is desirable and recommended for use.

### 3.3. Ultrasonic Machining (USM)

In Ultrasonic Machining (USM), abrasive particles (such as cemented carbide and aluminum oxide) and water present between the ultrasonically vibrated (at about 20 KHz frequency) soft material tool and workpiece cause the material to chip away from both the workpiece and the tool. During machining, the tool is fed downwards to compensate for the removed layers from both the workpiece. The tool feed occurs under either a constant feed rate or a constant cutting force, usually known as constant static force. A mirror image of the tool shape is generated on
the workpiece USM is able to fabricate complex features very hard, brittle materials such as glass and ceramics. These materials have many applications in several fields such as optics, electronics, MEMS, biomedical devices, and biotechnology [22-24].

Rotary Ultrasonic Machining (RUM), a related process is a hybrid machining process that involves simultaneous occurrence of ultrasonic machining and conventional grinding. The machining setup typically consists of an abrasive bonded tool which is rotated and fed towards the workpiece at a constant force or constant federate. Micro-USM and Micro-RUM are down scaled versions of USM and RUM. Micro-USM has been shown to effectively machine bovine bone while maintaining generated temperature to an acceptable level of 47 degrees centigrade [22].

Sustainability and safety issues pertaining to USM and sister processes are presence of electromagnetic field, ultrasonic frequencies and abrasive slurry.

3.4. Energy Consumption

The sustainability and energy consumption in industrial sector, especially manufacturing industries using unit processes are increasingly becoming topics of research and development. Machining processes are essential in many product manufacturing and constitute a major share in energy requirement [1,8-10]. It has been reported that unconventional processes such as EDM consumes more energy than conventional machining processes such as turning. For example, for generating the same surface quality, EDM requires 300 Joules per cubic millimeter while turning operation requires 2 Joules per cubic millimeter.

An environmental impact assessment of EDM, wire-EDM and micro-EDM based on a study of conducting one-hour roughing operation has indicated that the main contributors for the total impact are electrical energy (47%) and dielectric fluid (23%). Energy consumed in cooling operation during machining is about 19%. The remaining is attributed to dielectric disposal and work and tool material [10]. Thus, about 25% of the impact is caused by the production and treatment/disposal of hydrocarbon dielectric fluids. Alternate environmentally friendly dielectric fluids including water and gas based dielectrics as well as dry EDM (i.e. using air as dielectric) have been attempted with an objective of increasing productivity and reducing tool wear to improve accuracy. However, water and air based dielectrics are expected to be more environmentally friendly than oil based ones.

Tables 1 and 2 of various machining fluids and related hazards matters are reproduced below from [11].

Table 1: Machining Liquids [11]

<table>
<thead>
<tr>
<th>Liquid/ medium</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Etchants</td>
<td>Chemical machining</td>
</tr>
<tr>
<td>Electrolytes</td>
<td>Electrochemical machining</td>
</tr>
<tr>
<td>Dielectric liquids</td>
<td>Electro-discharge machining</td>
</tr>
<tr>
<td>Demonized water</td>
<td>EDM wire cutting</td>
</tr>
<tr>
<td>Abrasive slurry</td>
<td>Ultrasonic machining</td>
</tr>
<tr>
<td>Air + abrasive</td>
<td>Abrasive jet machining</td>
</tr>
</tbody>
</table>

Table 2: Hazardous materials of NTM processes [11]

<table>
<thead>
<tr>
<th>Process</th>
<th>Chips</th>
<th>Dust</th>
<th>Gas</th>
<th>Liquids</th>
<th>Mist</th>
<th>Slurry, Dielectric</th>
<th>Electrolyte, Etchant</th>
<th>Noise</th>
<th>Vibrations</th>
<th>Magnetic field</th>
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</thead>
<tbody>
<tr>
<td>CHM</td>
<td>X</td>
<td>X</td>
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<td>ECM</td>
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<tr>
<td>Type of medium</td>
<td>Properties</td>
<td>Applications (usage)</td>
<td>Process medium sustainability issues</td>
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<tr>
<td>Kerosene</td>
<td>Low viscosity</td>
<td>EDM (early days)</td>
<td>Harmful vapor (CO &amp; CH4)</td>
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<td>Good flushing capability</td>
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<td>Skin irritation</td>
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<td></td>
<td>Low flash point</td>
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<td>Odor</td>
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<td></td>
<td>High volatility</td>
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<td>High risk of fire &amp; explosions</td>
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<tr>
<td>Mineral seal</td>
<td>Petroleum based product</td>
<td>EDM (early days</td>
<td>Carcinogenic</td>
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<td></td>
<td>High flash point</td>
<td>specially in aerospace application)</td>
<td>Less expensive</td>
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<td>Low life span</td>
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<td>No longer recommended</td>
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<tr>
<td>Transformer oil</td>
<td>High flash point</td>
<td>EDM (early days)</td>
<td>High oxidation rate</td>
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<td></td>
<td>High dielectric strength</td>
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<td>High rate of sludge accumulation</td>
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<td></td>
<td>High thermal conductivity</td>
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<td>Frequent sludge removal (time &amp; cost)</td>
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<td></td>
<td>High chemical stability</td>
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<tr>
<td>Deionized water</td>
<td>Odorless</td>
<td>WEDM (alternative to hydrocarbon oil)</td>
<td>May cause slight eye and skin irritation</td>
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<td>High Chemical &amp; thermal stability</td>
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<td>Good flushing capability</td>
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<td></td>
<td>Environment friendly</td>
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<tr>
<td>Synthesis oil</td>
<td>High flash point</td>
<td>EDM</td>
<td>Cost (but provide better operator safety and health)</td>
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<td>Low volatility and evaporation</td>
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<td>Low odor (advantage)</td>
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<td>Electrolyte</td>
<td>High dissolution rate at very</td>
<td>ECM</td>
<td>Corrosions risk (tool, workpiece, and equipment)</td>
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<td>NaNO₃</td>
<td>large current densities</td>
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<td>High energy consumption</td>
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<td>NaCl</td>
<td>Cheap and available</td>
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<td>Complex Waste management</td>
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<td>Acids (hydro-chloride and hydro-sulfuric)</td>
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<td></td>
<td>Electrolyte disposal issues</td>
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<tr>
<td>Abrasive slurry (B4C, Al2O3 &amp; SiC)</td>
<td>Hard particle</td>
<td>USM</td>
<td>Liver, kidney and skin irritation though breathing, and eye/skin contact</td>
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<td>Handling and storage difficulty</td>
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Table 3: Commonly used NTM process medium

References


