International Journal of Current Engineering and Technology
E-ISSN 2277 – 4106, P-ISSN 2347 – 5161
Available at http://inpressco.com/category/ijcet

Research Article

Surface Residual Stresses Induced by Shot Blast Peening after EDM of AISI D2 Die Steel using two types of Electrode

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Accepted 25 Jan 2015, Available online 01 Feb 2015, **Vol.5, No.1 (Feb 2015)**

Abstract

Electrical discharge machining (EDM) is one of most popular nonconventional machining processes used for creating complex shapes within the parts and assemblies in the manufacturing industry. The present work deals with studying the effect of EDM input parameters (peak current, pulse-on time and the type of electrode) and the shot blast peening time on the induced surface residual stresses. The response surface methodology (RSM) has been used to plan the experiments. To verify the experimental results, analysis of variance (ANOVA) was used and regression models were built to predict the EDM output performance characteristics for the residual stresses for AISI D2 die steel in terms of input parameters. The results showed that maximum compressive surface residual stresses obtained when using the copper and graphite electrodes with minimum values of pulse current (8 A), pulse on duration (120 µs) and shooting time (60 min.), reaches (-847.636 MPa) and (-637.073 MPa), respectively. These results indicated that the copper electrodes improve the residual stresses by about (33%) compared with graphite.

Keywords: *EDM machining, RSM, Surface residual stresses, AISI D2 Die steel, Shot Blast Peening, X-Ray Diffraction.*

1. Introduction

Electric discharge machining (EDM) is an important 'non-traditional manufacturing method', developed in the late 1940s, progressed due to the growing application of EDM process and the challenges being faced by the modern, composites, ceramics, super alloys, hast alloy, nitralloy manufacturing industries, from the development of new materials that are hard and difficult-to-machine, such as tool steels, waspalloy, nemonics, carbides, stainless steels, heat resistant steel, etc. EDM machining processes are increasingly being used in the following areas: aerospace applications, automotive applications, biomedical applications and other industries (Y.H. Guu et al, 2003; S. Plaza et al, 2014). Many research attempted to improve the influence of EDM input parameters on the process responses characteristics. (M. Prabu et al, 2013), proposed a multi criteria optimization technique to optimize the electrical discharge machining parameter in machining of Al-CuTiB2 in-situ metal matrix composites. Discharge current, pulse on time and pulse off time are considered as machining parameter and material removal rate, tool wear rate and surface roughness as response parameters. (Apiwat M., 2015), carried out an experiments on Ti6Al4V. Performance in respect to MRR and electrode wear is compared for two graphite qualities.

The AISI D2 die steel is recommended for tools requiring very high wear resistance, combined with moderate toughness (shock-resistance). AISI D2 can be supplied in various finishes, including the hot-rolled, pre-machined and fine machined condition. The steel was chosen also because of its wide range of application in tooling and manufacturing sections.

The main aims of using the shot blast peening processes are to improve the fatigue strength, the wear resistance, endurance limit by induced residual compressive stress, the stress corrosion and limiting or prevention the of stress corrosion cracking for the tested material and to obtain better surface hardness and quality. (J. Stráský et al, 2013), worked on multi-method characterization of combined surface treatment of Ti-6Al-4V alloy for biomedical use. Surface treatment consists of consequent use of electric discharge machining (EDM), acid etching and shot peening. Shot peening significantly improves poor fatigue performance after EDM. Final fatigue performance is comparable to benchmark electropolished material without any adverse surface effect. (A. Dmowska et al, 2014), presents the results of the influence of basic electrical discharge machining EDM parameters on surface layer properties and on selected performance properties of machine parts after

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such machining. The investigations included texture of the surface, metallographic microstructure and fatigue strength. It was proved that the application of the roto-peen after the EDM resulted in lowering roughness height up to 70%. (Havlikova J. et al, 2014), presented an approach of surface treatment of electric discharge machining (EDM), chemical milling (etching) and shot peening shot-peening significantly improves the fatigue endurance of the material. Material after proposed combined surface treatment possesses favorable mechanical properties.

In EDM process, change in surface quality is directly related to the amount of energy used for removing material from the surface. The machining processes, which generate functional relevant surfaces, have a great importance for the development of the physical state of the surface and the residual stresses in it. Several researchers (J. C. Rebelo et al, 1998 ; Ekmekçi, B.et al, 2002) have investigated residual stresses induced due to EDM processes. (J. P. Kruth and Bleys P. 2000), attempted to measure the residual stresses in tool steel caused by wire EDM. These stresses were found to approach the upper tensile strength of the material at the immediate surface, and then fall rapidly to a relatively low value or to zero, before giving a way to small compressive residual stresses in the core of the material.

Due to the complexity in nature, there is a lack of analytical models correlating the process variables, which restrict the expanded application of the technology. (Izquierdo B, et al, 2013), proposed a new contribution to the simulation, and modeling of the EDM process was presented. (Jegaraj J. J. R. and Babu N. R. 2009), attempted to make use of Taguchi's approach and ANOVA using minimum number of experiments for studying the influence of parameters on the cutting performance in abrasive water jet (AWJ) machining considering the orifice and focusing tube bore variations to develop empirical models. (M. K. Pradhan and C. K. Biswas 2007), developed a regression model and two artificial neural networks (ANNs) namely: Back propagation and radial basis function to predict surface roughness in electrical discharge machined surfaces.

The X-ray method is a non-destructive technique for the measurement of residual stresses on the surface of materials. X-ray diffraction techniques exploit the fact that when a metal is under stress, applied or residual stress, the resulting elastic strains cause the atomic planes in the metallic crystal structure to change their spacings, then the total stress on the metal can then be obtained (S. Ganguly et al, 2006; P. J. Withers, 2007).

The present paper, attempted to develop a model based on the response surface methodology (RSM) to represent the surface residual stress induced by the effects of EDM parameters and the blast shot peening as a surface treatment. The principal aim of developing this model is to predict the nature and levels of these stresses resulting and to improve the stresses levels to obtain engineering parts with a higher fatigue endurance limits and longer service lives.

2. Experimental Work

AISI D2 die steel selected, is a high carbon and high chromium contents and is used for cold working processes. It is widely used in moulds and dies as drawing dies, forming rolls, powder metal tooling and blanking and forming dies. Three specimens were prepared for chemical composition by using the AMETEX SPECTRO MAX material analyzer. The average values of chemical composition for the used material are given in table (1) together with the standard, AISI D2 die steel according to ASTM A 681-76 standard specification for alloy and die steels (ASTM A 681-76). Four flat specimens were prepared for mechanical properties tests by using the universal testing machine type UNITED for tensile tests on the bases on ASTM-A370-77 steel standard for flat work piece (ASTM-A370-77), and for Rockwell hardness tests by using the hardness testing machine type INDENTEC. The results are given in table (2). The manufacturing of the workpieces are done by the wire electrical discharge machine (WEDM) type ACRA Brand/Taiwan and by a surface grinding machine then polished mechanically and manually by abrasive silicon carbide paper up to grade ASTM 3000. Measuring of the surface residual stresses before and after EDM machining and after the surface treatments by shot blast peening were carried out by using the X-RAY DIFRACTOMETER (XRD) testing equipment type lAB XRD-/Japan 5217A.

Two types of electrodes materials, Copper and Graphite are selected. The copper electrode material was examined for chemical composition properties using the X-MET 3000TX HORIZONT metal analyzer and the compositions obtained are: 0.006% Zn, 0.001% Pb, 0.0005% Sn, 0.005% P, 0.0002% Mn, 0.007% Fe, 0.004% Ni, 0.011% Si, 0.007% Al, 0.002% S, 0.005% Sb, and the remaining is 99.96% Cu. The electrodes were manufactured with a square cross-section of 24 mm and 30 mm lengths, with a quantity of 24 pieces for each type shown in figure (3). The prepared electrodes were polished as mentioned above.

Figure (3): The copper electrodes and AISI D2 workpieces after EDM processes

Table (1): The chemical composition for the selected workpiece material and the equivalent standard AISI D2 die steel

Sample	C %	Si %	Mn %	P %	S %	Cr %	Mo %	Ni %	Co %	Cu %	V %	Fe %
Tested plates	1.51	0.174	0.264	0.014	0.003	12.71	0.555	0.158	0.013 7	0.099	0.306	Bal.
Standard AISI D2	1.40 to 1.60	0.60 max.	0.60 max.	0.03 max.	0.03 max.	11.00 to 13.00	0.70 to 1.20	-	1.00 Max.	-	1.10 Max.	Bal.

Table (2): The mechanical properties of the used materials

	Ultimate Tensile stress (N/mm^2)	Yield strength (N/mm^2)	Elongation (%)	Hardness (HRB)
Average	704.25	415.25	18.125	90.25

The selected EDM parameters are the pulse current Ip (8 and 22 A), the pulse on time duration period Ton (40 and 120 µs), the gap voltage Vp (140 V) and the electrode polarity (+). The EDM experiments were done on ACRA CNC-EB EDM machine shown in figure (4). The kerosene dielectric was adjust from both sides of the discharge area between the workpiece and electrode with a flashing pressure =0.73 bar (10.3 PSI).

Figure (4): The ACRA/ CNC- EDM machine used in experiments

In the experimental work, two groups were designed. First group includes (11) experiments by using the copper electrodes, where a new set of workpiece and electrode in each experiment. The second group consists of (10) experiments by using the graphite electrodes with the same parameters. The EDM machining specimens and the used copper and graphite electrodes are shown in figure (5).

3. Shot Blast Peening Processes

For minimizing the tensile surface residual stresses induced by the thermal stresses produced by the EDM machining, both groups of experiments with all (21) specimens were surface treated by using the shot blast peening processes with 30, 45 and 60 minutes shooting time. In this process, (1.25 mm) diameter hardening abrasive steel balls are used with a drum type and a blast wheel (impeller) shot blasting machine (type Sinto-Kogio Ltd., model STB-OB/ Japan). The experiments were divided into three subgroups to study the effect of shooting time on surface residual stresses. The first subgroup includes the specimens numbers (1, 4, 7, 10, 12, 15, 18 and 20) using a shooting time (30) minutes. The second subgroup includes the specimens numbers (2, 5, 8, 11, 13, 16, 19 and 21) using a shooting time (45) minutes, while the third subgroup which includes the specimen's numbers (3, 6, 9, 14 and 17) using a shooting time equal to (60) minutes.

4. Modeling Surface Residual Stresses after EDM and Shot Blast Peening Processes

The design of experiments (DOE) was used with a full factorial design method (FFD) and the three level factorial response surface methodology (RSM) for two experimental groups. The three EDM input parameters or factors designed as (X1, X2 and X3) are transformed into an output response variable, (Y). The input EDM

Figure (5): The specimens and the used copper and graphite electrodes for both groups experiments after EDM machining

parameters and their levels for both groups are given in table (3). The designed EDM experimental matrix in a random manner with the selected factors (actual and coded) and the measured response (surface residual stress) by XRD method results for the both groups using the kerosene dielectric after using the EDM and

Table (3): The input EDM parameters and their levels

Factor	Name	Units	Min.	Max.	Coded Values		Levels
A	Shot peening time	(min.)	30	60	-1	+1	3
B	Pulse current (Ip)	(A)	8	22	-1	+1	2
C	Pulse on duration (Ton)	(μs)	40	120	-1	+1	2

Table (4): The designed experimental matrix for group (1) using copper electrodes after the shot blast peening processes

Std	Run	Input factors(Actual)			Input factors (Coded)			Response
		X1	X2	X3				Residual stresses (MPa)
		A: A:Shot peening time (min.)	B: Pulse current Ip (A)	C: Pulse on duration Ton (μs)	X1	X2	X3	
2	1	45	8	40	0	-1	-1	-494.883
10	2	45	22	120	0	+1	+1	-387.88
5	3	45	22	40	0	+1	-1	-446.504
6	4	30	8	120	-1	-1	+1	-704.634
8	5	60	8	120	+1	-1	+1	-847.636
9	6	30	22	120	-1	+1	+1	-359.298
1	7	30	8	40	-1	-1	-1	-455.82
7	8	45	8	120	0	-1	+1	-700.639
11	9	60	22	120	+1	+1	+1	-623.377
3	10	60	8	40	+1	-1	-1	-514.253
4	11	30	22	40	-1	+1	-1	-351.669

Table (5): The designed experimental matrix for group (2) using graphite electrodes after the shot blast peening process

Std	Run	Input factors(Actual)			Input factors (Coded)			Response
		X1	X2	X3				Residual stresses (MPa)
		A: A:Shot peening time (min.)	B: Pulse current Ip (A)	C: Pulse on duration Ton (μs)	X1	X2	X3	
10	1	60	22	120	+1	+1	+1	-626.864
6	2	45	8	120	0	-1	+1	-629.292
5	3	30	8	120	-1	-1	+1	-484.695
7	4	60	8	120	+1	-1	1	-637.073
3	5	30	22	40	-1	+1	-1	-498.443
2	6	45	8	40	0	-1	-1	-590.672
4	7	45	22	40	0	+1	-1	-537.173
9	8	45	22	120	0	+1	+1	-613.408
1	9	30	8	40	-1	-1	-1	-598.77
8	10	30	22	120	-1	+1	+1	-498.701

the shot blast peening processes for groups (1 and 2) using the copper and graphite electrodes are given in table (4) and (5), respectively.

The response results show that all the measured residual stresses after using EDM machining and the shot blast peening are in compressive residual stresses. The maximum residual stress for group (1), the surface residual stresses reaches a maximum of (-847.636 MPa) as shown in table (4), while the maximum residual stress for group (2) was (-637.073 MPa) as shown in table (5).

The (ANOVA) technique was used to analyze the significance of EDM process parameters, where the F-test ratio is calculated for a 95% level of confidence. The inversion model obeys the least squares theory (Lawson C. L et al, 1974; Kariya T. and Kurata H., 1975). The ANOVA function then runs in order to assess the results for group (1) experiments using the copper electrodes and by using the inverse forward

Table (6): The (ANOVA) table for the EDM machining input and response factors for group (1) experiments after the shot blast peening

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	3.137E-006	5	6.273E-007	28.23	0.0011	significant
A-Shot peening time	7.856E-007	1	7.856E-007	35.36	0.0019	
B-Pulse current (Ip)	8.587E-007	1	8.587E-007	38.65	0.0016	
C-Pulse on duration (T on)	2.516E-007	1	2.516E-007	11.33	0.0200	
AB	3.402E-007	1	3.402E-007	15.31	0.0113	
BC	3.875E-007	1	3.875E-007	17.44	0.0087	
Residual	1.111E-007	5	2.222E-008			
Cor Total	3.248E-006	10				

Table (7): The (ANOVA) table for the EDM machining input and response factors for group (2) experiments after the shot blast peening

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	3.344E-007	6	5.574E-008	16.96	0.0205	significant
A-Shot peening time	4.349E-008	1	4.349E-008	13.23	0.0358	
B-Pulse current (Ip)	5.885E-008	1	5.885E-008	17.91	0.0241	
C-Pulse on duration (Ton)	9.505E-008	1	9.505E-008	28.93	0.0126	
AC	6.612E-008	1	6.612E-008	20.12	0.0207	
BC	3.734E-008	1	3.734E-008	11.36	0.0434	
A^2	5.262E-008	1	5.262E-008	16.01	0.0280	
Residual	9.857E-009	3	3.286E-009			
Cor Total	3.443E-007	9				

transform for two factorial models given in table (6). The Model F-value of 28.23 implies the model is significant. The lower the p-value, the more significant in the results expected. In terms of statistical significance, it is often suggested that when the p value is more than 0.05, corresponding to a 5% confidence. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B, C, AB, BC are significant model terms.

The final empirical equation is

1/(Residual stresses)= -1.991E-003+3.573E-004 * A-2.930E-004*B+1.586E-004*C+2.351E-004*AB -1.968E-004* BC (1)

This equation in terms of actual factors can be used to make predictions about the response for given levels of each factor. Here, the levels should be specified in the original units for each factor. Table (7) shows the ANOVA analysis for group (2) experiments using graphite electrodes after the shot blast peening with an inverse reduced quadratic transform model. The model F-value of 16.96 implies the model is significant. In this case A, B, C, AC, BC, A^2 are significant model terms of estimated regression obtained as shown in table (7).

The final empirical equation in terms of actual factors for after EDM machining and shot blast peening processes is:

1/(Residual stresses) =-2.28618E-003+5.81567E-005* A-2.69367E-005* B-1.48822E-005*C+3.03036 E-007 *A* C +2.22733E -007* B * C-8.82929 E -007 * A^2 (2)

The diagnostic Process was used to evaluate the model fit will explanting in the next plots. Figure (6) shows the normal probability plot to check for normality of residuals before and after the shot blast peening processes. The plots show that the residuals are distributed normally on a straight line.

Figures (7 and 8) show the 3D graph for group (1) using copper electrodes with pulse on duration (40 μs and 120 μs), respectively. These figures show that the higher values of compressive surface residual stresses obtained when using the copper electrodes with lower values of pulse current (8A), high values of pulse on duration time (120 μs) with longer shooting time (60 min.), where the residual stresses reaches maximum value of (-831.986 MPa) experimentally (-847.638 MPa),. Figures (9 and 10) depict the 3D graph for group (2) using graphite electrodes with pulse current (8 and 22 A) respectively. These figures show that the higher values of compressive surface residual stresses obtained when using the graphite electrodes and similar EDM parameters and shooting times as with those used with copper electrodes as mentioned in the previous item. In this case, the residual stresses reaches a maximum value of (-633.343 MPa), experimentally(-637.037 MPa), and this means that copper electrodes improve the residual stresses by about (33%) as compare with graphite electrodes.

The reasons for these results are that using high current with a high resistivity copper electrode for long period of remelting and recooling cycles leads to generation a high level of hardening the surface white layer of the workpiece in the same manner of the steel quenching process which resists and eliminate the effects of shot blast peening treatments. These are repeated a thousand times during the machining time until hand, the use of low current with high a resistivity of copper electrode for the same period of remelting and recooling cycles leads to generation a low level of heat energy and consequently low level of hardening the surface white layer of the workpiece in the same manner of the steel annealing process which allows the higher effects of shot blast peening treatments especially during a long period of shooting times. In conclusion, it is better to use these levels of parameters and shot time with the copper electrodes. At the same time, these parameters levels and shot time give the higher compressive stresses with copper electrodes, which is more than with graphite electrodes by about (-210 MPa), i.e., reaching about (33%) improvement .

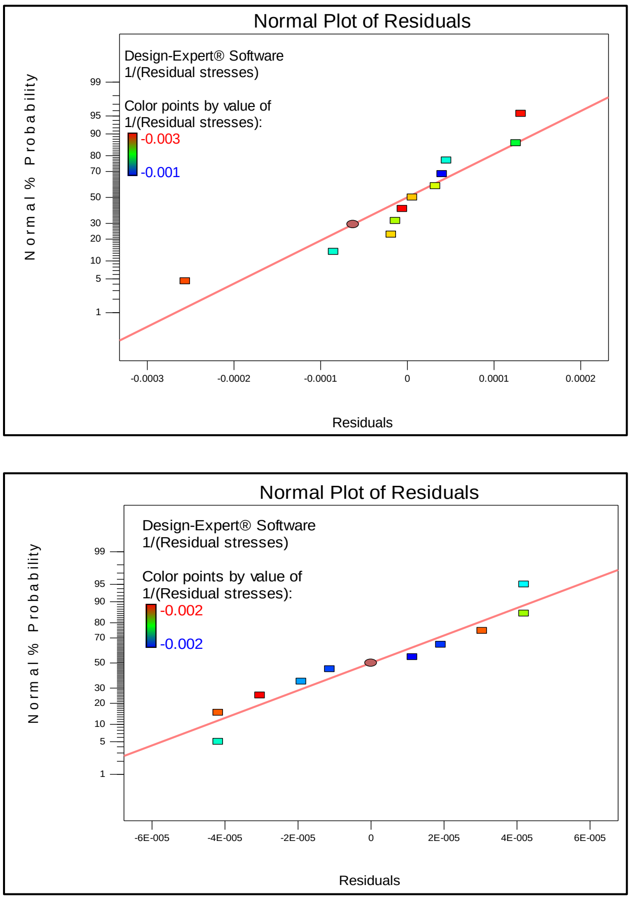
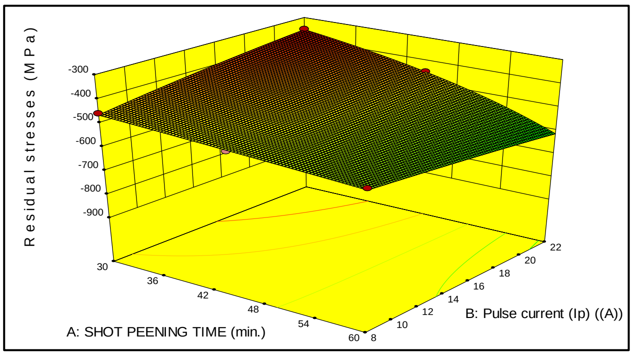
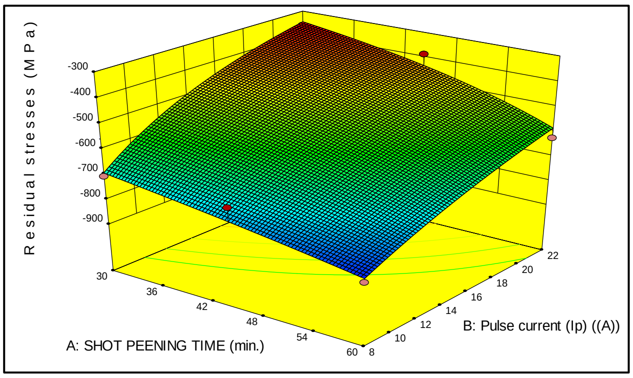


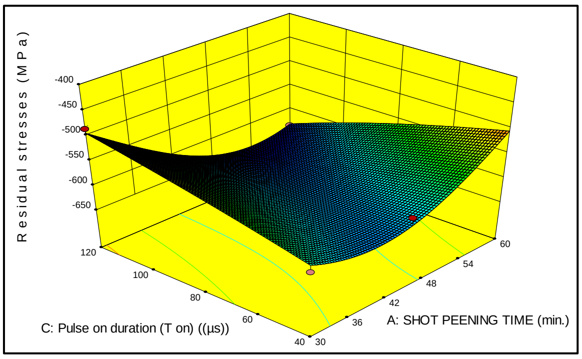
Figure (6): The normal probability plot the residuals, for group (1) (at the upper) and group (2) (at the lower)



Figures (7): The 3D graph for group (1) using copper electrodes with pulse on duration (40 μs)



Figures (8): The 3D graph for group (1) using copper electrodes with pulse on duration (120 μs)



Figures (9): The 3D graph for group (2) using graphite electrodes with pulse current (8 A)

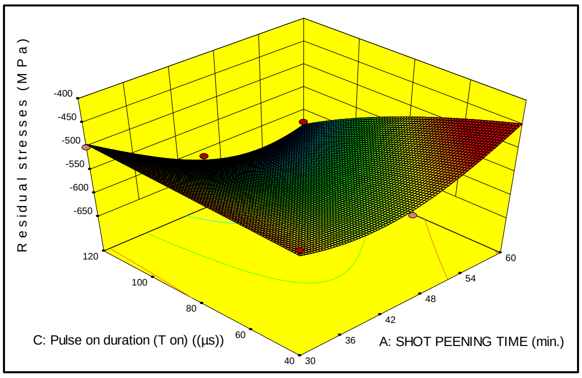


Figure (10) The 3D graph for group (1) using graphite electrodes with pulse current (22 A)

5. Numerical Optimization

For optimization and development the predicted model with the best EDM parameters, a set of new goals for the response will be conducted to generate optimal combination conditions for these parameters. The new objective function named the desirability will allow evaluating the goals by a proper combination. The main goals are to minimize the values of response surface residual stresses with the same ranges of the selected EDM parameters, the electrodes types and the best shot blast peening times as shown in table (8). The solution found for the desirability process shows that the optimum predicted values of the surface residual stresses obtained when using the copper electrodes with pulse current about (8.0 A), pulse of duration about (120 μs) and shooting time about (60 min.), gives the maximum compressive surface residual stresses (-831.986 MPa) with a maximum desirability ratio (0.968), as shown in table (9), while for graphite electrodes, the best solution found for the desirability process of the surface residual stresses when using the graphite electrodes with pulse current about (21.583 A), pulse of duration about (119.105 μs) and shooting time about (50.254 min.), gives the maximum surface residual stresses (-641.516 MPa) with a maximum desirability (1.0) .

Table (8): The new constraints goals for numerical optimization for copper and graphite electrode

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:Shot peening time	is in range	30	60	1	1	3
B:Pulse current (Ip)	is in range	8	22	1	1	3
C:Pulse on duration (T on)	is in range	40	120	1	1	3
Residual stresses	minimize	316.8	405.987	1	1	3

Table (9): The desirability process for optimization of the response for group (1) using the copper electrodes

No.	Type of electrode	Shot peening time	Pulse current (Ip)	Pulse on duration (Ton)	Residual stresses	Desirability	
1	Copper	60.000	8.000	120.000	-831.986	0.968	Selected
1	Graphite	50.254	21.583	119.105	-641.516	1.000	Selected

Conclusions

The main conclusions obtained can be summarized in the following:

1) For the EDM machining using the copper electrodes and with further shot blast peening processes, the best results for maximum compressive surface residual stresses obtained when using low values of pulse current (8 A), high pulse on duration (120 μs) and longer shooting time (60 min.), where the residual stresses reaches maximum value of (-847.636 MPa).
2) When working with EDM machining using the graphite electrodes and with further shot blast peening processes, the best results for maximum compressive surface residual stresses obtained with the same EDM parameters and shooting times as mentioned in item (1) above, where the residual stresses reaches a maximum value of (-637.073 MPa), and this means that copper electrodes improve the residual stresses by about (33%) when compare with graphite electrodes.
3) The optimization process gives the same results for all cases mentioned in items (1 and 2), the optimum predicted values of the surface residual stresses obtained when using the copper electrodes with pulse current (8 A), pulse of duration about (120 μs) and shooting time (60 min.) gives the maximum compressive surface residual stresses (-831.986 Mpa) with a maximum desirability (0.968) and when working using the graphite electrodes with pulse current (21.254 A), pulse of duration about (119.105 μs) and shooting time (50.254 min.), which gives the maximum surface residual stresses (-641.516 Mpa) with a maximum desirability (1.0).

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