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A Review on Machining of Titanium Grade 2 Alloy on Electric Discharge Machining

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ABSTRACT:

Titanium Grade 2 alloy is widely used in a variety of industries due to its unique combination of qualities, which includes a high strength-to-weight ratio, superior corrosion resistance, and biocompatibility. Titanium alloys are difficult to machine using traditional methods; therefore, non-conventional technologies are frequently used in various applications. Electric Discharge Machining (EDM) is one of those unconventional procedures that is regularly employed for shaping titanium alloys, each with its own set of benefits and drawbacks. Electric Discharge Machining (EDM) is a modern yet successful process for machining titanium alloys, with benefits such as low tool wear, non-contact machining, and the ability to cut complex shapes. This paper provides a comprehensive overview of the most recent research and developments in the machining of Titanium Grade 2 alloy using EDM. As a result, this study looks into several EDM procedures used to machine titanium alloys, such as Die-Sinker EDM, Wire-cut EDM, Micro EDM, and Pulsed discharge EDM. Based on the information available in the literature, the machining mechanism, tool electrode, dielectric, material removal rate (MRR), and surface integrity of all these processes are critically studied.

KEYWORDS: *Electric Discharge Machining, Titanium alloy, Tool electrode, Dielectric fluid, Process parameters, Machining parameters.*

1. INTRODUCTION

Titanium Grade 2 alloy has emerged as a material of paramount importance in a wide range of industrial applications due to its amazing combination of characteristics. Its high strength-to-weight ratio, excellent corrosion resistance, and bio compatibility make it a popular material in the aerospace, medical, chemical, and other industries. To realize the full potential of this extraordinary material, manufacturing processes must meet demanding precision, efficiency, and cost-effectiveness requirements [7,8]. Among the different techniques used to machine titanium alloys, Electric Discharge Machining (EDM) has gained widespread acceptance as a versatile and highly efficient approach[21]. Electric Discharge Machining is a non-traditional material removal procedure that uses controlled electrical discharges between an electrode and the workpiece to erode material. This technology has several advantages, including low tool wear, the capacity to machine complex shapes, and the ability to treat materials with high hardness and low heat conductivity. Given the material's unique properties and inherent problems, EDM holds special promise and interest in the context of machining Titanium Grade 2 alloy[28]. In doing so, we go into a multidimensional investigation that covers a wide range of key elements, such as tool selection, the influence of dielectric fluids, machining parameter optimization, and process parameter fine-tuning.

Because of its low thermal conductivity, proclivity for electrode wear, and the production of recast layers on the machined surface, machining Titanium Grade 2 alloy with EDM offers a complex conundrum[22]. As a result, researchers and engineers have launched an exciting quest to discover creative solutions that push the limits of EDM technology. These efforts include the investigation of new electrode materials, the development of novel tool designs, and the inventive adjustment of process parameters to handle the material's unique problems and realize its full potential. The review deals with a fundamental overview of EDM principles and their applicability to titanium machining, emphasizing the material’s inherent problems, such as low thermal conductivity, reactivity with electrodes, and the production of recast layers and also delves into the many solutions to overcome these difficulties, including enhanced electrode materials, tool design advances, and process parameter optimization. Furthermore, it looks into the most recent advancements in EDM technology, such as hybrid EDM processes, which combine EDM with other machining techniques to improve material removal rates and surface finish quality[14,27]. The paper also discusses the recent advances in modelling and simulation approaches, highlighting their importance in forecasting machining outcomes and optimization parameters, which are essential for precision manufacturing[15].

2. Die-Sinking EDM

Die-sinking EDM is extensively utilized in the creation of molds, dies, and tooling, which demand high precision and fine features. It is especially effective for materials that are difficult to process using traditional methods due to their hardness or complex shapes. The method is well-known for its ability to provide precise surface finishes while maintaining tight tolerances.

2.1 Mechanism

Die-Sinking Electrical Discharge Machining (EDM) for Titanium Grade 2 alloy machining requires a complex interplay of systems that allows for precise material removal. The procedure, which is especially difficult when applied to titanium alloys like Grade 2, necessitates careful consideration of several aspects, including tool selection, dielectric fluids, and machining and process parameters. Die-sinking EDM's basic mechanism involves the controlled production of electrical discharges between the tool electrode and the workpiece. This discharge produces a lot of heat, which causes localized melting and vaporization of the titanium alloy substance. As a result, little craters or cracks emerge on the workpiece's surface. The discharge current, pulse duration, and electrode wear ratio are all machining characteristics that have a substantial impact on the EDM process[9]. These settings can be adjusted to optimize the material removal rate, surface finish quality, and electrode wear. Furthermore, process characteristics such as tool-path strategy, electrode wear compensation, and servo control are critical for precision control and efficient machining.

Because of severe tool wear caused by cathodic tool polarity in sinking EDM, Ti6Al4V machining is not nearly as profitable as machining of many other metals. This is demonstrated by the formation of titanium carbide (TiC) in the workpiece's subsurface layer while the tool is operating. The carbon (C) required to make TiC is derived from the breakdown of hydrocarbon-based dielectric fluid used in die-sink EDM. TiC has a higher melting temperature than Ti6Al4V, making it difficult to process with EDM. Because of material adhesion on workpieces, the subtraction of Ti6Al4V reaches negative values during longer discharge times[9]. When machining begins, the removal rate of titanium alloys is often greater than that of iron alloys. This is owing to titanium alloys' poor heat conductivity, which causes intense localized temperatures and, as a result, increased material loss[22,23]. In the single discharge cavities, titanium carbide (TiC) does not develop. Whereas with continuous EDM, consecutive discharges greatly reduce the anodic clearance rate. During EDM, the localized temperature rises in tandem with the expansion of the plasma channel. This decomposes and adheres carbon to electrode surfaces, destabilizing the system and lowering discharge efficiency and MRR. Because an anodic tool revealed a greater diameter of single discharge cavities, the power concentration of each discharge is expected to be overly small to detach TiC, as opposed to cathodic polarity.

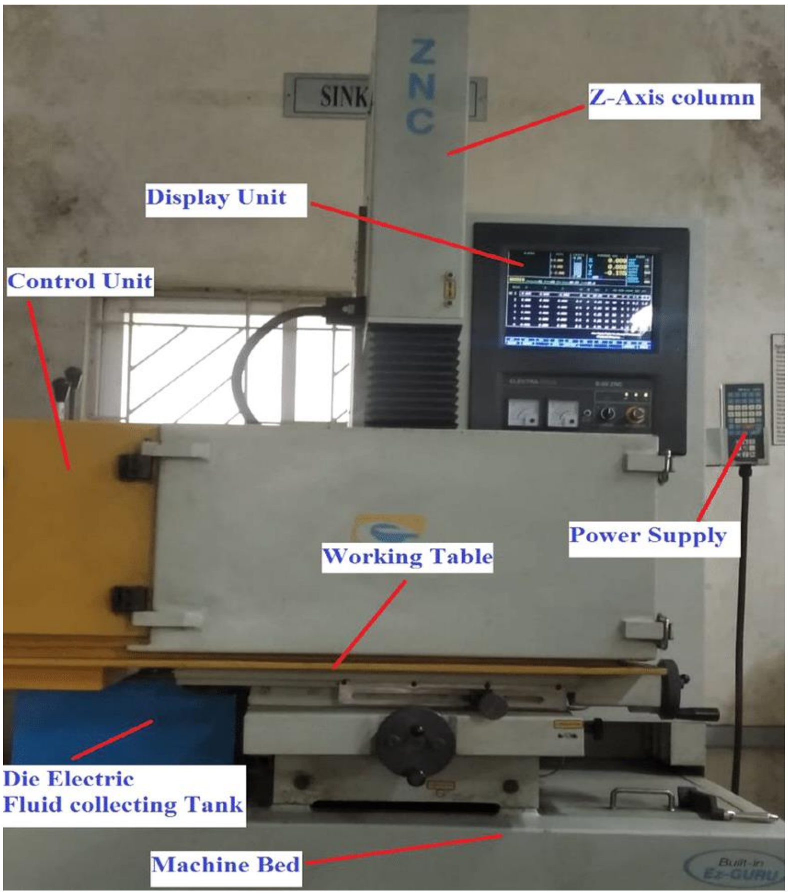

Figure 0.1 Die-Sinking EDM.

2.2 Tool Electrode

The most important requirements for tool electrode material during die sink EDM are higher electric conductivity, a higher melting point, and a reduced rate of wear. The researchers investigated graphite, aluminium, and copper electrode materials for the die-sink of Ti6Al4V titanium alloy and discovered that graphite electrodes provide the highest MRR, followed by electrolytic copper and aluminium. However, because of its higher melting temperature under all applied conditions, graphite electrodes contribute to a poorer surface quality and lower wear. In terms of surface roughness, the aluminium electrode performs best. Greater MRR usually comes at the expense of surface finish and, as a result, poor fatigue behaviour. In this case, a finishing cut is required to increase the performance of machined parts. Ti6Al4V titanium alloy was machined using steel (EN24), aluminium, graphite, electrolytic copper, tungsten copper, beryllium copper, and copper-impregnated graphite electrodes. Based on MRR, electrode wear, and overcut, copper-impregnated graphite was found to be the best-performing electrode of all. Graphite electrodes may reach a feed rate of 10.05 and 6.28 times higher than aluminium and copper electrodes during die sink EDM of titanium alloy, respectively[28]. Powder metallurgy copper slugs and buttons were also employed, which were produced at varied compressing pressures using highly pure (99%) powder with the greatest particle size of 50 m. In this situation, up to 29% of the electrode material was delivered to the workpiece surface. It was, however, 78% for powder compact (32 MPa) electrodes. A composite electrode made of Cu matrix enhanced with SiC particles was also employed[19].

The metallographic polished machined surface of Ti6Al4V after wire EDM has higher wear resistance, and the machined surface has a tougher recast layer that was generated due to the creation of new TiC and TiSi2 phases[30]. Cryogenically conditioned copper, regular copper, and tungsten material tool electrodes were employed. Cryogenically conditioned copper electrodes outperformed regular copper electrodes in terms of tool wear, surface quality, and MRR. Because of the reduced heat conductivity of the electrode and workpiece materials, the tungsten electrode had a rough surface and a lower MRR. For the same reason, TiC predominates alongside Al8V5 in the recast layer of workpiece material. Cryogenically conditioned copper electrodes showed significantly greater TiC precipitation than typical copper electrodes. The electrode could take the form of a solid-packaged die. When compared to solid electrodes, bundled electrodes provide a higher MRR and a lower tool wear rate, making rough machining of broad areas more practical. It was discovered that the bundled copper hollow electrode of hexagonal form could support a peak current of up to 127 A, which is significantly more than what is employed in solid single-electrode die-sinking. Internal flushing causes a continuous increase in flow speed from the centre to the border of the tool electrode in the radial direction. This successful flushing covers the electrode surface partially with ejected debris from melting workpiece materials, protecting the electrodes and ensuring uniform tool wear.

2.3 Dielectric Fluid

For die sink EDM of titanium alloy, the dielectric medium is often kerosene. Other dielectrics, however, can also be used for this purpose. Both oil and deionized water as the dielectric were used and found that deionized water had a higher MRR. Dielectric oil was also used. As discussed in the preceding section, the adverse effect of TiC production during machining in hydrocarbon dielectric is well recognized. Distilled water outperformed kerosene oil in terms of MRR and electrode wear. To improve MRR, there is an ideal concentration of additional particles in the dielectric fluid. In dielectric, change in the B4C powder content was found that MRR increased as the B4C powder content increased. This could be attributed to earlier dielectric disintegration, which reduces insulating strength and results in a higher MRR. Furthermore, the addition of surfactant and graphite powder to dielectric significantly improves MRR while decreasing tool wear rate (TWR), surface roughness (SR), and recast layer thickness (RLT) under various conditions. MRR initially increases as surfactant content increases, then decreases as surfactant level increases further.

During the micro-slit die-sink EDM of Ti-6A1-4V alloy, a revolving disk copper electrode was used beneath the workpiece. Individually, pure water and a SiC powder mix with a SiC powder concentration of 25 g/l were used as dielectrics. By using negative polarity, pure water dielectric for Ti-6Al-4V delivers higher MRR, lower TWR, and a smaller expanding slit. SiC powder combined with water produces more electrode wear and an increasing slit but a smaller burr than pure water. In pure water, SiC powder enhances conductivity. As a result, the breakdown voltage is lower than that of pure water, raising MRR. SiC powder in clean water promotes the formation of a bridge function and the dispersion of discharge energy. This implies that some discharge channels occur at different times throughout the targeted discharge period. As a result, one targeted discharge creates numerous discharge craters. Each discharging waveform has a distinct effect on the dielectric properties of pure water and SiC powder combined water. The discharge waveform was consistent with the input pulse in pure water, while the reacted waveforms were completely different from the primary input pulse in SiC mixed water. As a result of the dispersal of discharge energy, many discharging effects were generated from a single input pulse. A variety of scenarios may occur regarding how discharge energy distribution is affected in SiC powder mixed water. For better water insulation, the electrode spacing in pure water is narrower and the craters are greater.

2.4 Material Removal Rate

The pulse-on-time and discharge current have the greatest influence on MRR in die-sink EDM. On the contrary, tool wear was very sensitive to altering pulse off and on periods, whereas discharge current had no influence. The overcut is normally determined by the discharge current concentration about the pulse off and on times. A variety of input parameters concluded that dielectric flow rate, peak current, and interactions between peak current and pulse on time all have a significant role in altering MRR. In die-sinking EDM, the rate of dielectric flow and peak current have a significant impact on tool wear. When a maximum working current of 25 A is employed, the highest MRR of 77.181 mm3/min is obtained when a graphite electrode is used[20]. MRR increases as pulse-on-time increases until 200 s, then drops as pulse-on-time increases further. Material removal during die-sink EDM of Ti6Al4V alloy does not occur when the tool has positive polarity. This is because all discharge durations, as a result of the formation of a TiC layer on the machined surface, function as a heat barrier and hence greatly delay material removal. However, because the TiC layer was comparatively thin and discontinuous in nature, a tool with negative polarity is possible for this material. This incipient of TiC layers is erased by the advent of higher power density on the workpiece. The oil dielectric, rather than the graphite tool electrode, is the principal source of carbon buildup[28].

2.6 Surface Integrity

The positive polarity of the tool electrode produces a machined surface with a cluster of cracks but no discernible craters. However, the negative polarity of the tool produces curved surfaces in craters with no visible fissures. The formation of cracks is most likely owing to brittle/hard material classes on the machined surface as a result of anodic tool polarity, which resulted in a variable recast layer thickness within 4-11 m, where the rougher layer is visible with positive tool electrode polarity. Under tool negative polarity, the recast layer was considerably brighter, thinner, and sporadic, indicating the existence of TiC and a face-centered cubic (fcc) structure rich in carbon. The grain size of this layer was larger for anodic tool polarity than for cathodic tool polarity. The electrode materials diffuse to the machined surface as well. For example, Si and Cu were transported from the Cu-SiC electrode to the workpiece, where they formed the TiSi2 and TiC phases. Die-sink EDM Ti6Al4V surface integrity includes roughening caused by recast layer disintegration, micro fractures, melted droplets, and debris. A small tempered layer is seen just beneath the recast layer, similar to heat-affected zones (HAZ) in welded joints. Depending on the cooling rate of the material, the structure of such a layer might be hexagonal martensitic. Because of Ti24C15 production, the hardness of this layer is significantly higher than that of the bulk. Furthermore, carbon diffusion occurred on the EDM Ti-6Al4V surface, resulting in increased micro-hardness due to surface carburization.

3. Wire-Cut EDM

In this method, a metallic wire serves as the tool electrode in an EDM procedure similar to outline cutting with a band saw. To achieve three-dimensional forms, the wire electrode is moved using computer-assisted numerical control.

3.1 Mechanism

In general, the properties of titanium alloy WEDM are the same as those of other metal alloys. The temperature of each spark is believed to be 20000 C, which erodes a small quantity of material (106 - 104 mm3 /spark) through melting and evaporation[30]. The dielectric liquid in which the workpiece is submerged removes some of that material from the machining region. The wire electrode is kept under constant predetermined tension to reduce lateral vibration of the wire and hence avoid dimensional inaccuracies in machined workpieces. In this case, the wire electrode moves relative to the workpiece in two directions. These are (a) wire speed, which is the rate at which the wire electrode moves from the top spool to the bottom spool, and (b) wire feed, which is the rate at which the wire electrode moves towards the workpiece when machining.

Because titanium alloys require greater temperatures during WEDM, the wire electrode begins to deteriorate as soon as the machining begins. As a result, cleaner machining is typically observed at the top of the workpiece, while dirtier machining operations coupled with damaged wire electrodes are typically observed towards the bottom of the workpiece. The degree of dirtiness and degradation of wire electrodes is greatly controlled by workpiece thickness and associated machining parameters. The wire weakens significantly as it moves through the machining zone in a typical WEDM process for titanium alloy[30]. Furthermore, the number of debris increases as one descends. In some cases, particularly with titanium alloys, the wear rate of wire material is extremely high while removing workpiece material, resulting in a reduction in wire diameter. Under the impact of the maintained wire tension, this condition causes wire rupture at the place of the smallest cross-section area. During the removal process, a higher temperature is required to melt the titanium alloy. The heat generated in the machining zone is utilized to partially melt and vaporize the workpiece material.

Figure 0.1: Wire Cut EDM.

3.2 Wire electrode

Higher wear is caused by a lower melting temperature of the tool electrode material. Wire diameters are typically 0.2 and 0.3 mm for finish and rough, respectively. Nonetheless, the wire diameter commonly ranges from 0.05 to 0.3 mm. Tungsten, copper, brass, zinc-coated brass, and molybdenum, as well as multicoated wires, are commonly used. WEDM of titanium alloy is frequently performed using copper-tungsten or copper, brass, and graphite wires[30]. Brass is a preferred material due to its stronger strength, higher electric conductivity, better drawability, and ability to meet high tolerance criteria. However, due to its higher melting temperature and strength than brass wire, brass wire coated with zinc performs better on titanium alloys. Furthermore, zinc coating improves the efficiency of the machining process by inducing a cooling effect to preserve the core. The addition of zinc coating to brass reduces the melting point of wire due to ionization, resulting in an improved feed rate. In similar machining settings, the machining feed for high-speed brass wire is about 1.5 times that of zinc-coated wire. Wire breakage during titanium alloy EDM is highly common, with thermal load, wire strain, and dielectric cleaning capabilities all playing a role. Wire failure frequency is proportional to pulse on-time and pulse off-time. Increased discharge energy generates enough heat to trigger wire failure. Excessive heat weakens wire material and causes tension to build up when the technique pushes wire material beyond its ultimate strength[25]. Wire breaks occur more frequently with higher wire tensions and lower flushing pressures. Wire rupture occurs when the debris or waste of EDM is not cleaned properly, resulting in a sudden increase in temperature and the creation of unwanted arcs. Greater tension in the wire may cause it to burst at lower temperatures in the machining region. Wire rupture might be sudden or slow; however, the burst wire tips experience necking. Because of the quick change in discharge energy along with the thickness of the workpiece, the frequency of wire failure increases when machining complex geometries.

3.3 Dielectric fluid

So far, only de-ionized or distilled water has been utilized for wire-EDM of titanium alloys, according to the literature. Because of their low viscosity and rapid cooling effect when compared to hydrocarbon oil, these dielectric fluids are also used during wire-EDM of various materials. Furthermore, the lower cost and environmentally benign behaviour of deionized or distilled water contribute to its use as a promising dielectric for machining diverse materials[17].

3.4 Material Removal Rate

Dielectric injection pressure, machining voltage, wire tension, wire speed, and servo reference voltage are not significant process variables that affect MRR for feed rate. Peak current is a crucial parameter that determines MRR. The influence of interactions on the material removal rate for various combinations of pulse-on-time, pulse-off-time, current, and wire speed. It was discovered that increasing the wire speed and current increases the MRR, but the pulse-off time has no significant effect[16]. The MRR initially increases with increasing pulse-on time, then decreases with increasing pulse-on time. Peak current raises local temperature and discharge energy, increasing the MRR substantially. Increased feed rate and material removal are the results of amplified spark energy. In general, MRR grows as pulse-on-time increases but decreases when wire tension increases. Furthermore, MRR is reduced at lower dielectric pressure (7 MPa)[19]. As the flushing pressure increases, MRR rises and then virtually remains constant. At reduced flushing pressure, it appears that the debris clogs the machining region and sparks occur with no material removal. Instead, a consistent machining atmosphere is maintained at higher flushing pressure, resulting in a practically constant rate of material removal.

3.5 Key width

Peak current raises local temperature and discharge energy, resulting in a large rise in MRR. The use of amplified spark energy increases feed rate and material removal. In general, MRR increases with increasing pulse-on-time but decreases as wire stress increases. Furthermore, at lower dielectric pressure (7 MPa), MRR is substantially lower. As the flushing pressure increases, the MRR climbs and then practically remains constant. At reduced flushing pressure, it appears that the debris congests the machining region and sparks occur with no material removal. Instead, a constant machining environment is maintained at higher flushing pressure, resulting in a practically constant rate of material removal[18]. Other characteristics that affect net kerf width include wire material, wire tension, and feed rate, though not as strongly as discharge energy-related parameters. Kerf width is minimized for constant stable discharge and lower discharge energy. Furthermore, as wire tension was decreased, the kerf width increased. This is mostly owing to increased lateral vibration of the wire electrode, which equates to a higher concentration of discharges in the lateral direction. As a result, increased wire tension contributes to a more favourable and constant kerf width. However, extremely high stress is also undesirable because it increases the likelihood of wire rupture. As the pulse-on-time increases, so does the breadth of the kerf.

3.6 Surface Integrity

Regarding wire feed rate, the change in surface topography is small. When MRR is low, the surface is comparably smoother. Surface roughness of 2.44 m at 2.65 mm/min machining speed reduces with increasing cutting speed and is practically linear. Surface roughness deteriorates dramatically as machining speed is increased further. The pulse-off-time does not affect surface polish or dimensional inaccuracies. This is crucial because, in critical processing conditions, the pulse-off-time can be adjusted to meet the needs of the system's stability and precision of the cut. Crater size increases as feed rate increases during WEDM of titanium alloys[13]. A polished cross-section of the rim area produced by rough wire EDM, demonstrating the heat impacted zone, recast layer, and surface cracks in the machined surface. These flaws could be reduced by adjusting process parameters. WEDM of Ti6Al2Sn4Zr6Mo alloy with uncoated brass wire at 45 m depth of cut, 120 V voltage, 6 s pulse-off time, 0.1 s pulse-on time, wire speed of 8 m/min, wire tension of 20 N, and current of 0.4 A. These conditions resulted in a surface roughness of 1.72 m and a recast layer thickness of approximately 9 m.

4. Micro EDM

Micro-EDM stands for Micro Electric Discharge Machining. It is a modified version of electrical discharge machining technologies for the manufacturing of micro- and miniature parts and structures. It is a non-traditional and contactless technology used to create materials with high electroconductivity, hardness, and strength. The basic differences between micro-EDM and conventional EDM are in the type of pulse generator, the resolution of the X, Y, and Z axes movements, and the size of the tool used[1,2]. In micro-EDM, the pulse generator produces very small pulses within a pulse duration of a few microseconds or nanoseconds. Due to this, micro-EDM utilizes low discharge energies to remove small volumes of material. The most important factor that makes micro-EDM very important in micro-machining is its machining ability on any type of conductive or semi-conductive material with high surface accuracy, irrespective of material hardness[3].

4.1 Mechanism

EDM is based on a series of discrete electrical discharges that occur between two electrodes, a tool, and a workpiece that are both immersed in a dielectric fluid. The electrical energy is converted into heat energy during discharging. The thermal energy creates a plasma channel between the cathode and anode at temperatures ranging from 8000 to 12,000 °C and as high as 20,000 °C[12]. When the pulsating direct current source, which occurs at a frequency of around 20–30 kHz, is shut off, the plasma channel fails. A portion of the removed material evaporates, while the remainder forms debris particles that are removed by the dielectric fluid that is typically kept in motion during milling. Micro-EDM enables the machining of micro-features and devices for use in industry, aerospace, and, more recently, medicine. This mechanism initiates a substantial amount of heating and melting of materials at the surface of each electrode[3,4]. The fundamental issues related to micro-EDM are addressed, and some common strategies for the evaluation of machining performance are presented. Micro-electrical discharge machining (Micro-EDM) has become a widely accepted non-traditional material removal process for machining conductive and difficult-to-cut materials effectively and economically. difficult-to-cut material, titanium alloy suffers poor machinability for most cutting processes, especially the drilling of micro-holes using traditional machining methods. Although EDM is suitable for machining titanium alloys, the selection of machining parameters for a higher machining rate and accuracy is a challenging task in machining micro-holes[11]. An attempt has been made for simultaneous optimization of process performances like metal removal rate, tool wear rate, and overcut based on the Taguchi methodology. Thus, the optimal micro-EDM process parameter settings have been found for a set of desired performances[4,5]. The process parameters considered in the study were pulse-on time, frequency, voltage, and current, while a tungsten carbide electrode was used as a tool. this approach Pham has studied the electrode wear behavior of tube and rod electrodes, which are the two main kinds of electrodes for micro-EDM drilling, and has shown that in EDM drilling, the electrode tends to change shape in a specific way during machining. Bigot optimized parameters for roughing and finishing in micro-EDM and reported that negative polarity is best suitable for this process, and capacitance is the most significant parameter for metal removal rate (MRR) and surface roughness Kibria utilized different types of dielectrics, kerosene, boron carbide powder-suspended kerosene and deionized water, to explore the influence of these dielectrics on performance criteria such as material removal rate (MRR), tool wear rate (TWR), overcut, diameter variation at entry and exit holes, and surface integrity during machining of titanium alloy Yan combined micro-EDM with micro-ultrasonic vibration machining for making precision micro-holes in borosilicate glass and reported diameter variations between the entrances and exits as low as 2 µm in micro-holes with diameters of about 150 µm and depths of 500 µm under optimized conditions[10]. Also, a good number of publications on Taguchi method based optimizations have been reported Most of the publications are concerned with the optimization of single performance characteristics.

Figure 0.1: Micro EDM

4.2 Material Removal Rate

The MRR was calculated as the average volume of material removed over the machining time, which is expressed as cubic millimeters per minute Among all the machinability characteristics of a material, the MRR is of prime importance. Micro-EDM is more commonly an electro-thermal machining process. The discharge energy and the electrical and thermal properties of the workpiece and electrode materials are the main contributing factors determining the machinability of the materials for micro-EDM. It has been established that for work materials the MRR increases with the increase of discharge energies. During the micro-EDM process, a suitable pulse generator is used to generate electrical pulses containing small discharge energy suitable for micromachining purposes. An alternate method of MRR calculation is by measuring the loss in mass of the workpiece after machining. The mass material removal rate (MRRg) is then converted into a volumetric material removal rate (MRRv) by knowing the density of the workpiece material. However, such a method may lead to faulty values as dielectric oil sticks on both the workpiece and electrode. Also, after each experiment, the workpiece and electrode are required to be weighed which is undesirable as it disturbs the machine setting.

4.3 Tool Wear Rate

During the micro-hole drilling of a material When a micro-cylindrical electrode is used for drilling, the shape of the electrode rapidly changes during machining. Wear happens both at the electrode's end and on its side. End wear causes inaccuracies in estimating electrode length. Side wear affects the shape of the hole created and cannot be ignored in most cases. Pham performed experiments in their investigation and has shown that in EDM drilling, the electrode tends to change shape in a specific way during machining[12]. After the given erosion depth, the electrode continues to wear, but its shape remains constant. The intensity of the electrical field is initially stronger near the edge of the electrode tip, and it wears first, becoming blunt in the process. The highest intensity of the electric field shifts to the centre of the electrode tip, where there are the most sparks. It is hypothesized that the shape of the electrode changes in such a way as to eventually achieve uniform electric field intensity for the specific sparking conditions. As discussed previously, after a certain depth of erosion in micro-EDM drilling, the shape of the rod electrode remains constant.

5. Pulsed Discharge EDM

5.1 Mechanism

A non-traditional machining technique used for precise material removal is electrical discharge machining (EDM). The Pulse Discharge EDM technique, which uses electrical pulses of brief duration to remove material from a workpiece, will be thoroughly discussed in this review study. The foundation of EDM is the idea that electrical discharges take place between the tool electrode, which is often a metallic electrode, and the workpiece in a dielectric media, which is typically deionized water or oil. To produce sparks or discharges, a short, high-energy electrical pulse is delivered between the tool electrode and the workpiece. A worktable, a tool head, a power supply unit, a dielectric system, and a control system make up a standard pulse discharge EDM machine. The tool electrode is fixed on the tool head, and the workpiece is firmly fastened to the worktable. The workpiece and tool electrode are encircled by the dielectric fluid, which also acts as cooling and a conduit for electrical discharges. The development of a recast layer on the workpiece surface is a possible disadvantage of pulse discharge electrodeposition (EDM). The post-machining processes may be necessary to remove or enhance the recast layer, which is made up of solidified, resolidified, and re-deposited material. Precision components with intricate geometries and precise tolerances may be manufactured with pulse discharge EDM in a variety of sectors, including aerospace, automotive, tool-making, and medical device production.

To increase the effectiveness, precision, and surface quality of pulse discharge electro-discharge (EDM) processes, researchers are still investigating cutting-edge methodologies and control systems. The many mechanisms and methods employed in pulse-EDM are as follows: A single electrical discharge pulse is employed to degrade material in the basic pulse-EDM process. To obtain a range of material removal rates and surface finishes, the pulse's energy and length are adjusted. suitable for shaping and harsh machining operations. Multi-Pulse EDM removes material in a controlled and effective manner by using a number of closely spaced electrical discharge pulses that may be quickly sequenced to produce a string of sparks. In comparison to single-pulse EDM, it enables faster rates of material removal. To accomplish precise micromachining, micro-pulse EDM uses ultra-short pulses (in the nanosecond range). Small amounts of material are removed with a minimum number of heat-affected zones using extremely high-energy pulses. perfect for adding minute details and micro features to little works of art.

In this mechanism, the whole machining process takes place with the workpiece and tool electrode immersed in a dielectric fluid. The whole procedure is submerged, which reduces the chance of arcing and promotes effective cooling and debris removal. Gas-based EDM, commonly referred to as near-dry EDM, does not require a dielectric fluid. Instead, arcing is suppressed, and a clean machining environment is provided by a regulated flow of gas, such as nitrogen[18]. This method is especially helpful in situations where a dielectric fluid might not be desired. In rotary EDM, the workpiece or tool electrode can rotate throughout the cutting process (or both). This technology makes it possible to create intricate 3D curves and forms helpful when complicated spiral or helical elements are required. Adaptive control methods are included in advanced pulse-EDM devices. These systems continuously track a number of variables, including the spark gap, the rate of material removal, and the tool wear, and modify the pulse settings as necessary to get the best results. Precision and process stability are improved via adaptive control. EDM drilling is a specialized technique used to drill deeply into workpieces using tiny holes. Multiple electrical discharges are used to degrade the material and create holes. used for cooling turbine blade holes in industries like aerospace. A constantly moving wire electrode is used in wire-cut EDM, a form of pulse-EDM, to cut intricate shapes and profiles in workpieces. It is frequently used in the production of tools and dies and is suited for both coarse and precise machining. The development of sophisticated power supplies capable of dispensing precisely regulated and high-frequency pulses has resulted from advances in pulse generator technology. These developments help to enhance surface quality and machining performance.

5.2 Tool electrode

The electrode utilized in this precision machining method must be thoroughly discussed in a review paper on pulse discharge electrical discharge machining (Pulse-EDM). The electrode in Pulse-EDM is described in detail below: In Pulse-EDM, the electrode is crucial to precision, surface quality, and material removal. It performs the function of a tool that promotes the electrical discharges needed for machining. Here is a thorough explanation of the Pulse-EDM electrode Materials with strong electrical conductivity and resistance to wear and erosion are commonly utilized to make the pulse-EDM electrodes. High electrical conductivity, simple machinability, and exceptional erosion resistance are all attributes of copper Offers strong electrical conductivity and may be shaped using complex machinery. The electrode's surface finish plays a key role in producing the workpiece's desired surface finish. Fine surface textures and high-quality machined surfaces may be produced with the aid of smooth, defect-free electrode surfaces.

The minimal feasible feature size and the total material removal rate are influenced by the size and diameter of the electrode. Larger electrodes are utilized for quicker material removal, whereas smaller electrodes are used for fine and accurate machining. The electrode is frequently immersed in a dielectric fluid during the EDM process. The dielectric fluid has several uses, including cleaning off dirt and cooling the electrode and workpiece. The stability of the process depends on the effective dielectric flow around the electrode. Modern pulse-EDM machines have adaptive electrode control systems. These systems continuously track and modify the electrode location, improving the spark gap and preserving machining accuracy. Adaptive control helps to account for fluctuations in the workpiece and electrode wear. To prevent contamination or unfavourable reactions, the material of the electrode used must be compatible with the material of the workpiece.

To improve compatibility with certain workpiece materials, the electrode may get specialized coatings or treatments. Milling, grinding, and wire EDM are some of the methods that may be used to make electrodes. Wire EDM is frequently employed for producing complex electrode forms with great precision. For distinct applications, materials, and machining needs, many electrode types are created. The many kinds of electrodes used in pulse-EDM are as follows: A single piece of conductive material, such as copper, brass, or graphite, is used to create solid electrodes. They come in several sizes and forms, including cylindrical, conical, spherical, and bespoke profiles, and are often utilized for a variety of pulse-EDM applications. Solid electrodes may be used for a variety of machining operations and are reasonably simple to make and maintain. Tubular electrodes are hollow electrodes with an annular cross-section that are employed in processes that call for the insertion of cylindrical or tubular features into the workpiece. The manufacture of medical devices and the aerospace industry both greatly benefit from the use of tubular electrodes. Rotary electrodes are made to spin while being machined. They're utilized to make spiral or cylindrical features, such as cooling holes in turbine blades. Rotary electrodes are excellent for 3D contouring and come in solid or tubular forms. To perfectly fit the specified shape of the workpiece, custom electrodes are manufactured. They carry out detailed, difficult, and highly specialized machining operations. Custom electrodes may be made in just about any form needed for a given application. Multi-channel electrodes are used to create many holes or features concurrently, increasing productivity. They contain multiple discharge channels placed within a single electrode.

Multi-channel electrodes are frequently employed in devices like sieves and fuel injection nozzles. Electrodes having a hexagonal or honeycomb-like cross section are known as honeycomb electrodes.

5.3 Dielectric fluid

It is crucial to offer a thorough understanding of the dielectric fluid utilized in this machining process in a review paper that focuses on pulse discharge electrical discharge machining (Pulse-EDM). The efficiency and efficacy of pulse-EDM are substantially impacted by the dielectric fluid, which performs a number of crucial tasks. Here is a thorough explanation of the pulse-EDM's dielectric fluid, The dielectric fluid, commonly referred to as EDM fluid or EDM oil, is vital to the electrical discharge process because it aids in cooling the workpiece and electrode and draining out eroded material. The pulse-EDM dielectric fluid is described in detail here: In pulse-EDM, insulating liquids with poor electrical conductivity are commonly utilized as dielectric fluids. Deionized water, dielectric hydrocarbon oils, and synthetic dielectric fluids are examples of common dielectric fluids. The unique application, the material being machined, and the capabilities of the machine all influence the dielectric fluid choice. The dielectric fluid's main purpose is to act as an electrical insulator between the tool electrode and the workpiece. By separating the two components, it avoids premature electrical discharges or arcing and permits regulated sparking.

The heat produced during the electrical discharge process is dissipated using dielectric fluid as a coolant. Cooling is necessary to avoid heat damage to the tool electrode and workpiece. For consistent machining results, a constant and regulated temperature must be maintained. This assures a clean machining environment, prevents the formation of recast layers, and maintains constant material removal rates. The dielectric fluid runs continually through the machining region, flushing away eroded material and debris. Dielectric pumps and circulation systems, which maintain a consistent pressure and flow rate of the dielectric fluid to provide uniform cleansing and cooling, are features of pulse-EDM devices. For a process to be stable, proper dielectric circulation is necessary. Filtration and purification devices are frequently built into the process to preserve the quality of the dielectric fluid. These systems eliminate impurities and particles that might build up in the dielectric fluid while machining. The dielectric fluid is housed in a reservoir or tank, which is an essential component of the EDM machine. The fluid is continually pumped back and forth from the reservoir to the machining area.

Different dielectric fluids have unique benefits and characteristics. They are utilized for their superior cooling capabilities and low environmental effects. Deliver effective cooling and flushing, appropriate for tough machining processes, and provide better oxidation resistance and thermal stability, making them suited for precision machining. Operators of Pulse EDM systems should think about how dielectric fluids can affect the environment, particularly when utilizing hydrocarbon oils[24]. Important factors to think about include recycling, appropriate disposal, and using eco-friendly dielectric fluids. Based on their characteristics and compatibility with certain applications and materials, several dielectric fluids are chosen. The following are several dielectric fluids frequently utilized in pulse-EDM: One of the most popular dielectric fluids in pulse-EDM is deionized water, sometimes known as DI water. It acts as a superb insulator between the tool electrode and the workpiece and is electrically non-conductive.

Deionized water can absorb a lot of heat, which makes it a good cooling agent for machining. Talk about the most recent advancements, studies, and emerging trends in the use of dielectric fluids to improve machining precision, effectiveness, and environmental sustainability. A review of research on pulse discharge electrical discharge machining (Pulse-EDM) must include the various dielectric fluid types used in this precision machining technique. Several dielectric fluids are selected based on their qualities and suitability for particular applications and materials. Several of the dielectric fluids typically used in pulse-EDM include the following: Deionized water, sometimes referred to as DI water, is one of the most widely used dielectric fluids in pulse-EDM. It is electrically non-conductive and serves as a great insulator between the tool electrode and the workpiece. DI water is a good cooling agent since it can absorb a lot of heat. Anti-wear agents, anti-corrosion substances, and other specialist components are examples of additives.

These additions can improve fluid characteristics and increase the dielectric fluid's lifespan. In gas-based EDM, gases rather than liquids are employed as the dielectric medium, such as nitrogen or argon. These gases offer effective cooling and cleansing and are electrically non-conductive. For situations where avoiding the use of liquids is preferable, gas-based EDM is frequently selected. Green dielectric fluids are substitutes that are friendly to the environment and are made to have less of an impact. They strive to reduce waste, energy use, and hazardous material releases throughout the machining process. Environmentally acceptable additives may be used in water-based solutions for green dielectric fluids. For certain materials or uses, some dielectric fluids are specially prepared. For instance: Dielectric fluids are designed for aircraft alloy machining and for advanced composite materials or ceramics. High-performance dielectric fluids are made to survive difficult machining situations and harsh environmental conditions. They have cutting-edge qualities, including superior dielectric strength, high flash points, and low vapor pressure.

5.4 Material Removal Rate

It's crucial to provide readers with a thorough grasp of the material removal rate (MRR) in a review paper on pulse discharge electrical discharge machining (Pulse-EDM). The essential variable of material removal rate has a direct impact on the efficacy and efficiency of pulse-EDM. The following is a thorough explanation of the material removal rate. In pulse-EDM, the amount of material removed from the workpiece per unit of time is referred to as the material removal rate (MRR). It is a vital performance indicator that measures the productivity and efficiency of the machining process. Numerous variables affect the MRR in pulse-EDM, which may be determined using the formula below: MRR is equal to V_f times. The material removal rate (in cubic millimeters per minute or other suitable units) is MRR. The volume fraction of material removed from each discharge (usually a negligibly small portion of the tool electrode's volume) is denoted by the symbol (V_f). The number of sparks or discharges that occur per unit of time, often represented in sparks per second, is known as the discharge frequency, or (A). T is the length of each spark in time. The material removal rate (MRR) in pulse-EDM is the quantity of material removed from the workpiece per unit of time. It is an essential performance indicator for gauging the effectiveness and productivity of the machining operation.

The material removal rate, or MRR, is measured in cubic millimetres per minute or other appropriate units. The symbol (Vf) designates the volume fraction of material eliminated from each discharge, which is typically a negligibly small amount of the tool electrode's volume. The discharge frequency, also known as the rate of sparks or discharges per unit of time (typically expressed in sparks per second), Materials with high melting temperatures and low thermal conductivity often have a lower MRR. Conductive materials, on the other hand, are typically simpler to machine at a greater MRR than non-conductive materials. The MRR is influenced by the spark gap between the tool electrode and the workpiece. Smaller spark gaps can result in greater discharge frequencies, which in turn increase MRR. Stable MRR requires a constant spark gap, which must be maintained. Proper dielectric circulation promotes steady MRR by limiting excessive heat accumulation. Adequate dielectric fluid flow and pressure guarantee effective cooling and debris removal. Adaptive control techniques are frequently used by advanced pulse-EDM devices. These systems continuously monitor the machining operation and modify the pulse settings to maximize MRR while preserving machining stability and precision.

The MRR and the choice of pulse parameters can be influenced by the workpiece's desired surface finish. While roughing operations may prioritize maximizing material removal, finishing operations may favor accuracy over high MRR. The intended surface quality of the workpiece might have an impact on the MRR and pulse parameter selection. While optimizing material removal may be a roughing operation's top priority, finishing operations may value precision above high MRR. Depending on the material being machined, MRR varies greatly. Compared to non-conductive materials like ceramics, conductive materials like metals often have a greater MRR. Modifying the MRR can be necessary to achieve a certain surface finish. Lower MRR is sometimes the result of less material being removed per spark with finer surface finishes.

Between roughing and finishing procedures, a different MRR is needed. High MRR is prioritized in roughing operations to remove material quickly, whereas accuracy and surface quality are needed in finishing. Proper dielectric cooling and flushing increase the machining efficiency, which in turn improves MRR. Dielectric fluid characteristics and circulation have an impact on MRR. Advanced Pulse-EDM devices could make use of adaptive control methods. These systems continuously track and modify pulse parameters to enhance MRR while preserving machining stability. MRR has an effect on how economical the machining procedure is. The key to achieving economic viability is striking a balance between MRR, operating expenses, and desired product quality. High MRR might lead to more energy and dielectric fluid being used. Sustainable manufacturing requires that the effects of machining operations on the environment be taken into account.

5.5 Surface Integrity

It's crucial to convey a thorough grasp of the surface integrity features related to this machining method in a review article on pulse discharge electrical discharge machining (Pulse-EDM). Surface integrity refers to a variety of qualities and features of the machined surface that influence its performance, quality, and usefulness. Here is a thorough explanation of how pulse-EDM handles surface integrity[29]. In pulse-EDM, surface integrity refers to the entire collection of characteristics and circumstances on a workpiece's machined surface. It is a crucial step in the machining process, especially in situations where the workpiece's surface quality, dimensional accuracy, and functional performance are crucial. In pulse-EDM, surface integrity includes a number of crucial elements. Surface imperfections or deviations from a smooth surface on the machined workpiece are referred to as surface roughness. Depending on the process variables and the electrode settings, pulse-EDM may generate surfaces with varied degrees of roughness[25,26]. Achieving the necessary functional and aesthetic qualities of the workpiece requires controlling and optimizing surface roughness.

The microstructure of the workpiece material can change as a result of the EDM process, including pulse-EDM. Recast layers, heat-affected zones, and microstructural modifications are a few examples of these modifications. It's important to comprehend and characterize these changes, especially in materials with particular mechanical or thermal characteristics. Pulse-EDM can have metallurgical effects on the workpiece material, such as recrystallization, phase shifts, and grain growth. These factors may affect the material's tensile strength, fatigue resistance, and hardness. Such flaws can weaken the workpiece and have a detrimental effect on how well it performs. Assessing and reducing surface flaws is essential to ensuring the dependability of machined components. The heat cycling and material removal in pulse-EDM might leave residual strains in the workpiece material. The workpiece's dimensional stability and susceptibility to fatigue failure may be impacted by residual stresses. For machined components to last and operate well, residual stresses must be managed and controlled. Pulse-EDM may cause phase shifts or fluctuations in workpiece hardness, depending on the material and process circumstances.

For applications where material qualities are crucial, understanding these variances is essential. A crucial component of surface integrity is achieving the proper surface quality and texture. Surface quality may be greatly affected[29]. Such imperfections may weaken the workpiece and have a negative impact on how effectively it functions. For machined components to be reliable, it is crucial to evaluate and minimize surface defects. The workpiece material may still have residual stresses after pulse-EDM's heat cycling and material removal. Residual stresses may affect the workpiece's dimensional stability and susceptibility to fatigue failure. Relative stresses need to be handled and regulated in order for machined components to last and perform well. Depending on the material and process conditions, pulse-EDM may result in phase shifts or variations in the hardness of the workpiece. Understanding these variations is key in situations where material characteristics are important. Having the appropriate surface quality and texture is essential for maintaining surface integrity. Surface quality might have a major impact. It's crucial to examine the many types or features of surface integrity connected to this machining technique in a review article on pulse discharge electrical discharge machining (Pulse-EDM). Surface integrity refers to a variety of traits and qualities that affect the caliber, usefulness, and efficacy of the machined surface.

The following are some surface integrity issues for Pulse-EDM: Surface imperfections, waviness, and deviations from a smooth surface on the machined workpiece are referred to as surface roughness. Surface roughness can vary depending on the machining circumstances, electrode materials, and dielectric fluids used. The workpiece's sealing, friction, and wear resistance are all impacted by the surface roughness. The recast layer, which develops on the machined surface during the EDM process, including pulse-EDM, is a thin layer of resolidified material. The features of the recast layer, including its thickness, may be controlled or reduced by optimizing the pulse-EDM settings. A region close to the machined surface that is subject to thermal impacts but does not melt is known as the heat-affected zone. It may display changed material characteristics, such as variations in hardness and microstructural alterations. Particularly in the case of heat-sensitive materials, understanding and managing the HAZ is essential. Surface cracks, pits, and microstructural flaws may be created during the EDM process, particularly pulse-EDM. The workpiece's structural stability and fatigue life may be impacted by these flaws.

Reliability requires that such flaws be reduced in frequency. Pulse-EDM can cause grain refinement, recrystallization, or phase transitions in the workpiece material's microstructure. These modifications may affect the hardness, tensile strength, and fatigue resistance of the material. Due to the pulse-EDM's heat cycling and material removal, residual tensions may form in the workpiece. They may affect the workpiece's dimensional stability as well as its vulnerability to cracking and deformation. Phase shifts or variations in hardness inside the workpiece might result from pulse-EDM machining, depending on the material and machining circumstances. The performance and material qualities of these adjustments may be impacted. Depending on the application, a different surface finish and texture may be preferred. Surface finish control is crucial for meeting both practical and aesthetically pleasing needs. Pulse-EDM can cause metallurgical effects in the workpiece material, such as recrystallization, phase shifts, and grain growth. The mechanical characteristics of the material may be impacted by these processes. Adaptive control systems may be included in advanced pulse-EDM machines to track and modify process variables in real-time. While preserving machining effectiveness, these technologies can aid in optimizing surface integrity. Material removal rate (MRR) and surface integrity must be balanced, and this is a crucial factor[29]. Surface integrity may be significantly impacted by high MRR; however, these effects can be reduced by optimizing the process parameters. To improve surface integrity and fulfill standards, some applications could need post-machining processes, including surface grinding, polishing, or heat treatment[29].

6. CONCLUSION

As a result, this review serves as a compass, guiding readers through the maze of EDM methods for milling Titanium Grade 2 alloy, shedding light on the various aspects of tooling, dielectric fluid selection, machining and process parameters, and the most recent technological advances. We will gain a complete understanding of the issues, innovations, and opportunities in Titanium Grade 2 alloy machining as we embark on this journey, allowing us to explore previously undiscovered realms of efficient, sustainable, and high-precision titanium machining. The very desirable features of titanium alloy increase complexity and make machining more difficult when compared to conventional materials. EDM techniques have many arrangements for removing materials by using various types and materials of tool electrodes, dielectric fluid, and machining parameters. However, the mechanism of material removal is comparable in different EDM procedures in which an electric arc is formed near the workpiece. This generates a lot of heat, which melts and vaporizes the workpiece along the path of the tool electrode movement. Because of the high-temperature generation, low thermal conductivity, and high cooling rate, the machined surfaces produced by EDM procedures have cracks, recast layers, residual stress, and heat-impacted zones.

Die-sinking EDM and wire EDM are critical precision manufacturing pillars in the area of titanium alloy components. These processes, with their distinct advantages, have enabled manufacturers to tackle the complexities of titanium machining, satisfying the needs of industries that require high precision and quality. Die-sinking EDM and wire EDM are positioned as vital tools in the drive for more efficient, sustainable, and high-precision titanium alloy component manufacture as the EDM landscape evolves with innovations and sustainability at the forefront. Their continued importance exemplifies the manufacturing sector's ever-evolving symbiosis between technology and accuracy. Micro EDM and Pulse EDM have proven to be essential tools in the precision manufacturing arsenal, notably for the machining of titanium alloys. Manufacturers can realize the full potential of these approaches by carefully evaluating tools, and dielectric fluids, and managing machining and process conditions. The growing landscape of EDM technologies is distinguished by innovation, precision, and sustainability, making these processes increasingly important in a variety of industries. As the search for more efficient, sustainable, and high-precision machining continues, Micro EDM and Pulse EDM stand out as dependable and growing techniques destined to define the future of titanium alloy component manufacturing.

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