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Electrical discharge machining of René 108 DS nickel superalloy for aerospace turbine blades

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Abstract

Manufacturing industries aim for high quality production with decreased cost and time. To this purpose, optimization of the processing parameters is required, in order to reduce the machining time and match the quality standards. This study has been conducted to electrical discharge machining on Renè 108 DS. In the process, the electrode material is crucial for metal removal and tool wear, whose optimization usually leads to conflicting goals. Therefore, two electrode materials, graphite (Poco EDM-3) and copper-infiltrated-graphite (Poco EDM-C3) have been tested in a factorial plan including current, voltage, duty cycle and electrode polarity. The process is discussed in terms of material removal rate, tool wear rate, wear ratio and final surface roughness of the work-piece.

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Keywords: Electrical discharge machining (EDM); Nickel; copper-infiltrated-graphite electrode.

1. Introduction

In aerospace, the use of materials with high resistance to temperature, creep, corrosion and fatigue, as well as the need for components with specific shape and tight tolerances, have led to the development of subtractive processing methods without mechanical removal. These are referred to as non-conventional processes and are widely diffused for aerospace propulsion. In particular, the components are generally created and then post-processed to produce hollows, cambers, thin walls and any other complex geometry which is not possible via direct casting [1-2].

In this frame, Electrical Discharge Machining (EDM) is based on a series of discrete sparks between the work-piece and the tool electrode in a dielectric fluid, eroding material from the work-piece and causing tool wear. Alternatively, a conductor wire is used as tool electrode for cutting in wire electrical discharge machining (WEDM). Both of them are thermo-electrical processes; time of execution, costs and final surface roughness depend on a number of processing parameters, which have been investigated in the literature with respect to different materials. Therefore, some models have been developed to evaluate the effect of the leading parameters, to control the process and to optimize material removal rate (MRR), tool wear rate (TWR) and roughness as a measure of quality. Proper methods can be chosen depending on the goals and the parameters under examination.

Shabgard et al. [3] developed a method to set the processing parameters in EDM on tungsten carbide based on fuzzy logic. Shandilya et al. [4] used the responses surfaces method to optimize the leading factors in WEDM on metal matrix composites (SiCp/6061 Al MMC). Rajmohan et al. [5] discussed EDM of stainless steel alloy 304B based on the ANOVA and surface response. Rajesh and Dev Anand [6] proposed a new method of optimization for EDM based on genetic algorithms: a linear regression has been considered to represent the relation among the processing parameters and the response variables; an optimum condition has been suggested.

Although a number of works have been developed, only few of them have dealt with the effect of electrode material and polarity which is generally chosen upon preliminary trials. Nevertheless, interactions are expected with the electrode material, the work-piece material, the current intensity and the

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time of discharge. In particular, Haron et al. [7] tested two electrode materials, copper and graphite, the latter allowing higher MRR; Muttamara et al. [8] compared graphite and copper-infiltrated-graphite when a conductive coating is laid on the work-piece. Moreover, positive and negative polarity have been compared: when the electrode is made anode, higher MRR and lower TWR are benefited, although better surface quality is achieved when the electrode is made cathode. A one-factor-at-a-time approach is common feature, anyway. For instance, Singh and Shukla [9] firstly changed the duration of discharge, then the current intensity for given base levels of the other parameters. Lee and Li [10] conducted a first test to select the electrode, then a second test for polarity; voltage has been finally selected in a third test aiming to maximize MRR and minimizing TWR.

Hence, this work aims to discuss the effect of polarity and electrode material in a plan including traditional parameters of EDM such as current, voltage and duty cycle with design-of-experiments rather than one-factor-at-a-time approach, so that a comparison of the results for multiple processing levels would be possible.

2. Experimental methods

2.1. The component

This study is conducted to investigate EDM on a real component (Fig. 1) which is part of the second stator stage of a low-pressure turbine. The base metal is nickel-based superalloy René 108 DS which is specifically developed to cope with high inlet temperatures and to reduce the operating cost [11-12]. Its nominal chemical composition is given in Table 1 [13]. EDM is performed to produce 5.3 mm deep, 15.7 mm large, 0.5 mm wide holes for heat-shielding joining plate housing. Leakage of hot gas through the gas-path, which would result in efficiency loss, thus increasing the temperature of others components, is hence prevented.

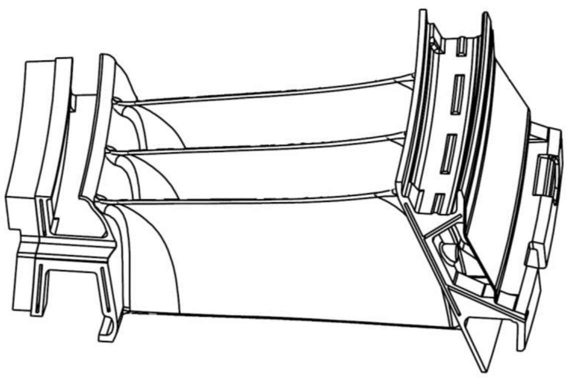

Fig. 1. René 108 DS low-pressure turbine blade: holes for heat-shielding joining plate housing.

Table 1. René 108 DS, nominal chemical composition (wt.%).

Co	Re + W	W	Cr	Al	Hf	Ni
9 ÷ 10	9.7 max	9.3 ÷ 9.7	8.0 ÷ 8.7	5.25 ÷ 5.75	1.30 ÷ 1.70	Bal.

2.2. Processing parameters

In order to select proper and significant factors to be included in the plan, a brief description of the process must be considered. In principle, EDM is based on erosion of an electrical conductive material by means of spark discharges. Both the electrode and the work-piece are placed in a dielectric fluid (light lubricating oil in general) and are connected to a dc power supply. Spark discharges between the work-piece and the tool electrode erode material from the work-piece then resulting in tool wear also; a desired shape is obtained on the work-piece, while a gap is taken between the tool and the work-piece [2].

Referring to Fig. 2, when a potential difference is applied between the tool and the work-piece, voltage quickly increases to its highest value (v_i) whereas current is still zero since the dielectric fluid still acts as insulator between anode and cathode. Voltage is then kept constant and current is zero until the dielectric ionizes and a discharge channel is formed. At this point, current increases to its maximum (i_e) while voltage decreases to discharge voltage (v_e). In this phase, erosion takes place in the pulse-on time (T_{on}); subsequently, voltage and current concomitantly decrease to zero; the pulse-off time (T_{off}), i.e. the time between two consecutive discharges, is allowed before a new cycle begins.

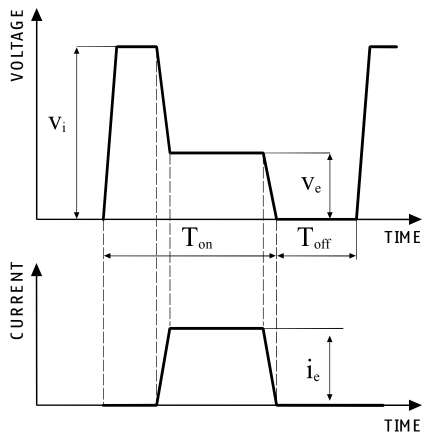

Fig. 2. Voltage and current in EDM; pulse-on and pulse-off time.

To the purpose of material removal, discharge current and discharge voltage are hence critical, therefore they must be considered in the experimental plan. With respect to the time, the use of a synthetic factor is common practice. The duty cycle is then included in the plan, as obtained with different pulse-on and pulse-off time, and is defined as:

$$\text{duty cycle} = \frac{T_{on}}{T_{on} + T_{off}}$$

The tool can be made positive or negative: generally for both graphite and copper electrode, the tool is made anode to reduce tool wear; on the other hand, the tool is made cathode when significant removal is required, but tool wear increases as a consequence. Therefore, polarity severely affects the processing time and must be investigated. Moreover, a dependence on the electrode material is also expected [14]. Graphite (Poco EDM-3) and copper-infiltrated-graphite (Poco EDM-C3) are considered in this study; their main features are given in Table 2. Poco EDM-3 is ultrafine grain graphite with high wear resistance and good quality surface; Poco EDM-C3 is high quality graphite with copper infiltrations and is recommended for any application where processing speed and resulting roughness must be favoured.

The effect of temperature and pureness of the dielectric fluid has been neglected in the plan and deemed to act as minor noise. Flushing conditions, the type of dielectric and the gap between electrode and work-piece are taken as constant during the tests. The ranges of the processing parameters have been defined according to literature and past experience; additional preliminary trials have been performed. Eventually, two levels have been appointed for each factor, as given in Table 3. A full experimental plan with 32 testing conditions has been arranged when combining the processing levels; the tests have been performed in random mode.

Table 2. Main features of graphite (Poco EDM-3) and copper-infiltrated-graphite (Poco EDM-C3).

	Poco EDM-3	Poco EDM-C3
Average particle size [μm]	2	3
Bending strenght [MPa]	93.1	112.7
Compression strenght [MPa]	147	205.8
Shore hardness	76	67
Electrical resistivity [μΩm]	14	3

Table 3. Factors and levels of the experimental plan.

Factors	Level –	Level +
Discharge current [A]	15	100
Discharge voltage [V]	150	220
Electrode polarity	Negative	Positive
Duty cycle	0.12 (T_{on}=55 μs, T_{off}=400 μs)	0.50 (T_{on}=170 μs, T_{off}=170 μs)
Electrode material	Poco EDM-3	Poco EDM-C3

2.3. Response variables

At a pre-design stage, proper measures of performance have been chosen to the purpose of the work. Processing time, tool wear (i.e., the difference in length of the electrode before and after the process), surface features (roughness and possible cracks), final dimension of the hole for plate housing in terms of cross-sectional area and depth have been measured; from these, MRR and TWR representing the main responses have been calculated. The TWR to MRR ratio, which is referred to as wear ratio (W_r) in the literature [2] is also considered for additional conclusions. After preliminary visual inspections for possible cracks, a transversal cross-section has been cut, embedded, polished, etched and investigated via both optical and digital microscopy for each sample. The remaining of the slot has been used for roughness measurements, representing the additional output.

3. Surface features and typical defects

A series of modifications in the structure of the base material, as a consequence of strong thermal gradients resulting from electrical discharges are promoted during EDM. Surface characteristics can be preliminary investigated via visual inspections and are expected to depend on the processing conditions. Highly irregular surfaces have been noticed for the samples resulting from using Poco EDM-C3 with negative polarity. In particular, damage from arcing has been produced when setting high voltage and current with a duty cycle of 0.50. The defect is shown in Fig. 3: the potential difference between the electrode and the work-piece exceeded the dielectric strength of the dielectric fluid; the highest energy density was produced by the highest levels of the processing parameters.

Pores and cracks relate to localized melting and solidification of the base metal. Indeed, a remelted layer is produced on the surface: the extension of cracks starting from the remelted layer heading to the base metal is thought to be favoured by possible carbides at grain boundaries. Based on customer standards for surface cracks compliance; the processing condition with Poco EDM-3, negative tool polarity, 220 V discharge voltage, 15 A current and 0.12 duty cycle (Fig. 4) has been rejected.

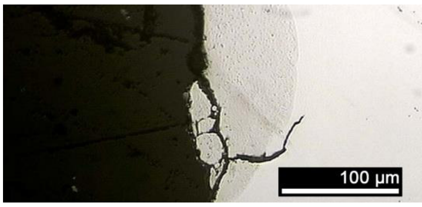

Fig. 3. Example of damage from arcing (Poco EDM-C3 cathode, 220 V, 15 A, 0.50 duty cycle).

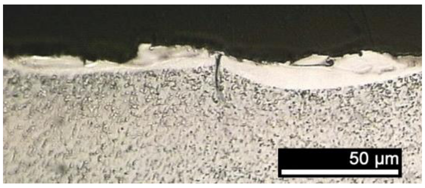

Fig. 4. Example of crack occurrence in the remelted layer (Poco EDM-3 cathode, 220 V, 15 A, 0.12 duty cycle).

4. Analyses of the responses

In order to discuss the responses as a function of the input variables, the average values of the outputs as chosen at pre-design stage are given in Table 4.

4.1. Effect of discharge voltage and current

MRR and TWR are shown in Fig. 5 and 6 as a function of discharge voltage and current, for given electrode and polarity. As total energy in EDM depends on the number of discharge sparks per time and the energy of each spark, MRR and TWR are generally in direct proportion with energy, hence in direct proportion with discharge voltage and current. In this case, an increase in discharge voltage actually yields an increase in both MRR and TWR, irrespective of the electrode material and the polarity; nevertheless, when discussed with respect to discharge current, they increase for both Poco EDM-3 and Poco EDM-C3, provided that tool is made anode.

Table 4. Average values of the responses for each processing condition.

Electrode	Tool Polarity	Discharge voltage [V]	Discharge Current [A]	Duty Cycle	MRR [$mm^3 s^{-1}$]	TWR [$mm^3 s^{-1}$]	W_r	R_a [µm]
Poco EDM-3	Positive	220	100	0.12	0.04	0.00128	0.03	10.98
				0.50	0.08	0.00356	0.04	2.73
			15	0.12	0.05	0.00804	0.17	5.63
				0.50	0.14	0.00630	0.05	7.09
		150	100	0.12	0.36	0.06131	0.17	7.72
				0.50	0.04	0.00056	0.01	6.73
			15	0.12	0.07	0.00282	0.04	6.93
				0.50	0.05	0.00804	0.17	5.63
	Negative	220	100	0.12	0.01	0.00240	0.18	6.13
				0.50	0.05	0.00805	0.18	4.34
			15	0.12	0.17	0.03107	0.18	4.85
				0.50	0.02	0.00061	0.03	3.02
		150	100	0.12	0.11	0.00611	0.05	9.85
				0.50	0.04	0.00097	0.02	4.30
			15	0.12	0.05	0.00459	0.09	4.32
				0.50	0.03	0.00068	0.02	4.93
Poco EDM-C3	Positive	220	100	0.12	0.02	0.00361	0.21	4.29
				0.50	0.11	0.00847	0.08	6.97
			15	0.12	0.06	0.00195	0.03	10.07
				0.50	0.09	0.00396	0.04	1.45
		150	100	0.12	0.04	0.00192	0.04	7.72
				0.50	0.27	0.04719	0.17	10.21
			15	0.12	0.08	0.01316	0.16	6.94
				0.50	0.07	0.01510	0.22	4.43
	Negative	220	100	0.12	0.03	0.00611	0.19	5.56
				0.50	0.05	0.00877	0.16	6.46
			15	0.12	0.30	0.04781	0.16	9.62
				0.50	0.27	0.04317	0.16	10.52
		150	100	0.12	0.02	0.00262	0.17	3.87
				0.50	0.17	0.03124	0.18	5.36
			15	0.12	0.03	0.00110	0.04	6.22
				0.50	0.03	0.00061	0.02	8.41

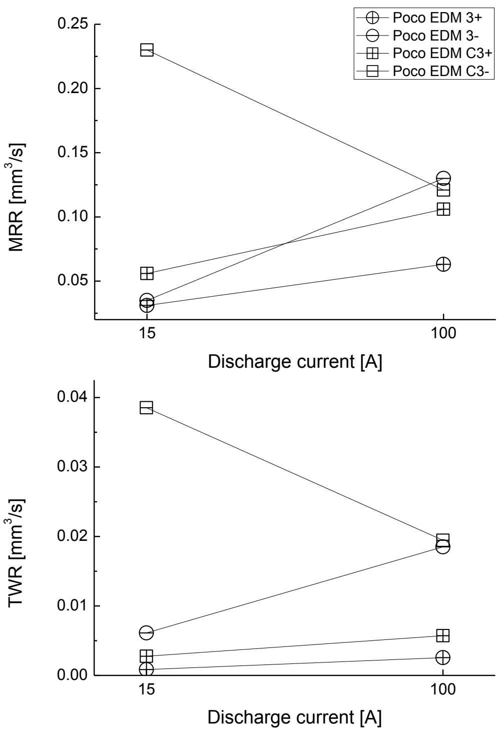

Fig. 5. MRR and TWR as a function of discharge current.

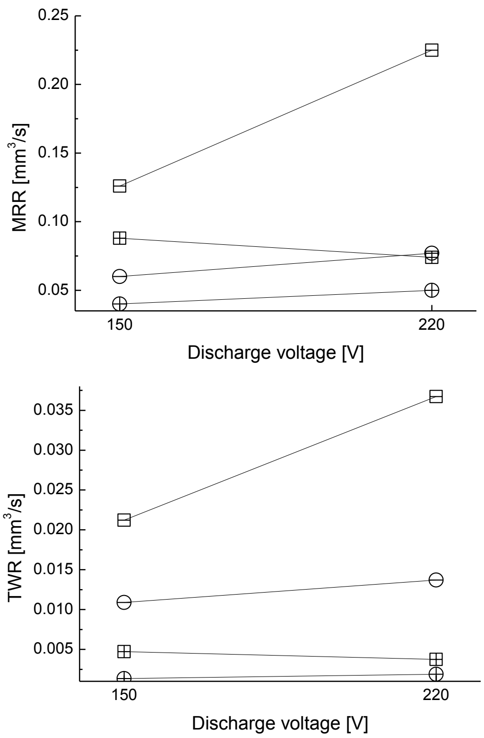

Figura 6. MRR and TWR as a function of discharge voltage.

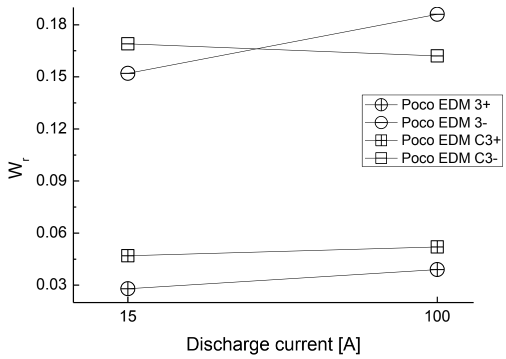

Fig. 7. W_r as a function of discharge current.

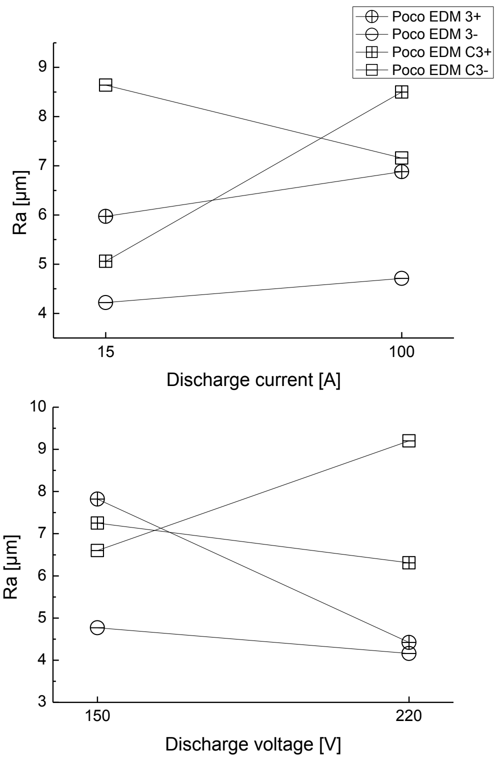

Fig. 8. Surface roughness as a function of discharge current and voltage.

Reversion of polarity has been proven to affect the distribution of energy percentages between anode and cathode [16,17]; however, for nickel-based superalloys, the highest level for discharge current resulted in ineffective processing condition with low wear rate for both the tool and the work-piece with consequent extended processing time if Poco EDM-C3 is made cathode. Namely, the highest possible MRR is benefited with negative tool polarity at high current level when using Poco EDM-3, at low current level when using Poco EDM-C3. The difference is thought to be due to significant dissimilarities in terms of physical properties between the electrode materials, being the melting point, the thermal conductivity and the electrical resistivity higher for Poco EDM-3 in comparison with Poco EDM-C3 [15].

As the same trend is noticed for MRR and TWR with respect to discharge voltage and current, the choice of a proper processing condition which would result in the highest MRR with the lowest TWR is not intuitive. The wear ratio is hence considered; its trend as a function of discharge current is given in Fig. 7; a similar trend resulted as a function of discharge voltage. Interestingly, polarity is crucial: namely, the tool must be made anode in order to reduce the wear ratio, irrespective of electrode material, current and discharge voltage. For instance, the lowest wear ratio is benefited when Poco EDM-3 is made anode.

Further conclusions can be drawn when considering surface roughness (R_a), as given in Fig. 8 as a function of discharge current and voltage: increasing discharge voltage and decreasing current result in decreasing roughness for any polarity of Poco EDM-3, whereas a dependence on polarity is in place for Poco EDM-C3, as discussed with respect to MRR and TWR. For this reason, within the domain of the experimental plan, a condition with the lowest level of discharge current, the highest level of discharge voltage with Poco EDM-3 as anode is suggested.

4.2. Effect of duty cycle

As for any metal alloy, the effect of duty cycle on MRR depends on polarity for both electrode materials. The trend is shown in Fig. 9: when the tool is made anode, MRR decreases for increasing duty cycle; on the other hand, when the tool is made cathode, an inverse trend is noticed. Conveniently, the results must be discussed in terms of duration of discharge [5]. Indeed, a duty cycle of 0.12 is obtained from longer pulse-off than pulse-on time; therefore, when the tool is made anode, a longer time is needed to restore the initial flushing conditions for efficient processing; in this sense, longer pulse-off times are suggested. Furthermore, extending the pulse-on time results in uncontrolled expansion of the discharge channel, with consequent reduction of fused metal and energy density within the channel [18]; extended pulse-on time is suggested instead to maximize MRR when the tool is made cathode, in agreement with other findings in the literature [9], as the highest percentage of discharge energy applies to the work-piece.

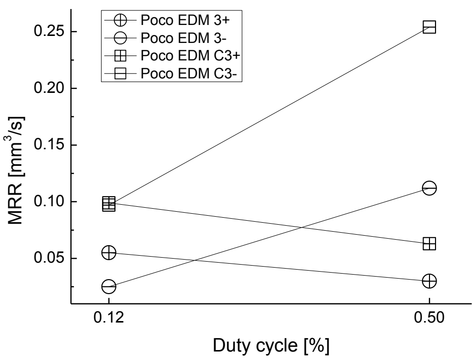

Figura 9. MRR as a function of duty cycle.

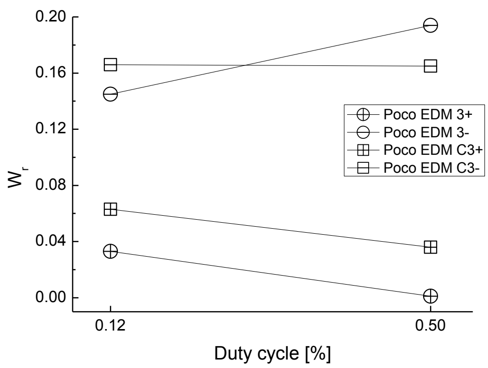

Fig. 10. W_r as a function of duty cycle.

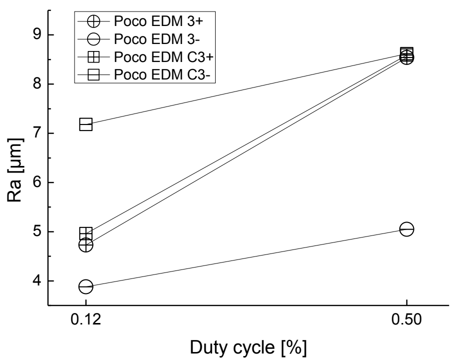

Fig. 11. Surface roughness as a function of duty cycle.

As TWR follows a similar trend, further conclusions must be drawn considering the wear ratio, whose trend is shown in Fig. 10: better performances are benefited when Poco EDM-3 is made anode. As concerning the surface roughness, whose trend is shown in Fig. 11, increasing the pulse-on time results in wide and shallow craters on the work-piece. Moreover, the amount of metal debris in the gap become significant; a channel of higher electrical conductivity between the tool and the work-piece is formed in turn, with possible electric arcs and consequent damage from arcing in both the electrode and the work-piece [10]. Indeed, damage from arcing resulted with a duty cycle of 0.5. Therefore better surface finish can be obtained with shorter pulse-on time, hence duty cycle of 0.12 in the experimental plan, irrespective of the other processing conditions.

Conclusions

In this paper, two electrode materials, graphite and copper-infiltrated-graphite, have been tested to process nickel-based superalloys via electro discharge machining. The material removal rate, the tool wear ratio and the surface roughness have been considered to discuss the effects of discharge voltage, discharge current, duty cycle and reversion of polarity. In order to reduce the wear ratio when processing René 108 DS, the tool is suggested to be made anode; furthermore, the lowest wear ratio in the domain of investigation has been benefited when using graphite with low level for discharge current and high level for discharge voltage. Better surface finish result from extended pulse-off time, hence reduced duty cycle.

References

[1] Yusup N, Zain AM, Hashim SZM. Evolutionary techniques in optimizing machining parameters: Review and recent applications (2007-2011). Expert Syst Appl 2012; 39: 9909-27.

[2] Ho KM, Newman ST. State of the art electrical discharge machining (EDM). Int J Mach Tool Manu 2003; 43:1287-1300.

[3] Shabgard MR, Badamchizadeh MA, Ranjbary G, Amini K. Fuzzy approach to select machining parameters in electrical discharge machining (EDM) and ultrasonic-assisted EDM processes. J Manuf Syst 2013; 32,1: 32-9.

[4] Shandilya P, Jain PK, Jain NK. Parametric optimization during wire electrical discharge machining using response surface methodology. Procedia Enginnering 2012; 38: 2371-7.

[5] Rajmohan T, Prabhu R, Rao Subba G, Palanikumar K. Optimization of Machining Parameters in Electrical Discharge Machining (EDM) of 304 Stainless Steel. Procedia Engineering 2012; 38: 1030-6.

[6] Rajesh R, Dev Anand M. The Optimization of the Electro-Discharge Machining Process Using Response Surface Methodology and Genetic Algorithms. Procedia Engineering 2012; 38: 3941-50.

[7] Che Haron CH, Ghani JA, Burhanuddin Y, Seong YK, Swee C.H. Copper and graphite electrodes performance in electrical-discharge machining of XW42 tool steel. J Mater Process Tech 2008; 201: 570-3.

[8] Muttamara A, Fukuzava Y, Mohri N, Tani, T. Effect of electrode material on electrical discharge machining of alumina. J Mater Process Tech 2009; 209: 2545-52.

[9] Singh H, Shukla DK, H.SINGH, D.K.SHUKLA. Optimizing electric discharge machining parameters for tungsten-carbide utilizing thermo-mathematical modeling. Int J Therm Sci 2012; 59: 161-75.

[10] Lee SH, Li XP. Study of the effect of machining parameters on the machining characteristics in electrical discharge machining of tungsten carbide. J Mater Process Tech 2001; 115: 344-58.

[11] Reed RC. The Superalloys, Fundamentals and Application. New York: Cambridge University Press; 2006.

[12] Donachie MJ. Superalloys: a technical guide. Materials Park: ASM International; 2002.

[13] Davis JR. Nickel cobalt and their alloys. Materials Park: ASM Specialty Handbook; 2000.

[14] Wang HL, Gelgele HL, Wang Y, Yuan Q, Fang M. A hybrid intelligent method for modeling the EDM process. Int J Mach Tool Manu 2003; 43: 995-9.

[15] Chen SL, Hsieh SF, Lin HC, Lin MH, Huang JS. Electrical discharge machining of TiNiCr and TiNiZr ternary shape memory alloys. Mat Sci Eng A-struct 2007; 445,446: 486-92.

[16] Janmanee P, Jamkamon K, Muttamara A. Investigation of Electrical Discharge Machining of Tungsten Carbide using EDM-C3 Electrode Material. European Journal of Scientific Research 2012; 76,1:133-42.

[17] Khan DA, Hameedullah M. Effect of tool polarity on the machining characteristics in electric discharge machining of silver steel and statistical modeling of the process. International Journal of Engineering Science and Technology (2011); 3: 5001-10.

[18] Maji K, Pratihar DK. Modeling of Electrical Machining Process Using Conventional Regression Analysis and Genetic Algorithms. J Mater Eng Perform 2010; 20:1121-7.