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Review on effect of cryogenic treatment on different process parameters in EDM

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Abstract

Electric Discharge Machining (EDM) stands out as a highly esteemed non-conventional machining technique renowned for its proficiency in cutting hard materials and temperature-resistant alloys, which pose challenges for conventional machining methods. A primary obstacle in EDM lies in the elevated tool wear rate and diminished material removal rate caused by the continuous electric sparks generated between the tool and the workpiece. To address this challenge, cryogenic treatment is administered to the tools prior to machining. This treatment enhances the machining performance of the process, as evidenced by metrics such as material removal rate (MRR), tool wear rate (TWR), and surface roughness (SR). Cryogenically treated materials exhibit prolonged part life, improved fatigue resistance (resulting in fewer failures due to cracking), enhanced thermal properties (including increased thermal conductivity), improved electrical properties (such as reduced electrical resistance and increased electrical conductivity), decreased coefficient of friction, and enhanced ease of machining.

Keywords*:* EDM, Cryogenic treatment, MRR, TWR.

Introduction

Electric Discharge Machining (EDM) is widely employed for the high-precision machining of exceptionally hard steels and exotic metals, particularly in mold and die making, with significant applications in aerospace and electronics manufacturing [1]. It finds extensive use in machining hard materials such as Titanium, Tungsten, and Inconel, as well as brittle materials like boron carbide and silicon carbide, which are challenging to machine using traditional methods. Material removal occurs through a series of spark discharges between the tool and workpiece, generating temperatures ranging from approximately 8000ºC to 12,000ºC at the machining zone, sufficient to melt material from both the tool and workpiece. Subsequently, the molten metal is flushed away from the machining zone by the dielectric fluid.

A major drawback of conventional EDM is its low Material Removal Rate (MRR), higher Tool Wear Rate (TWR), and poor surface finish, limiting its utility in manufacturing industries. To enhance machining efficiency, metal particles in powder form are incorporated into the dielectric. The concentration of powder is a critical factor significantly influencing machining performance. These metal particles act as conductors, reducing the breakdown strength of the insulating liquid between the spark gap. This leads to increased gap contamination and improved ignition processes, thereby enhancing machining stability. The interlocking of metallic powders accelerates the spark generation rate, resulting in faster erosion, increased MRR, and reduced tool wear. Furthermore, the presence of blended powder particles alters the plasma channel, uniformly distributing sparks and reducing spark density. Consequently, shallow craters are produced, improving the surface finish of machined parts [2].

Cryogenic treatment

The term "cryogenic" originates from the Greek words "kryos," meaning "frost" or freezing, and "genic," indicating "produced" or generated. It refers to a stress-relieving technology involving the deep subzero treatment of metals and alloys. Cryogenic treatments encompass two main types: shallow cryogenic treatment and deep cryogenic treatment (DCT). Shallow cryogenic treatment involves subjecting the material to temperatures around -110°C and maintaining this temperature for 18-25 hours before gradually returning it to room temperature [17]. Deep cryogenic treatment (DCT) is a one-time permanent process. In conventional cryogenic treatments, materials are gradually cooled to temperatures around -185°C and held for a duration ranging from eight hours to several days. After this soaking period, the material is slowly reheated to ambient temperature [17].

Cryogenic treatments are typically conducted in specialized chambers cooled using liquid nitrogen, controlled by computer-operated solenoid valves. DCT offers numerous advantages, including dimensional stability, enhanced wear resistance, increased strength, and hardness of materials. Literature suggests that cryogenic processing improves crystal perfection, refines grain size, and realigns grain boundaries, leading to significant enhancements in electrical and thermal conductivity. This facilitates the efficient removal of heat generated during tool operation, thereby extending its lifespan.

Authors emphasize that cryogenic processing does not solidify metal like quenching and tempering; rather, it complements heat-treating processes. While most alloys may not exhibit significant changes in hardness due to cryogenic processing, there is notable improvement in abrasion and fatigue resistance. It's important to note that cryogenic processing affects the entire volume of the material and is not a surface coating.

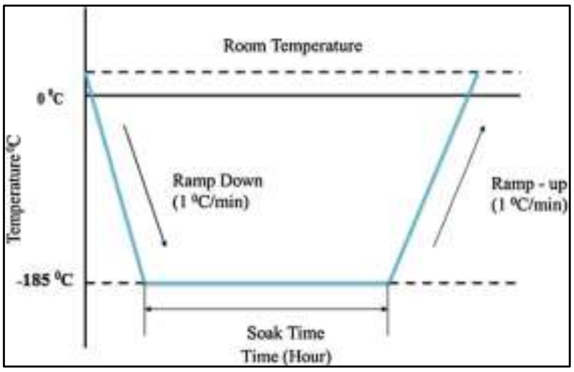

Fig.1. Time vs. temperature vs. cure for the cryogenic treatment [1]

Rahul et al. conducted deep cryogenic treatment on the tool electrodes to enhance their properties. In this process, they cooled the workpiece and tool to approximately -185°C at a cooling rate of 10°C/min, holding them at this temperature for 24 hours, and then gradually heated them back to ambient temperature at the same rate of 10°C/min. The deep cryogenic treatment cycle they employed is illustrated in Figure 1 [1].

Literature Review

3.1 Tool wear rate

Vinoth Kumar et al. (2017) conducted an investigation into the impact of cryogenic cooling on electrode wear, resulting in an 18% reduction in wear. They observed that as the discharge current increased, the electrode wear ratio also increased. This observation was attributed to the sharp increase in discharge current, which elevated pulse energy, generating considerable heat at the electrode-workpiece interface, leading to rapid melting and vaporization of the electrode. Additionally, they found that machining with cryogenic electrode cooling led to improved surface roughness [1]. Sanjeev Kumar et al. (2017) studied the effect of deep cryogenic treatment (DCT) on the tool wear rate during electric discharge machining of Ti-5Al-2.5Sn titanium alloy by varying various process parameters, specifically cryogenic treatment of electrode material, peak current, pulse-on & off time, and flushing pressure. They observed a significant reduction in tool wear of copper-tungsten [2]. Vineet Srivastava and Pulak M. Pandey (2012) investigated the effect of process parameters on the performance of EDM process with ultrasonic-assisted cryogenically cooled electrode. They found that ultrasonic-assisted cryogenically cooled electrodes provided better tool life, retention of tool shape, and improved surface integrity than conventional EDM [3].

Rahul et al. (2015) investigated the surface integrity and metallurgical characteristics of the machined Inconel825 work surface in relation to Electrical Discharge Machining (EDM) using Cryogenically Treated Tool (CTT) compared to Non Treated Tool (NTT). They found that the surface crack density was relatively less (73%) for the EDMed Inconel 825 work surface obtained by using CTT, as compared to the case of NTT. Anand Pandey et al. (2018) carried out a study using cryogenically treated Cu-tool electrodes to fabricate holes on Ni-based superalloy (Inconel-718) using Taguchi’s Methodology [11]. Vinoth Kumar S. and Pradeep Kumar (2015) investigated the machining of AISI D2 tool steel via Conventional electrical discharge machining (CEDM) and Cryogenic cooled electrode in electrical discharge machining (CCEDM). They observed that Ra in CCEDM decreased by approximately 19% compared with that in CEDM. The results also indicated that the surface morphology of the workpiece machined via CCEDM was better than that of the workpiece machined via CEDM [5]. Mohanty, C. P et al. (2016) proposed an experimental investigation and optimization of various machining parameters for the die-sinking electrical discharge machining (EDM) process using a multi-objective particle swarm (MOPSO) algorithm. They observed that tool material, discharge current, and pulse-on-time had a significant effect on the machinability characteristics of Inconel 718 [7]. Sahu, J. et al. (2015) studied Multi–response optimization of EDM parameters using data envelopment analysis [8]. Amandeep Singh et al. (2015) performed deep cryogenic treatment on copper, brass, and graphite electrodes. They found a significant improvement in material removal rate and reduction in tool wear rate with cryogenic treatment. They found that cryogenically treated Copper, Brass & Graphite electrodes have 18%, 9%, and 31% less TWR compared to untreated electrodes [16]. Vineet Srivastava et al. (2013) examined the process performance of sintered copper (Cu)–titanium carbide (TiC) electrode tips in ultrasonic-assisted cryogenically cooled electrical discharge machining (UACEDM). They found that an increase in pulse-on time decreases the values of the electrode wear ratio. This is because of the fact that the diameter of the discharge column increases with the pulse duration which eventually reduces the energy density of the electrical discharge on the discharge spot.

Kumar et al. (2012) performed experimentation to evaluate machining efficiency with additive powder mixed in the dielectric fluid of electrical discharge machining on Inconel 718 with copper and cryogenically treated copper electrodes. They found that both TWR and WR are minimum with the utilization of cryogenically treated copper electrode. This might be because of an increase in wear resistance, hardness, toughness, and improvement in thermal and electric properties of the electrode after cryogenic treatment [14]. They reported that the cryogenic process increases the homogeneity of the crystal structure, dissolving gaps and dislocations of the alloying elements and consequently, the resulting improved structural compactness improves electrical conductivity. When thermal conductivity increases, the local temperature rise would be less due to faster heat conducted to the bulk of the tool and thus less tool wear [15]. Gill and Singh (2010) researched the Effect of deep cryogenic treatment (DCT) on the machinability of Ti 6246 alloy in electric discharge drilling (EDD) by conducting experimental investigations on the production of 10mm diameter blind holes with an electrolytic copper tool. The result demonstrates that the Tool wear rate of the copper electrode is less when drilling DCT Ti 6246 alloy workpiece as compared to the tool wear rate of the non-treated tool. Electric sparks created during EDD disintegrate the kerosene dielectric into carbon and hydrogen and the carbon penetrates into the machined surface depending upon the microstructure of the material to be machined to form a TiC layer. The melting point of TiC is sensibly higher than that of Ti 6246 alloy, hence large discharge energy is required for breaking this layer before the actual drilling. That is why the presence of the TiC layer increases the TWR and reduces the MRR [13].

3.2. Material removal rate

Anand Pandey et al. (2018) discussed machinability in terms of material removal rate (MRR) and reported the advantages of cryogenically treated Cu tool electrodes for improved metal removal. They noted that the rotating effect with helical threads assists in enhancing MRR, and observed that an increase in tool-electrode diameter correlates with an increase in MRR [11]. Vineet Srivastava et al. (2013) investigated the effect of process variables on MRR and surface roughness (SR) using ultrasonic-assisted cryogenically cooled copper electrodes (UACEDM). They presented the effects of discharge current, pulse-on time, and duty cycle on MRR, noting that after a certain value of pulse-on time, an increase in discharge energy conducted into the machining gap within a single discharge causes an increase in MRR. They also found that an increase in the duty cycle leads to an increase in MRR, as longer application of the discharge results in higher MRR [3]. Gill and Singh (2010) conducted experimental investigations on the Effect of deep cryogenic treatment (DCT) on the machinability of Ti 6246 alloy in electric discharge drilling (EDD). They observed that the MRR for both workpieces decreases with longer drilling operations, possibly due to the inability of the flushing jet to wash away debris from deeper holes. Interestingly, they found that the MRR of DCT-treated workpieces was initially less than that of non-treated workpieces for shorter drilling times, but this trend reversed for longer drilling durations, indicating a breakeven point beyond which DCT treatment enhanced MRR, resulting in higher productivity [13]. Amandeep Singh et al. (2015) performed experiments on copper, brass, and graphite electrodes with or without deep cryogenic treatment, using EN-31 as the tool material. They observed that cryogenic treatment of electrodes, coupled with an increase in current value, led to higher MRR. The authors attributed this to the higher heat energy striking the workpiece surface with increasing current, resulting in more material erosion and MRR. They found that cryogenically treated copper, brass, and graphite electrodes exhibited significantly higher MRR compared to non-treated ones [16]. Vineet Srivastava and Pulak M. Pandey (2012) investigated the EDM process using ultrasonic-assisted cryogenically cooled copper electrodes (UACEDM) during machining of M2 grade high-speed steel. They observed that in UACEDM, material removal primarily occurs due to melting and evaporation, with some contribution from oxidation and decomposition. The authors noted that the mechanism of sparking and material removal is modified in UACEDM due to the ultrasonic vibrating motion of the electrode, resulting in more turbulence and cavitations, leading to better ejection of melted metal and increased material removal rate [3].

Conclusion and future prospective

Based on the literature review, it is evident that cryogenic treatment significantly enhances the performance of Electrical Discharge Machining (EDM), with several key observations:

- Cryogenic treatment applied to EDM is an effective method for enhancing output parameters such as Material Removal Rate (MRR), Tool Wear Rate (TWR), and surface roughness.
- While there is considerable focus on cryogenic treatment of tools, less attention has been given to its impact on surface integrity.
- Studies have primarily focused on materials such as Titanium Alloy (Ti-6246, Ti-6Al-4V, Ti-6246), alloy steels (High Carbon High Chromium (HCHCr), WC 6, WC 9), AISI D2 steel, Al-10%SiCP, and M2 grade high-speed steel. However, research on nickel-based superalloys is limited.
- Optimal improvement is observed with a 24-hour cryogenic treatment duration, while fewer studies have investigated variations in soaking time and lower cryogenic temperatures.
- Cryogenic treatment has been predominantly applied to copper and brass electrodes, indicating potential for further exploration with materials such as copper-tungsten, tungsten, graphite, and various composite electrodes.
- In conclusion, there is limited published research on the effects of varying current and pulse-on time when applying cryogenic treatment to both tool and workpiece in EDM. Further studies are warranted to explore the potential benefits of cryogenic treatment on tool-workpiece interactions during EDM processes.

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