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STUDY ON EFFECT OF PROCESS PARAMETERS ON RESPONSES DURING PLANETARY EDM OF TITANIUM GRADE 5 ALLOY

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Abstract: Planetary or Orbital tool actuation is one of the process improvement techniques used in Electro Discharge Machining (EDM) process which has multi facetted advantages. In present work, an attempt has been made to study the effect of various process parameters during planetary EDM of Ti-6Al-4V; a material which is difficult and expensive to machine by conventional methods. Parameters viz. Pulse ON time, Polarity of the tool electrode, Duty factor, Gap voltage and Pulse OFF time have been considered to study the process in terms of tool wear rate, wear ratio and surface roughness. Results suggest that Pulse ON time and Polarity of the tool electrode have significant effect on the responses. Comparative study between Planetary and Die sinking strategies suggest that planetary tool actuation in EDM have the potential to machine Titanium alloys more efficiently than conventional die sinking EDM.

Key words: Titanium, Machining, Wear, Roughness, Planetary, Orbital.

1. INTRODUCTION

Titanium is the ninth most abundant element and seventh most abundant metal in the Earth's crust. This metal has wide range of application in fields like aerospace, military, automotive, medical prosthesis etc. due to its excellent combination of high strength to weight ratio and good resistance even at elevated temperatures (Pathak et al., 2002). Despite its value, the utility of this material is limited because of the difficulties in extraction, melting and machining of the same (Pervaiz et al., 2014). The lower property values for elastic modulus, thermal conductivity, volume specific heat and high chemical reactivity towards tool materials of this metal and its alloys make its machining very complex and completely different, thereby resulting into high tool wear and poor machined surface quality (Kosaraju and Anne, 2013).

Electro discharge machining process is a viable technique to machine these types of materials as it removes material from any electrically conductive material with the help of controlled and repetitive sparks in the presence of a dielectric medium. The impacts of sparks result in to localized rise in temperature and leads in to melting and vaporization of material from the job surface as well as from the electrode and the molten metal is forced out from the job surface by the collapsing of the plasma channel. The debris formed is carried out from the machining zone by the dielectric fluid (Ho and Newman, 2003). Being a machining process in which the mirror image of the tool is generated on to the work piece, any complicated shape, unlike conventional machining process can be generated with the aid of proper tool design and tool kinematics, if required. The process is widely used manufacturing industries despite its critical limitation in terms of wear on the tool electrode (Cogun et al., 2012).

Application of EDM for machining titanium based alloys has been reported by many researchers. The feasibility of different tool electrode materials Hascalik and Caydas, 2007), tool geoemetries and kinematics (Gu et al., 2012, Shabgard and Alenabi, 2015), dielectric fluids with different types of suspensions (Ndaliman et al., 2013, Kumar et al., 2014) etc. have been reported and are observed to have effects on important process characteristics like erosion rate, surface quality etc. As the material removal rate using EDM is relatively lower for these materials, techniques to improve the same have also been reported (Sen et al., 2012, Gill and Singh, 2010).

During literature, it has been observed that even though attempts have been put up by researchers for studying rate of material removal and tool wear during the process, concept of wear ratio is not studied in detail. Further, due to its poor EDM machinability, majority of the studies have targeted on generation of shallow features. Different machining conditions may be aniticipated at larger machining depths.

Exposure of material with inferior thermal properties for longer machining durations may lead to heat accumulation at both tool electrode as well as the work piece. Further, at higher machining depths the debris expulsion from the inter electrode gap will also be difficult. Both these situations might lead to the condition of unstable machining and hence result into lower process efficiency. So it is important to incorporate appropriate process improvement techniques to avoid such conditions. Application of actuation techniques like rotation or vibration to either tool or workpiece can be beneficial in this aspect (Son and Chakraverti, 1994, Prihandana et al., 2012). However orbiting or planetary actuation of the tool electrode is one such strategy which has multiple advantages relative to these techniques.

Orbiting or planetary actuation of the tool electrode is one such technique used in both micro and macro EDM, in which a relatively smaller electrode is actuated on a path that will articulate its outer surface on a trajectory that is similar to the shape of the hole (Mathai et al., 2014). Such a strategy can enhance the flushing at the inter electrode gap thereby reducing chances of debris accumulation in the machining zone, temperature rise in tool and workpiece and reduction in tool cost (Sriani et al., 2010, Rajurakar and Royo, 1989). It has also been reported that wear on the tool electrodes used under such conditions are lower and more homogeneous, thereby helping in attainment of lower wear ratios (Teicher et al., 2013, Yu et al., 2002). Different modes of planetary tool actuation viz. spiral, helical, z slicing, cylindrical slicing, z-spiralling etc. have been reported for generation of circular features (El-Taweel and Hewidy, 2009, Bamberg and Heamawantanachai, 2009, Guo et al., 2013). Simultaneous application of tool rotation along with planetary tool actuation has also been reported for processs improvement (Egashira et al., 2005, Ziada and Koshy, 2007).

It has been understood from literature survey that even though the concept of orbiting the tool electrode is reported long back, very few detailed parametric studies have been reported considering this aspect. Moreover, majority of the studies related to tool orbiting in EDM have been focussed on the generation of simple circular features. Also, being a strategy that improves the machining performance in multiple aspects, application of the same may facilitate more efficient and relatively easy machining of titanium and its alloys using EDM. So, the objective of the present study is to understand the effect of various process parameters on responses during generation of square shaped cavities on titanium grade 5 (Ti6Al4V) material using planetary EDM.

2. DETAILS OF EXPERIMENTATION

2.1 Tool motion strategy

From authors' prior experimental studies in the aspect of effect of tool path strategies on non-circular cavity generation, it has been understood that the two tool path strategies possible for the generation of a square cavity are helical and diagonal and results suggested that helical strategy is preferable to diagonal strategy owing to its relatively better performance in terms of tool wear rate, material removal rate and surface quality (Mathai et al., 2014, 2015). So in present study, helical strategy has been selected for tool actuation.

In Helical strategy, the tool is scanned along a path parallel to the edges of the final intended cavity. This path will be at a distance equal to the tool offset (τ_o) from the centre axis of the final cavity. Since motion along Z axis is also provided during the tool motion, the final tool path will look like a square shaped helix. Figure 1 shows the schematic diagram of the helical tool path strategy. It can be clearly seen from the figure that if 'a' is the edge length of the face of the tool electrode and 'τ' is the tool path offset, the size of final cavity that can be generated using planetary strategy is '$a + 2\tau_o$'.

2.2 Experimental plan and procedure

For experimentation, Titanium grade 5 alloy has been selected as the work piece material due to its wide range of applications in fields of aerospace, biomedical, chemical industries etc. Blocks of size 25mm x 15mm x 15mm have been used for carrying out experimentation. Copper has been selected as the tool electrode material as it is a widely used tool electrode material in EDM process owing to its high good thermal and electrical conductivity. Electrodes having cross sectional size of 9mm x 9mm and length 20mm with a tool path offset of 0.5mm have been employed for feature generation.

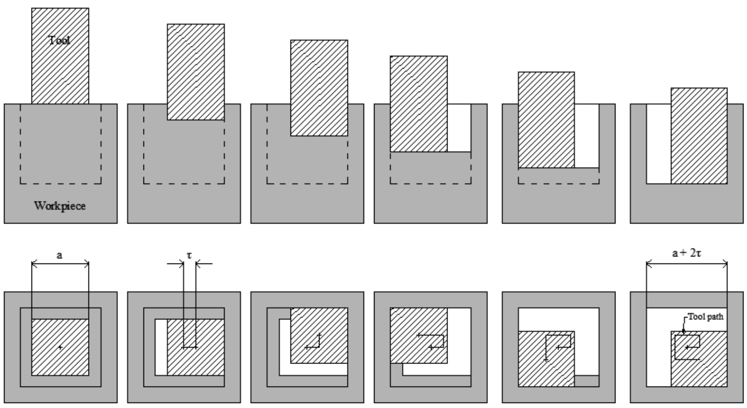


Fig. 1. Helical Tool motion strategy used for generating square cavity

The experiments have been carried out using one factor at a time methodology in which one parameter is varied keeping the rest of the parameters at a constant level. Current has been kept at a constant level of 13A for all experiments. Five process parameters viz. pulse ON time, duty factor, polarity of the tool electrode, gap voltage and pulse OFF time have been varied for studying the effect of the same on various response characteristics. Pulse ON time is the time duration during which the sparking takes place in the total machining duration (Pulse ON time + Pulse OFF time). As the values available for pulse ON and OFF times on the machine tool used for experimentation are preset, it was difficult to select parameter levels with equal difference between them. However, care has been taken to maintain the same to the possible limit. Duty factor is the ratio of pulse ON time to the total machining duration. Gap voltage is the potential that is applied between the tool and work piece and it defines the gap between them. Table 1 shows the consolidated experimental design used for carrying out the study.

Table 1. Parameters and their levels considered for experimentation

		Variable parameters				
		t_{ON}	**DF**	**Pol.**	**V**	t_{OFF}
Constant parameters	t_{ON}	40, 100, 165, 240	0.3	-	70	Depends on t_{ON}
	DF	240	0.2, 0.3, 0.4	-	70	Depends on *DF*
	Pol.	40, 240	0.3	-, +	70	Depends on t_{ON}
	V	240	0.3	-	40, 70, 100	550
	t_{OFF}	240	Depends on t_{OFF}	-	70	275, 410, 550, 690

t_{ON} = Pulse ON time (µs), DF = Duty factor, Pol. = Polarity of tool electrode,V = Gap voltage (V), t_{OFF} = Pulse OFF time (µs)

To assess the process effectiveness, three responses viz. tool wear rate (*TWR*), wear ratio (*WR*) and surface roughness of the cavity have considered. Tool wear rate is the rate at which the amount of amount of material is eroded or removed from the tool. Wear ratio (*WR*) has been defined as the ratio of volume of material removed from the work piece to that eroded from the tool electrode surface. The equations used for calculating the above mentioned responses are given below:

Tool Wear Rate,

$$\text{TWR} = \left(W_{tb} - W_{ta}\right) \times 60 / \left(\rho_t \times t\right) \text{ mm}^3/\text{min} \qquad (1)$$

Wear Ratio,

$$\text{WR} = \left(\frac{W_{wb} - W_{wa}}{\rho_w}\right) \bigg/ \left(\frac{W_{tb} - W_{ta}}{\rho_t}\right) \qquad (2)$$

where $W_{tb/a}$ = Weight of the tool electrode before and after machining, $W_{wb/a}$ = weight of the work piece before and after machining, $\rho_{t/w}$ = density of the tool/work piece material (8.94 gm/cm^3 for Copper and 4.43 gm/cm^3 for Ti6Al4V) and t = machining time in seconds.

The experiments have been carried out on Joemars AZ50R ZNC electro discharge machine with orbital attachment for providing the required tool motion. Commercially available dielectric fluid has been used as medium for experimentation. Side injection flushing with a pressure of 0.25kg/cm^2 has been provided during machining. The machining time has been recorded using a digital stop watch having a least count of 0.1 seconds. Size of the cavity has been fixed to 10mm x 10mm x 10mm. For all experiments, the scanning speed of the tool electrode has been kept constant at 0.13mm/s.

On completion of the process, both tool electrode and work pieces have been rinsed and cleaned using acetone. Afterwards, the weight measurements have been taken using a digital weighing balance having a least count of 0.1mg. Surface roughness of the cavities has been measured using Mitutoyo's SJ400 surface roughness tester using diamond tip stylus having a tip radius of 5µm. Eight readings have been taken at different locations of the vertical wall of the cavity and they are averaged out for further analysis. End condition of the tool electrodes have been studied using vision measurement system.

3. RESULTS AND DISCUSSIONS

3.1 Effect of Pulse ON time

To study the effect of pulse ON time, the experiments have been carried out at four levels and figure 2(a-c) shows the effect of the same on various responses. It can be clearly seen that lower pulse time leads to very high tool wear and with increase of the same, the response is observed to reduce significantly. At higher pulse ON time, the heat build up in the tool electrode will result in to dissociation of hydrocarbon based dielectric fluid in its proximity. The carbon thus generated will form a layer on the tool surface and same will act as a protective layer on the tool electrode thereby safeguarding it from further erosion. Further, at higher pulse ON time, the energy density of the discharge spot will be lower due to the expansion of the plasma channel because of the increase in temperature, leading to smaller level of erosion from both tool electrode and work piece.

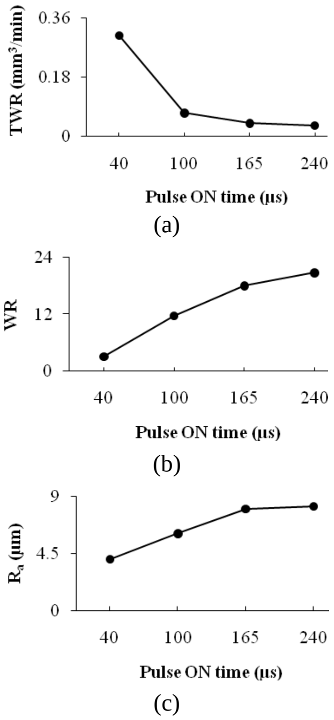


Fig. 2. (a – c) Effect of variation of Pulse ON time on responses

Figure 2(b) depicts the effect of pulse ON time on Wear Ratio. It can be clearly understood that higher pulse ON time is preferable for higher wear ratio. Surface roughness of the cavities machined at different levels of pulse ON time is graphically shown in figure 2(c). Results suggest deterioration of surface with increase in Pulse ON time.

Figure 3 shows the wear characteristics of the tool electrodes used under different pulse ON time conditions. It can be clearly seen that the wear is very high on the tool electrodes used under lower pulse ON time conditions. It is also worth noting that the wear at the flushing side (left side in present case) of the electrode is lower. The intensity of wear is observed to increase with increase in distance from the flushing.

This wear pattern may have a relation with the presence of debris at the inter electrode gap and the flow pattern of the dielectric fluid carrying the debris particles from the machining zone. Since the existence of debris at the flushing side is difficult due to constant fluid flow, the concentration of debris in this zone will be less. But, at the symmetrically opposite side, where the fluid flow will be relatively lower, the debris concentration will be higher. At these regions, the machining condition may not be stable, leading into the generation of secondary sparking by these debris particles, which may lead to intense tool wear as shown in figure 4.

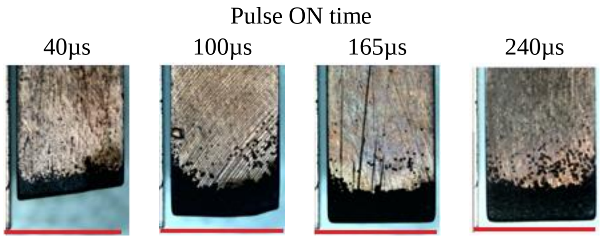


Fig. 3. Tool electrode after using under different Pulse ON time conditions (Magnification = 17.5X)

3.2 Effect of Duty Factor

Duty factor is a critical process parameter in electro discharge machining as it decides process stability as well as machining time. Higher duty factor levels have not been employed for experimentation as such conditions may result in to thermal distortion in Ti6Al4V due to its poor thermal conductivity (Fonda et al., 2008). Figure 5(a-c) shows the effect of variation of duty factor on mulitple responses. It is evident from figure 5(a) that the tool wear rate increases with increase in duty factor. At higher duty factor, the time for providing flushing at the inter electrode gap will be lower. This will result in accumulation of debris at the machining zone, leading to the condition of unstable machining and thereby leading to higher tool wear.

Figure 5(b) shows the effect of variation in duty factor on wear ratio. It can be clearly seen that the wear ratio decreases with increase in duty factor. So, in terms of wear ratio, low duty factor is preferrable. But it is also worth noting that the the rate of reduction of wear ratio is higher at higher values of duty factors.

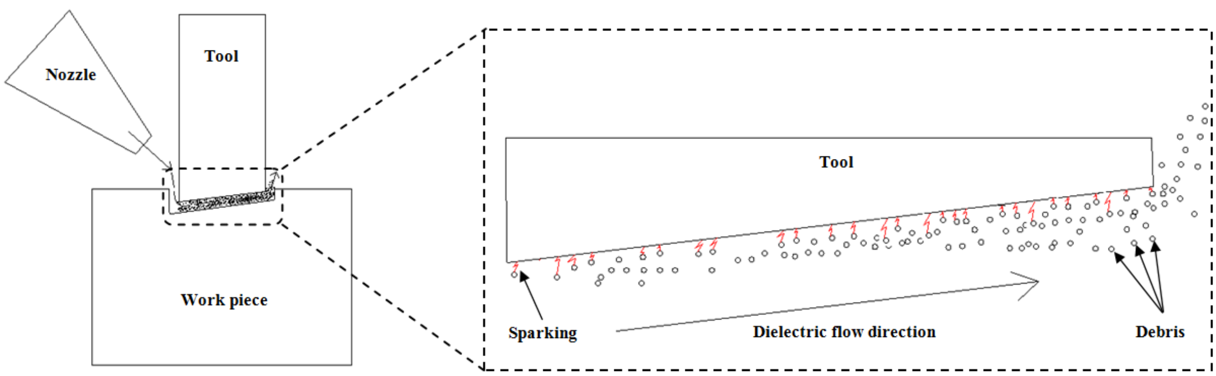
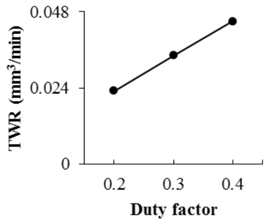
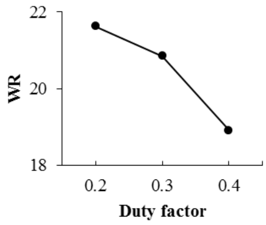


Fig. 4. Mechanism of Tool wear under Side Injection flushing

Effect of variation of duty factor on surface roughness is shown in figure 5(c). It can be seen that the surface roughness increases with increase in duty factor. This may be due to the unstable machining conditions that may arise because of ineffective flushing at higher duty factor levels. The unstable machining conditions will lead to the occurrence of secondary sparking arcing which result into deterioration of the surface and there by increase in roughness of the machined surface.



(a)



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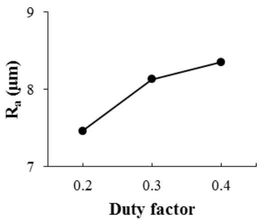


(c)

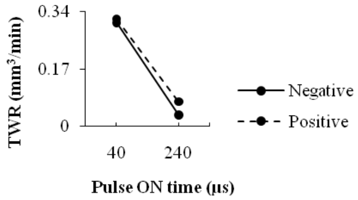
Fig. 5(a – c). Effect of variation of Duty factor on responses

3.3 Effect of Polarity of the Tool electrode

Polarity of the tool electrode can be influencial in a process like electro discharge machining as the discharge energy applied varies significantly with variation of the same (Wu et al., 2005). In this study, the effects of both negative and positive polarity of the tool electrode at low as well as high pulse ON time conditions on responses are studied.

From figure 6(a), it can be observed that the tool wear rate is lower when negative polarity is employed at both low as well as high pulse ON time conditions. The wear intensity may vary based on the type of particle that impact on the tool electrode – positive ion or electron. As electrons have higher mass than ions, they possess higher kinetic energy and the impact of the same on a positive electrode may result into higher wear on it. This variation in wear intensity with respect to tool electrode polarity can be clearly seen in figure 7.

In terms of Wear ratio, it can be clearly observed from figure 6(b) that the use of negative polarity is beneficial as at both lower as well as higher pulse ON time, the response is higher under negative polarity. This may be because of the lower material removal rate obtained under postive polarity of the tool electrode. This clearly suggests that for removing the material from the work piece at the expense of least tool wear, negative polarity of the tool electrode is preferable.



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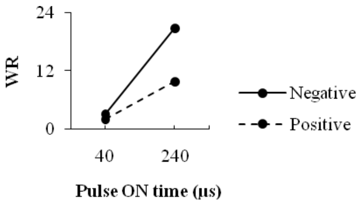

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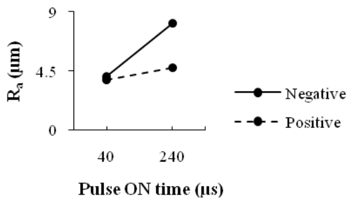


(c)

Fig. 6(a – c). Effect of variation of tool electrode polarity on responses

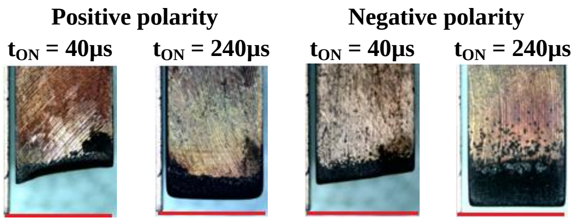


Fig. 7. Tool electrodes after using under different Pulse ON time and Polarity (Magnification = 17.5X)

Figure 6(c) shows the effect of polarity on surface quality of the job surface. It can be seen that the surface roughness is higher under the use of tool electrode with negative polarity at both lower as well as higher pulse ON time conditions. Under postitive polarity of tool electrode, the material removal will take place with the help of positive ion impingement, which have lower kinetic energy and momentum. This may result in removal of material in very small craters from the workpiece surface leading to lower surface roughness.

3.4 Effect of Gap voltage

Effects of variation of gap voltage on multiple responses are shown in figure 8(a – c). It can be seen from figure 7(a) that the tool wear rate is gradually decreasing with increase in gap voltage.

As gap voltage defines the inter electrode gap, a lower gap voltage condition will result into smaller gap between the tool electrode and the workpiece surface. This makes the removal of debris from the machining zone difficult. This may give rise to conditions for unstable machining and hence intense wear on the tool electrode. With increase in gap voltage, the inter electrode gap will increase, which may facilitate more effective flushing at the machining zone and attainment of stable machining conditions. Similar observation can be seen in the case of wear ratio also (fig. 8(b)). It is also worth noting that variation of gap votlage doesnot have a dominant effect on both tool wear rate and wear ratio.

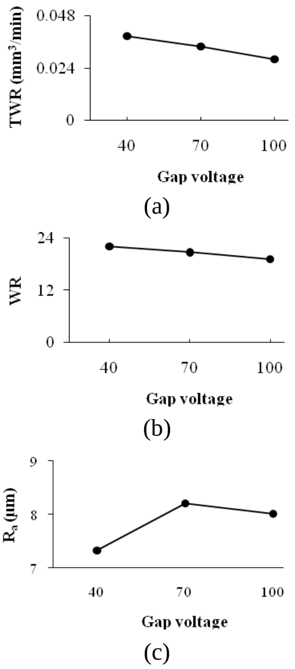


Fig. 8(a – c). Effect of variation of Gap voltage on responses

Effect of gap voltage on surface roughness is shown in figure 8(c). It can be observed that the response intially increases upto 70V and then decreases. As discharge energy is a function of gap voltage, an increase in gap voltage will result into removal of large amount of material from the work piece surface and thus formation of big micro craters. But as gap voltage also determines the inter electrode gap, a larger gap voltage will result into larger inter electrode gap, which will lead to reduction in the intensity of discharge spot and thus remove material in relatively smaller quantities and will yield a surface with lower roughness.

3.5 Effect of Pulse OFF time

Selection of pulse OFF time levels for experimentation has been done in such a way that the duty factor will not cross 0.5 as such conditions may lead to thermal distortion of Ti6Al4V. Figure 9(a) shows the effect of variation of pulse OFF time on tool wear rate. It can be clearly observed that the response decreases with increase in pulse OFF time. This is due to the fact that at higher pulse OFF time conditions, the debris concentration at the inter electrode gap will be lower, there by reducing the chances for occurrence of arcing or undesirable sparking.

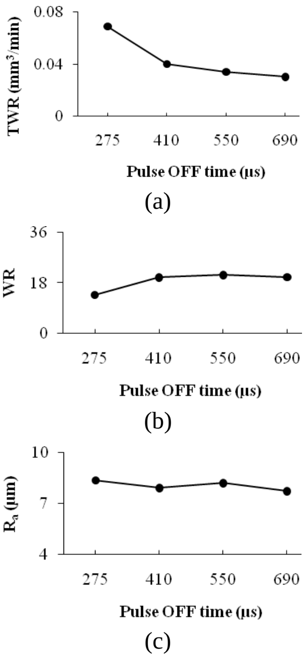


Fig. 9(a – c). Effect of variation of Pulse OFF time on responses

Even though the tool wear rate reduces with increase in pulse OFF time, such conditions may lead to reduction material removal rate also as the increase in pule OFF time results in to increase in the unproductive time in total machining cycle. However, the reduction of the response is not that significant in terms of the reduction obtained on tool wear rate. This accordingly results into increase in the wear ratio which can be clearly seen in figure 9(b).

Figure 9(c) show the effect of pulse OFF time on surface roughness of the job surface. It can be clearly understood from the figure that even though higher pulse OFF time, results in to conditions of improved flushing at the inter electrode gap, no significant difference in surface quality is observed.

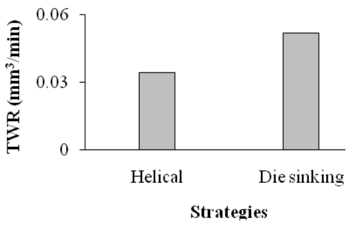
3.6 Performance comparison of Planetary EDM with Die sinking EDM

As the application of planetary EDM is done to improve the process efficiency, it is important to compare the performance of the strategy with conventional die sinking EDM method to assess its effect on responses. Table 2 shows the parameter level that has been employed to carry out the experimentation. The feature size has been kept at a constant size of 10mm x 10mm x 10mm. So, for planetary EDM, a tool electrode having size of 9mm x 9mm with tool path offset set as 0.5mm has been employed where as for die sinking experiment, a tool electrode having a size of 10mm x 10mm with zero tool path offset has been used.

Figure 10(a – c) shows the effect of the machining strategies on critical responses. From Figure 10(a), it can be clearly seen that the tool wear rate under EDM using helical strategy is lower than that in the case of die sinking. It is also worth noting that in terms of wear ratio, which is shown in Figure 10(b), helical strategy have better performance capability than die sinking, thereby clearly showing the effectiveness of the strategy of machining a material like Ti6Al4V. However, the surface quality is slightly inferior in the case of application of helical strategy.

Table 2. Experimental conditions used for comparing EDM of Ti6Al4V using Planetary and Die sinking strategies

Parameter	Value	
Current	13A	
Pulse ON time	240μs	
Duty factor	0.3	
Gap voltage	70V	
Tool electrode polarity	Negative	
Cavity size (l x b x d)	10mm x 10mm x 10mm	
Tool electrode size	Planetary	9mm x 9mm (with planetary offset = 0.5mm)
	Die sinking	10mm x 10mm (with no planetary offset)
Scanning speed	Planetary	0.13mm/s
	Die sinking	No scanning motion



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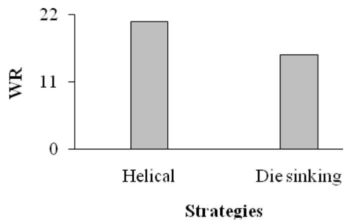

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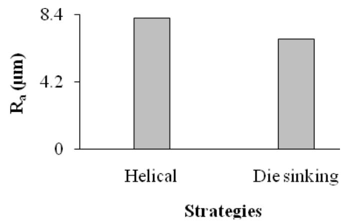

(c)

Fig. 10(a – c). Comparison between Helical and Die Sinking EDM strategies in terms of (a) Tool Wear Rate, (b) Wear Ratio, (c) Surface roughness

4. CONCLUSIONS

Effect of various process parameters on critical responses like tool wear rate, wear ratio and surface roughness during planetary EDM of Ti6Al4V have been studied. It has been observed that the Pulse ON time and current have a dominant effect on the responses. Appropriate selection of duty factor is necessary as very low levels may result into very high machining time and too high levels may lead to attainment of inferior responses. Negative polarity of the tool electrode is preferable to positive polarity as it resulted in achieving relatively lower tool wear rate and higher wear ratio. Parameters like gap voltage and pulse OFF time do not have significant effect on the response characteristics.

Further, to assess the influence of planetary EDM strategy in machining titanium alloys, the responses obtained under the same has been compared with responses obtained under die sinking EDM and results suggest that planetary actuation of the tool electrode during EDM is beneficial for efficient machining of titanium alloys. However, more detailed studies by incorporating variation of parameters related to tool kinematics viz. tool path offset and scanning speed must be carried out to arrive at more concrete and optimized results.

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