Operational feasibility of Maglev EDM using powder mixed dielectric for machining Ti-grade 5 alloy

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EDM,
PMEDM,
Titanium,
Urea.

ABSTRACT

The current work aims to investigate the feasibility of the novel Maglev (electro-discharge machine) EDM for machining aerospace Ti-grade 5 alloy using urea powder mixed dielectric. The novel setup utilizes the combined effect of permanent and electromagnet to diminish arcing and short-circuiting. The set control parameters were 27 V open-circuit voltage and 1 A peak current while maintaining a duty factor of 95.5%. The dielectric fluid is prepared using urea powder mixed with deionized water at a concentration of 75g/l. The measured discharge voltage and discharge current were 25 V and 200 mA respectively. The machined surface of the workpiece has been analyzed using scanning electron microscopy (SEM) micrograph and energy dispersive spectroscopy (EDS) report. The newly developed Maglev EDM feasibility to machine Ti-grade 5 alloy using urea mixed dielectric has been confirmed in the present work with an average MRR of 0.293 mg/min.

1. Introduction

In recent years, material science advancements have led to the development of advanced alloys with light weight and good mechanical, thermal, and electrical properties. Machining these materials using conventional techniques is very challenging. Overcoming limitations such as for machining hard-to-cut and delicate-to-handle materials, requires exploring non-conventional machining processes broadly used nowadays, among which electric discharge machining (EDM) is predominant. EDM is the process of machining electrically conductive materials by using precisely controlled sparks between a tool and a workpiece in the presence of a dielectric fluid. Despite the several advantages of EDM, it has some downsides like poor surface finish, low productivity, and recast layer formation, limiting its applications in industries (Sahoo et al., 2023). To overcome these limitations, researchers have developed a new advanced variant of EDM by adding metallic/non-metallic powder with the dielectrics called powder-mixed EDM (PMEDM).

The suspended powders reduce the dielectric strength, consequently increasing the discharge gap. Nowadays, adding different powders with dielectric fluid results in the fusion of different materials into the workpiece surface to get the desired surface property (Philip et al., 2021). Mixing nitrogen-rich powder with the dielectric makes machining and nitriding occur simultaneously, reducing the post-machining nitriding cost. Nitriding is a process of heating the material in the presence of ammonia or any nitrogenous materials to deposit nitrogen onto the surface. It has a lot of tribological advantages, like it increases corrosion resistance, bending fatigue resistance, and decreases coefficient of friction. It also increases the ability to withstand thermal stresses, improving the component's life under high temperatures (Yan et al., 2005). During the EDM operation, the generation of sparks and transaction of heat energy occurs within a narrow gap (microns to submicron domain) between the interacting faces of the electrodes. The gap controlling mechanism is essential for carrying out the machining operation (Sahoo et al., 2020). Normally, the servo mechanism is implemented in EDM for gap control which is designed using a lead screw and gear-based systems, which imposes mass inertia, backlash, and wind-up losses.

Various researches have been done for higher (material removal rate) MRR, better surface finish, and accuracy in dimensions by modifying

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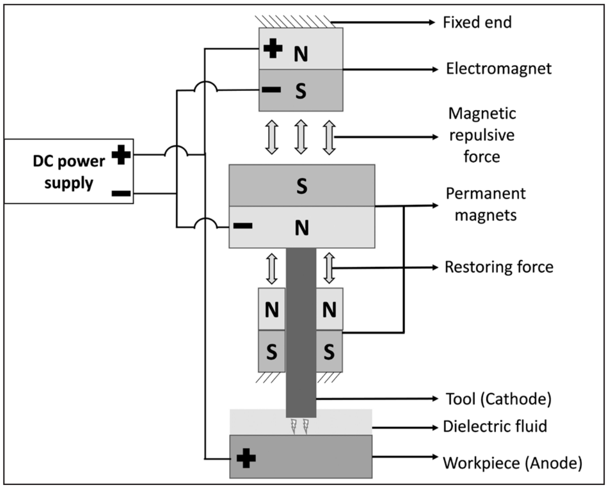

Fig. 1. Schematic illustration of Maglev EDM mechanism.

the EDM subsystems. Vision towards enhancing the servo mechanism used in EDM has been limited, which controls the inter-electrode gap. Sisodiya et al. (2022) investigated the micro-machining operation in Maglev dry-EDM through a literature based comparison with the conventional EDM. The terms of comparison were machining rate, discharge characteristics, tool erosion rate and surface topology. Zhang et al. (2008) & He et al. (2010) reported a gap control subsystem by implementing 5-(degree of freedom) DOF controlled actuator attachment to a conventional EDM setup. They attained gap control along the vertical and radial directions using a 2 mm positioning stroke actuator having a submicron and micro-radian positioning resolution. They observed a 21.8% improvement in machining rate for obtaining ø 1 mm holes as compared to traditional EDM. Some researchers have reported the usage of urea mixed dielectric in conventional EDM with effects of various performance responses with the variation in machining conditions. Santos et al. (2017) investigated the influence of electrode material and urea solution diluted in deionized water during the nitriding process of AISI 4140 steel in EDM. The results indicated that deionized water intensifies nitrogen enrichment on the sample and hardens the nitrogen layer. Yan et al. (2005) studied process parameters' effect on machining pure titanium using urea mixed distilled water solution in straight polarity condition. They observed that improved wear and friction characteristics could be obtained on pure titanium in EDM under appropriate machining conditions.

The current system works on the principle of magnetic levitation-based servo control i.e., Maglev. The designed novel servo system helps control the electrode gap during EDM operation while overcoming the conventional setbacks. The present work investigates the feasibility of machining Ti-grade 5 alloy using Maglev EDM in a urea mixed deionised water dielectric environment. The study emphasizes on the discharge characteristics and machining rate by analysing the voltage-current (V-I) characteristics during the operation. The machined surface topology and characteristics have been analysed using the scanning electron microscopy (SEM) micrograph and energy dispersive spectroscopy (EDS) report.

2. Materials and Methods

2.1. Maglev EDM

The present system implements a combination of four magnets (one electromagnet M_E, one movable permanent magnet M_{Pm}, and two fixed permanent magnets M_{Pf}) arranged in such manner to establish two sets of magnetic-repulsive forces. Figure 1 illustrates the schematic view of the mechanism of maintaining the electrode gap and the movement of the magnets. The repulsive force (F_1) between M_E & M_{Pm} tries to move M_{Pm} downward, and the repulsive force (F_2) between M_{Pm} & M_{Pf} works as restoring force that tries to move M_{Pm} upward. The repulsive force F_1 depends on the electromagnet's strength, which changes with a change in input current. With open circuit voltage, the electromagnet is with its full strength and pushes the tool attached with a movable permanent magnet downward. The gap between tool and workpiece decreases after the breakdown point discharge occurs. The electromagnet and electrodes are in parallel connection; when the voltage drops at the time of discharge, the electromagnet's strength decreases. At that time, the restoring force dominates over the repulsive force, and the gap is increased again. Thus, balancing the repulsive force and restoring force inter-electrode gap is maintained (Sisodiya et al., 2022).

Comparison based on different aspects and functionalities of previous conventional EDM setup, the servo mechanism used was mainly a lead screw-based (or) gear-based complex system. The current system uses a simple magnetic repulsive force for tool positioning. Conventional EDM uses an RC-based (or) transistor-based power supply, while the Maglev EDM uses a pure DC power supply. In RC-circuit, the charging of the capacitor

Table 1
Comparison of key advantages of conventional and Maglev EDM.

Sl. No.	Features	Conventional EDM	Maglev EDM
1	Servo mechanism	Lead screw-based (or) gear-based complex system	Simple magnetic repulsive force (magnetic levitation)
2	Power supply	RC-based (or) transistor-based	Pure DC
3	Positioning Response	Slow positioning response (mass inertia and backlash issue)	High positioning response
4	Maintenance	High cost	Zero maintenance cost
5	Component	Key components are Imported	All local component
6	Size	Very heavy	Lightweight and compact size

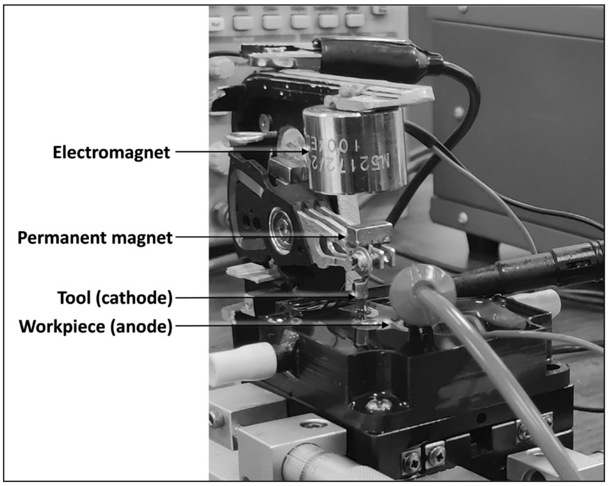

Fig. 2. Maglev EDM setup and its components.

takes time then is used for discharge and in the case of a transistor-based circuit, it uses logic gate control which is complex (Kumar et al., 2020). Moreover, in Maglev EDM, the tool retraction occurs with quick response due to magnetic action, reducing the arcing and short-circuiting phenomena. Maglev EDM overcame the problems raised in improving the servo mechanism to generate improved stability of EDM and overcome setbacks such as complex circuit design, expensive servo system, and high system maintenance. Table 1 shows the key advantages of Maglev EDM as compared to conventional EDM.

2.2. Materials and machining conditions

A self-developed novel Maglev EDM setup has been used in the present study to conduct experiments on a Ti-6Al-4V workpiece (15 mm × 15 mm × 3 mm) using a cylindrical mild steel tool (ø = 3.3 mm). The Maglev EDM consists of a machining unit and a power system with parametric controls. The machining operation is carried out in 75g/l concentration of urea mixed deionized water dielectric at stagnant condition with no flushing mechanism. Titanium alloys are mostly used in aerospace and biomedical sectors due to high biocompatibility and strength-to-weight ratio.

Table 2
Materials and machining conditions.

(a) Selected materials	
Workpiece	Ti-grade 5 (15 mm × 15 mm × 3 mm)
Tool	Mild steel (ø = 3.3 mm)
Dielectric	Urea-mixed deionized water
Polarity	Straight
(b) Parametric conditions	
Set peak current	1 A
Open circuit voltage	27 V
Discharge voltage	25 V
Discharge current	200 mA
Duty factor	95.5%
Dielectric concentration	75g/l
Machining time	10 mins

The experiments are conducted at open circuit voltage (27 V) and peak current (1 A) with straight polarity. The output responses were evaluated and acquired at discharge voltage (25 V), discharge current (200 mA), and duty cycle (95.5 %) for every experimental repetition. Table 2 presents the materials utilized and the machining conditions chosen for the current investigation. Figure 2 shows the Maglev EDM setup and its components.

3. Results and Discussions

3.1. Analysis of V-I characteristics

Pulse discrimination for determining the real-time discharge voltage, current and pulse duration is considered to be a crucial aspect in monitoring and controlling the spark gap during EDM operation. Analyzing the pulse signals is necessary to understand the happenings at the narrow discharge gap and develop better control over machining parameters for the desired outcome. Figure 3 indicates that V-I waveforms are stable during Maglev EDM operation. During each pulse cycle, it is observed that the ignition delay is negligible allowing better utilization of discharge energy throughout the pulse duration.

The duty factor was maintained at 0.955 during the operation while producing discharge power of around (5.0 – 5.5) watts. The study of Maglev EDM pulse waves show the lack of ignition delay resulting in complete utilization of pulse duration for better efficiency. The absence of frequent arcing and short-circuiting confirms better tool positioning control in comparison to conventional EDM.

3.2. Machining rate and surface morphology

In EDM, sparks are generated at the interacting faces of the electrodes (workpiece and tool) by the influence of the high-temperature plasma channel, as the electrode faces are submerged inside a dielectric media. Under the influence of the applied voltage, the dielectric fluid breaks down, and it loses its insulating property at a certain voltage, allowing the passage of discharge current by forming a conductive plasma between the electrodes. The complete operation occurs when the electrodes are placed by maintaining a certain gap (discharge gap) inside the dielectric fluid. Material is removed from the tool and workpiece surface through melting and vaporization. To determine the feasibility of the Maglev EDM setup for machining Ti-grade 5 alloy using urea mixed deionised water as dielectric, machining was performed at 25 V discharge voltage and 200 mA discharge current with proper repetitions. Figure 3 illustrates the voltage-current characteristics curve generated during the operation. The curve shows a discharge voltage of 25V with no sign of arcing or short-circuiting. Figure 4 presents the SEM micrograph of the machined region. The machining operation was executed using mild steel tool with circular cross-section (ø = 3.3 mm) at

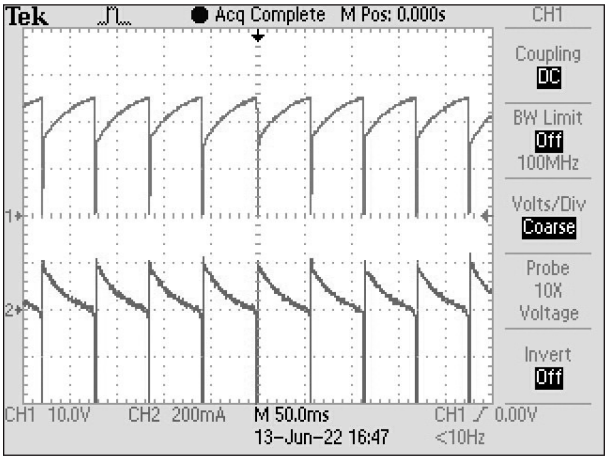

Fig. 3. Voltage-current characteristics curve.

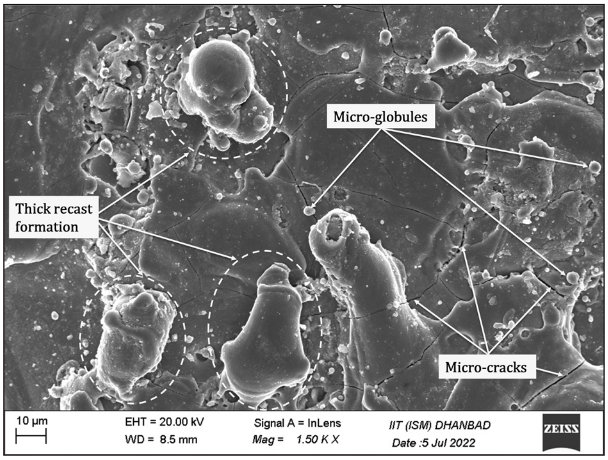

Fig. 4. Machined region on Ti-grade 5 workpiece.

12.5 W discharge power (i.e., 25 V discharge voltage and 200 mA discharge current) on a Ti-grade 5 plate (15 mm × 15 mm × 3 mm). The achieved material removal rate (MRR) during the machining of Ti-grade 5 alloy in Maglev EDM using urea mixed dielectric was around 0.293 mg/min.

On analyzing the machined surface in figure 4, micro-cracks are evident due to residual stress. Many dispersed micro-globules signify resettling of debris on the molten material after the spark occurrence. Thick recast layer formation throughout the surface illustrates resettling of molten material due to lack of flushing mechanism (Sahoo et al., 2022).

3.3. Material characterization

In EDM, rapid fluctuation in temperature and pressure due to plasma generation and termination results in formation of semi-circular craters and various surface anomalies. The material erosion in EDM occurs in the form of micro-craters at the point of spark contact

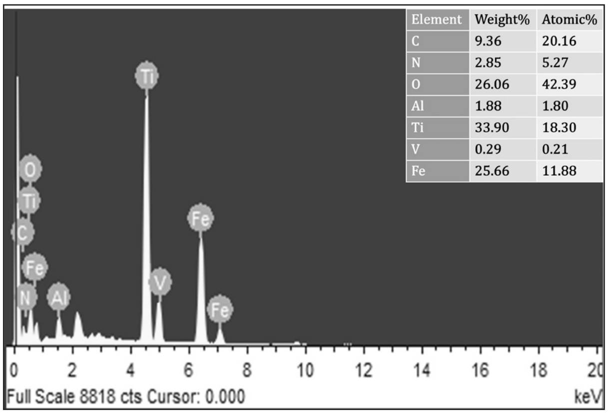

Fig. 5. EDS report of machined workpiece surface.

during discharge phase. Due to continuous formation of overlapping craters on the machined region, an uneven surface profile is formed (Yan et al., 2005). The presence of small white uneven micro-globules on the machined surface shows surface nitriding, confirmed through the EDX reports as depicted in figure 5. Thin recast layer formation throughout the surface illustrates carbide and oxide formation due to dielectric breakdown. The presence of tool material and non-uniform white layer also confirms material migration from the electrode and dielectric material.

In EDM, due to sudden cooling and solidification, some portion of molten material settles on the machined surface in the form of a thin non-uniform recast layer (Santos et al., 2017). The presence of such thick recast layers on the machined surface prevents from achieving the desired surface quality as shown in figure 5.

4. Conclusions

From the above observations it can be concluded that

- The newly developed Maglev EDM is feasible to machine Ti-grade 5 alloy using urea mixed deionised water dielectric with an average MRR of 0.293 mg/min.
- Maglev EDM provides better stability and higher efficiency during machining as observed from the V-I waveforms.
- The achieved machining rate is higher compared to conventional EDM due to negligible pulse-off-time. Moreover, absence of arcing and short-circuiting enhances the machining process.
- The machined surface characterization depicts presence of thick recast layers and non-uniform micro-globules due to resettling of molten material and debris particles. Additionally, the material characterization confirms the surface alloying phenomena through the presence of N, C and O migrated from the dielectric and Fe migrated from the tool.

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