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A Review on Ecological and Health Impacts of Electro Discharge Machining (EDM)

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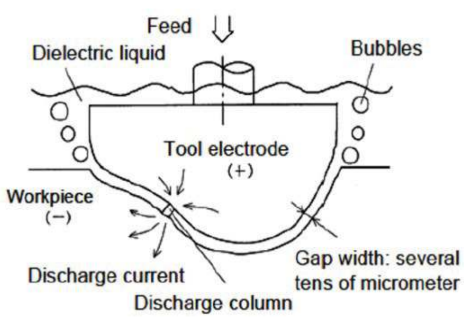
Abstract. Electro Discharge Machining (EDM) is one of the most popular methods of shaping objects, used mostly for surfaces with complex shapes and materials of great hardness which are difficult to machine. An increasing interest in machining processes and their influence on the natural environment and operators' health has led to research aimed to decrease their negative impacts by designing new machining modes or modifying the existing ones. The article analyzes those properties of EDM which pose a threat to the environment and health of EDM machine operators as well as presents directions of the development of EDM with respect to its environmental impact and application related characteristics.

INTRODUCTION

Electro Discharge Machining (EDM) is one of the most popular modes of machining among unconventional methods of shaping objects, used mainly for surfaces with complex shapes. It is frequently used to machine cores and cavities in the injection molding industry, also in plastic forming, in the aviation, nuclear and medical industries. EDM is applied for hard and brittle materials such as hardened and hardly machineable steels because of no direct contact between the tool and machined surface and great concentration of energy per surface unit, which causes material particles to melt and evaporate. The machined materials should have high electrical conductivity which conditions the electro-thermal processes during impulse electrical discharge between the electrode and machined surface separated by the dielectric fluid. Practically, there are two types of electro-discharge machining which differ in a shape of the tool and process kinematics: sink EDM in which a machined surface is shaped after the geometrical profile of the electrode, and wire EDM in which a surface is machined as a result of programmed movements of the workpiece against a specifically positioned wire electrode (Fig. 1).



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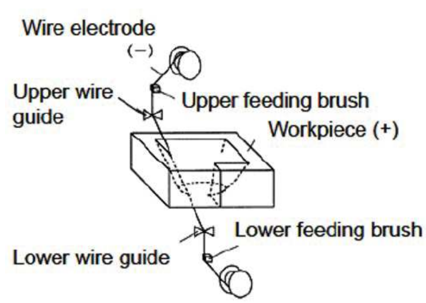

(b)

FIGURE 1. Diagram of EDM (a) and wire EDM (b) [1].

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ENVIRONMENTAL IMPACT OF ELECTRO-DISCHARGE MACHINING

Despite many technological advantages in shaping complex surfaces of hard and hardened materials, EDM poses several potential threats to both the direct surrounding of the workplace as well as to the natural environment. These threats result from the character of the electro-thermal phenomena taking place during the process caused by the electrical discharge. The side products of the EDM process are toxic and harmful to the surrounding. They include small particles of the eroded material, gases and aerosols, products of thermal decomposition of the dielectric fluid and post erosion slurry. All these consist of heavy metals and other products of erosion which are harmful to machine operators and the environment [2)].

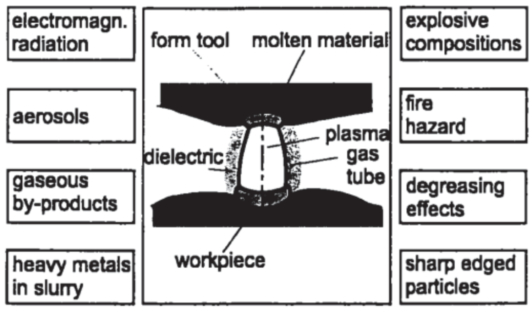


FIGURE 2. Environmental and safety aspects of EDM processes [3].

Out of the negative byproducts of EDM presented in Fig. 2, the most critical to operator's health and immediate work surrounding are gases and aerosols generated in high temperatures. Their intensity depends on the type of erosion, properties of the dielectric fluid as well as on the type of material used for electrodes and the machined piece. What also count are the machining parameters – especially the amperage and duration of the current impulse [4, 5, 6]. It has been determined that aerosols contain about 69% of metallic particles and 12.2% of hydrocarbons associated with them. The research conducted by Levy [7] showed that the concentration of emission of volatile products of erosion in the air, depending on the conditions of EDM, ranges from 60 to 155 mg/m^3, the maximum permitted dose being 20 mg/m^3. It should also be noted that greater amounts of gases and aerosols are produced during rough machining. The remaining contents include coal dust and unidentified particles of the tool and workpiece. Their size ranges from 25 to 29 nm and they are usually spherical in shape [6]. An additional source of danger is flammable and explosive properties of the dielectric and potentially harmful magnetic radiation.

In the process of creating the work place environment one needs to focus on the design and application related properties of EDM machines. These include: technical condition, consumption of energy and lubricating media, technological parameters and work safety, isolating properties, availability of gas/aerosol/dust/impurities removal systems as well as noise protection and dielectric anti leakage protection. An analysis of the environmental impact of these components of EDM roughing process during one hour operation is shown in Fig. 3 [8].

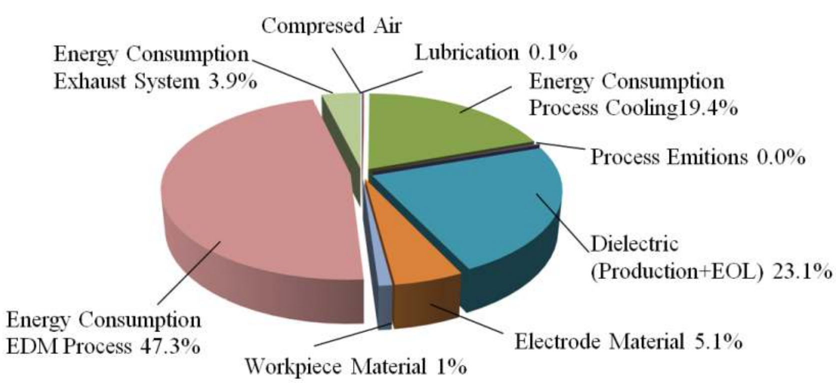


FIGURE 3. Distribution of the environmental impact during 1 hour of EDM roughing process [8].

Sinking EDM

The negative impact of EDM side products depends on the type and content of harmful elements. When it comes to potential threat to the environment and health, the properties of the used dielectric fluid are of great importance. In conventional electro-erosion the dielectric fluids are usually highly refined fractions of mineral oil, synthetic hydrocarbons and kerosene. Application of fluids based on mineral or organic oils causes emission of such substances as: polycyclic aromatic hydrocarbons, aliphatic hydrocarbons, non-specific aliphatic hydrocarbons, benzene, vapors and aerosols of mineral oils and various byproducts due to dissociation of oils and their additives. The smokes and fumes generated during erosion largely depend on the composition of the dielectric and its viscosity. In the case of synthetic dielectric fluids the generated gases and aerosols contain non-specific aliphatic hydrocarbons and steam as well as, to a smaller extent, aliphatic hydrocarbons, aerosols and benzene [7]. Application of glycerin results in its decomposition into small amounts of acrolein which, in case of direct contact with eyes, may cause irritation and lachrymation. These factors lead EDM machine manufacturers to replace hydrocarbon dielectric fluids with fluids based on deionized water, which is less toxic than their hydrocarbon equivalents. However, as concluded in the research [9], application of water-based dielectric fluids does not eliminate their negative impact on the environment. During erosion such toxic substances are emitted as carbon monoxide, nitrous oxide, ozone and other harmful aerosols which pollute the surrounding of the machine. A clear disadvantage of these fluids is their corrosive action. In order to avoid this harmful impact of water-based dielectric fluids effective filters have to be used which can direct them into the sanitation system [7]. Also the volatile particles of the workpiece released into the air and subsequently cooled down to form bits sized 20-50 nm are counted as dangerous and even carcinogenic. They include titanium and tungsten carbides, chrome, nickel, molybdenum and barium [4, 10]. Besides the size, what also matters is their amount, shape and surface size. It has been concluded that metal particles comprise 69% of the aerosol content [6]. Its content, apart from the chemical composition of the workpiece, also depends on the electrode material. In EDM it is most frequently copper, graphite, sometimes steel, bronze or brass. The greatest concentration of gas emissions and aerosols occurs on the surface of the dielectric fluid and it becomes smaller as the distance from the erosion area increases. Therefore an important factor for the intensity of their emission is the level of the dielectric fluid above the surface of erosion which should exceed 40 mm. This causes condensation and absorption of a considerable amount of emitted gases. The recommended level should be 80 mm [10]. Increasing the level of electrolyte above the erosion area leads to decreased emissions.

The observed harmfulness of the products of the EDM process necessitates an application of counter measures such as filters or extraction systems which remove volatile emissions from the surroundings of the process and isolate the machining zone (Fig. 4) [3].

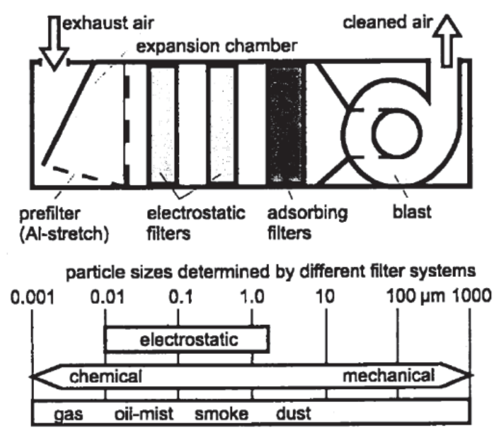


FIGURE 4. Multistage filtering installation [3].

In order to properly select such installations one needs to know the chemical composition and quantity of the emitted gases and aerosols. The most effective are closed ventilation systems. Their biggest disadvantage, however, is a danger of explosion of the dielectric fluid whose ignition properties should be taken into account while designing such a system. A negative feature of open and semi open ventilation systems is their lower efficiency compared to closed systems. An important role in ventilation systems is played by filtering devices used to extract microscopic solid particles found in aerosols. The type of filters to be used depends on the intensity of particle buildup and the mode of

electro-discharge machining. In order to treat dielectric fluids quartz filters are used which, for improved efficiency, are equipped with additional paper filters of a 1 μm porosity as well as membrane tubular or spiral filters with a porosity of 0,45 μm [11].
An important source of environmentally harmful byproducts of the EDM process is the amount of slurry extracted by the filtering system of a machine. It consists of particles of the eroded workpiece and electrodes and also of the products of dielectric fluid decomposition and filter wear (Fig. 5). Because of their negative impact on the environment, they should be closely monitored and documented [3, 4].

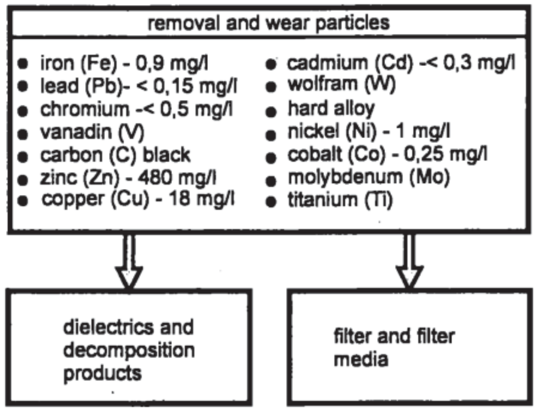
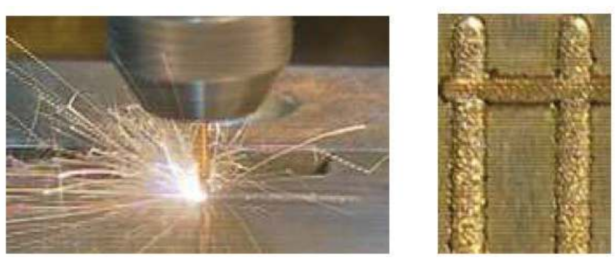


FIGURE 5. Components of erosion slurries [3].

The actions taken to alleviate the negative impacts of the EDM process are targeted at: (1) to reduce the harmfulness of the used dielectric fluids – erosion in water or in gas, (2) to decrease the amount of the fluid or eliminate it – erosion dry or with a minimal amount of fluid and (3) to reduce the amount of gases and aerosols in the air by optimizing process parameters and applying covers and extraction systems. The comparative research [12] into electro-erosion in kerosene or tap/distilled water as well as in a 25/75% mixture of both showed that application of tap water leads to an increased volume efficiency of the process and a reduction of copper electrode wear. The dimensional accuracy in these conditions was lower but the surface smoothness was higher. A supply of oxygen in the electrode gap additionally increased the volume efficiency in electro erosion in water. Similar effects were observed with pressurized gaseous nitrogen supplied to the gap. Compared to hydrocarbon dielectric fluids, favorable erosion conditions were reached when using a highly concentrated glycerin aqueous solution [12]. Despite environmental advantages these methods have not become popular in industry and still are a subject of research.

What has been welcomed enthusiastically is electro-erosion dry in which widely used hydrocarbon fluids have been replaced with gas. Its main purpose is to remove workpiece particles from the electrode and to cool the area of the electrode gap (Fig. 6). Apart from environmental advantages, eliminating fluids leads to additional benefits related to the cost of the process and dielectric fluid. It also results in a simpler design of EDM machines (Fig. 7) [13].



(a) (b)

FIGURE 6. Dry EDM and machined surface [13].

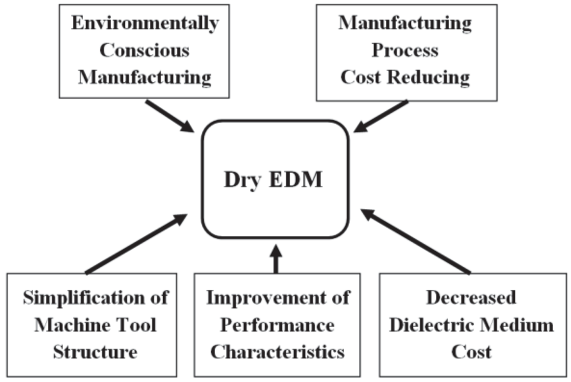
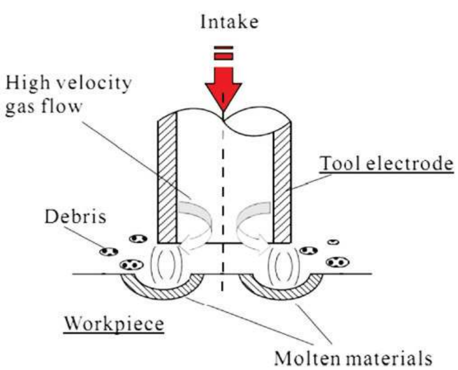


FIGURE 7. Advantages of dry EDM [13].

The elimination of dielectric fluid in dry EDM of sintered carbides [14] led to an increased erosion time and worse surface roughness resulting from adherence of erosion products to the electrode with a simultaneous decrease in electrode wear. However, taking into account environmental restrictions dry EDM seems to be an alternative to conventional EDM even despite the increased time. Increasing erosion efficiency due to an increased volume of eroded craters and frequency of electrical discharge makes it easier to supply gases such as oxygen, nitrogen, carbon dioxide or argon to the electrode gap (Fig. 8) [15, 16]. Numerically controlled movement of the electrode facilitates accurate control of gas flow in the gap. The gas can be forced or sucked in it. In case of the former the surface roughness was observed to be lower than when the air was sucked. Unfortunately, with time the gas flow through holes in the electrode is blocked by EDM products [17].



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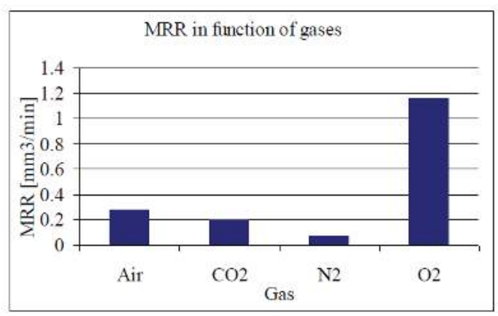

(b)

FIGURE 8. EDM with application of gas (a) [18], MRR in function of gasses (b) [17].

A further development of dry EDM with gas is dry ultrasonic vibration electrical discharge machining (UEDM) [19, 20] with a frequency of 17 to 25 kHz with air or oxygen used for small and deep holes in hard materials (Fig. 9).

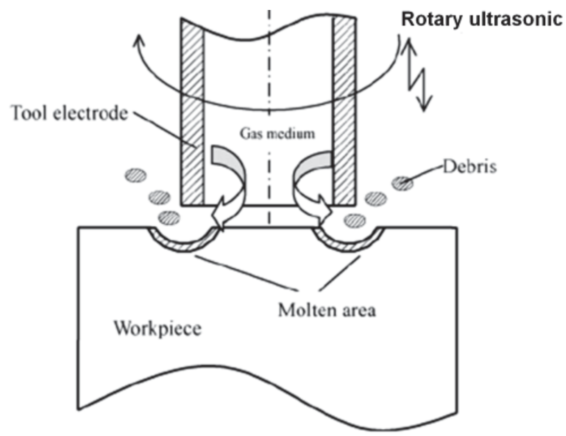

FIGURE 9. Ultrasonic vibrations assisted dry UEDM [20].

Another method to improve gas assisted dry EDM is applying pulsating magnetic field in the electrode zone. According to Joshi [21] and Lin [22] research it leads to a 130% increase of efficiency and a reduction of electrode wear. As a result of ionization, the magnetic field boosts the flow of thermal energy into the workpiece, which means better efficiency, shape accuracy and surface finish after dry EDM (Fig. 10).

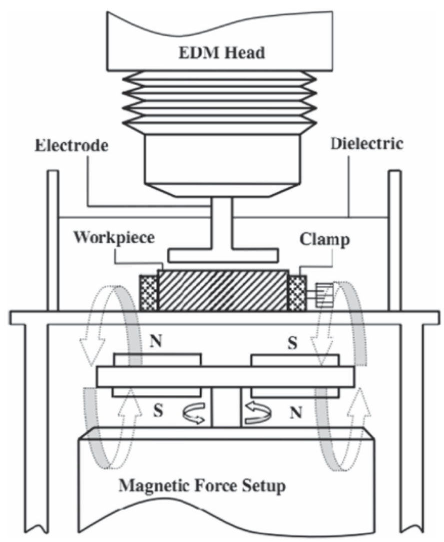

FIGURE 10. Magnetic field assisted dry EDM [22].

Following type of dry EDM designed to eliminate the dielectric fluid is EDM with a cryogenically cooled workpiece and/or electrode (Fig. 11). Application of this method in electro-erosion of titanium alloy Ti-6Al-4V0

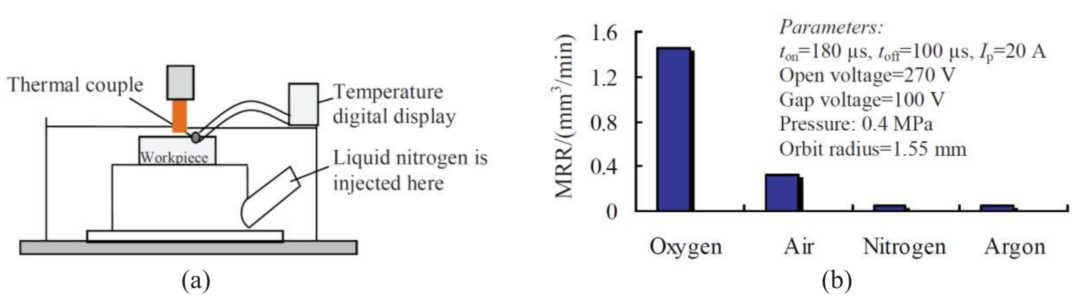

FIGURE 11. Cryogenic assisted dry EDM (a), MRR comparison of dry EDM in different gases (b) [15].

caused less wear of the electrode by about 27% in comparison to conventional EDM. At the same time the surface roughness was lower and process efficiency higher. Polarity of the electrode and workpiece is of great importance when it comes to the value of these parameters [15, 17].

In order to reduce harmful products of dry EDM – lower process efficiency and surface quality, researchers focus on EDM with a minimum quantity of a dielectric fluid mixed with air. This applies both to sink EDM and wire EDM. Compared to conventional EDM, application of minimum quantity of the fluid-air mixture results in an increase of process efficiency. At the same time the discharge energy is lower and the electrode gap narrower. However, it also causes an increased thermal load of the electrode, which in case of wire EDM may result in breaking the wire [23]. The comparative research on EDM drilling confirmed a positive effect of a water-air mixture on the quality of hole edges and the machined surface. A minimal quantity of a dielectric fluid (5-35 ml/min) eliminated workpiece particle deposits on the eroded surface and decreased the amount of generated aerosol which accessed the surrounding. A clear disadvantage of this electrolyte is its high corrosive action.

Another type of EDM with a minimal quantity of a dielectric fluid which improves process stability, its efficiency and surface smoothness after dry EDM is EDM with a mixture of a dielectric fluid with gas and nanopowders (powder mixed near dry electrical discharge machining PMND-EDM) (Fig. 12) [24, 25, 26]. In the research performed so far 70-80 nm grains of powdered graphite, aluminum, silicon, silicon carbide and molybdenum sulphide have been used. Adding powdered aluminum and molybdenum disulphide to a mixture of a dielectric fluid and air led to a high surface finish [12].

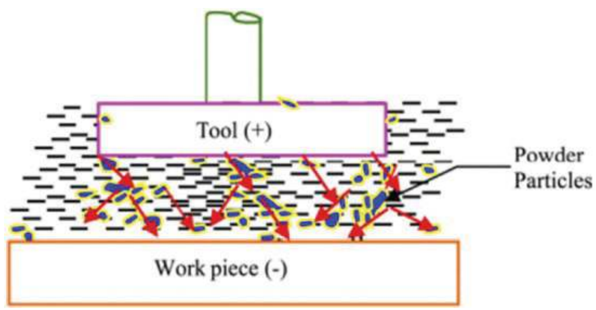

FIGURE 12. Powder mixed assisted dry EDM [25].

Wire EDM

In wire EDM one of the used dielectric fluids is deionized water with high molecular weight polymers whose purpose is to remove magnesium, calcium, molybdenum, chrome, vanadium ions and other heavy metals created in the EDM process. Harmful products of wire EDM with deionized water include: carbon monoxide, nitrogen oxide, ozone and aerosols which contain erosion products. It is worth noting, however, that deionized water is considered to be the least toxic to the natural environment. Electrodes in wire EDM are usually made of the same materials as those in sink EDM. While they are not so harmful to health, as part of erosion slurry they constitute a considerable load to the natural environment and require proper utilization [3]. Elimination of the dielectric fluid from wire EDM resulted in an increased accuracy of cutting and lower surface roughness of the machined surface [7, 12, 27, 28]. In dry wire EDM the forces that act on the wire and electrode vibrations are lower than in cutting with a dielectric fluid (water). This causes a more narrow and rectilinear gap which means a better cutting quality, important especially for precision work (injection mold cores and cavities) (Fig. 13). At the same time, similarly to dry EDM, the process efficiency is lower compared to conventional wire cut EDM. A flow of air under high pressure instead of a dielectric fluid improves surface finish and process efficiency which improve as the air pressure, wire feed and depth cut increase [27]. In order to improve the process efficiency and surface quality research is performed into wire EDM assisted by a minimal quantity of a dielectric fluid mixed with air (Fig. 14). Machining with a limited amount of a dielectric fluid leads to a greater thermal load on the electrode and may result in breaking the wire [23].

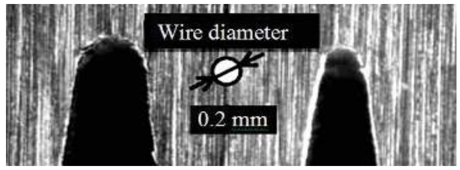

FIGURE 13. Cutting kerfs after dry wire EDM (a) and with dielectric wire EDM [27].

FIGURE 14. Near dry wire EDM with air-water mixture [23].

HEALTH RELATED ASPECTS OF EDM PROCESS

Taking into account the impact on the natural environment and a potentially harmful effect on health, it is the widely used dielectric fluids based on hydrocarbon oils that play the biggest role. They affect the skin, respiratory and digestive systems. An analysis of the emissions generated in EDM with hydrocarbon-based dielectric fluids revealed the presence of such toxic substances as polycyclic aromatic hydrocarbons, paraffinic fog, oil aerosol, metal particles, nitro aromatic compounds, aldehydes, acetylene, ethylene, hydrogen, carbon monoxide and dioxide, soot, xylene, butyl and alcohols [29]. The presence in the polluted by hydrocarbons surrounding causes headaches, dizziness, eye and nose irritation, memory and digestion problems [9]. Metal particles may also cause allergies, asthma and other lung diseases. Metals such as nickel, chrome, cobalt are believed to be the primary cause of skin irritation. Skin inflammation and allergic rashes constitute from 50 to 80% of occupational diseases [5]. They are caused by irritating chemical substances, surfactants which dilute the protective fat layer of the skin, chips which cause minor damage and skin irritation and secondary components such as mold and bacteria resulting from chemical or biological decomposition. A negative influence of fogs and aerosols on the respiratory system and lungs has not been fully proved but it is believed that they can decrease immunity against respiratory and digestive diseases. The substances that are dangerous to the skin and respiratory system due to their carcinogenic properties include: nitrosamines – an effect of the reaction between sodium nitrite, corrosion inhibitor, ethanolamine and chlorocarbons [5]. Generated during EDM aromatic hydrocarbons, sulfur dioxide and monoxide may lead to malignant tumors [30]. Also benzene and benzopyrene are considered to be a cause of cancers [31]. Their amount in the air is reduced as the level of electrolyte rises above the erosion surface. Inhaling toxic components of kerosene may cause increased sensitivity, anxiety, astigmatism, sleepiness, convulsions, coma and death from chronic presence in the environment filled with kerosene aerosols. Also skin irritation is frequent. Using compressed air or its mixture with inert gases increases the concentration of microparticles around EDM machines, which leads to respiratory and lung problems. In EDM with a minimal amount of water based electrolyte, the used agents that prevent electrolyte corrosion also pose a threat to health. For this reason water fog is not recommended as a dielectric medium. The aerosol generated in these conditions directed under high pressure to the erosion zone causes an increase in the amount of toxic substances in the immediate surroundings of the machine operator, which practically restricts the application of aerosols in the EDM process [2].

SAFETY ASPECTS OF EDM PROCESS

The research has shown that apart from the environmental and health impact, EDM may be a threat to the safety of the process and of the operator. Apart from harmful emissions of gases and aerosols, other dangers include self-ignition of the dielectric fluid, its explosion or electric shock. The used dielectric fluids have a low ignition and burning temperature. Dielectric fire belongs to the most frequent threats when the temperature becomes close to the ignition point, especially in closed and poorly ventilated rooms. In order to prevent the dielectric fluid from self-ignition one needs to install a cooling system. Proper care and maintenance are also necessary. The widely used hydrocarbon oils require forced ventilation systems to reduce the amount of dangerous gases and fogs which may lead to the self-ignition of a dielectric fluid [31]. The research [6] into potential causes of fire due to a low ignition temperature and strong electromagnetic radiation revealed that for safety reasons the dielectric fluids with an ignition point below 65^{o} should not be used in electro-discharge machining. The dielectric fluids with an ignition point above 100^{o} are recommended. The presence of the magnetic field during impulse electric discharge and the electromagnetic radiation resulting from plasma creation is one of non direct dangers to the operator [4]. Another type of hazard are chemical detergents used in cleaning the dielectric power system and the bacteria which gather in dielectric fluid tanks which, because of this, require periodical cleaning and fluid change. In dry EDM, the hazards for the operator are limited to an unpleasant smell of burned air and gases. Gas dielectrics of low viscosity cannot limit the channel of generated plasma, which facilitates free distribution of process products such as aerosols and an increased influence of electromagnetic radiation on the operator.

SUMMARY

Assessment of production processes in terms of their harmfulness to the natural environment has become the focus of many scientific investigations. The findings serve as a base for legal regulations on work and environment safety. Because electro-discharge machining is becoming more and more popular, the related hazards to the machine operator and natural environment attract much attention. These results in actions aimed at reducing their negative impact as well as finding new methods of limiting process products which are most detrimental to the environment. The primary focus is on eliminating hydrocarbon dielectric fluids (dry EDM), reducing their negative impact by replacing them with eco-friendly fluids such as water and gas and reducing their amount in the process (EDM with a minimal amount of the dielectric fluid. In order to increase the efficiency of these processes and to improve the quality of a machined surface hybrid solutions are used, where additional process components are introduced such as high frequency vibrations, magnetic field or fine grain powder. An increasing awareness and knowledge of the environmental and health related impacts of EDM, and also of hazards to operators' safety is a basis for proecological solutions in EDM technology.

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