Effect of Electrical Discharge Machining and Shot Blast Peening Parameters on Fatigue Life of AISI D2 Die Steel

Ahmed Al-Khazraji
Assistant Professor
University of Technology- Mechanical Engineering Department
E-mail: dr_ahmed53@yahoo.com

Samir Ali Amin
Assistant Professor
University of Technology- Mechanical Engineering Department
E-mail: alrabiee2002@yahoo.com

Saad Mahmood Ali
Lecturer
University of Karbala - Mechanical Engineering Department
E-mail: smaengg@yahoo.com

ABSTRACT

The present paper deals with studying the effect of electrical discharge machining (EDM) and shot blast peening parameters on work piece fatigue lives using copper and graphite electrodes. Response surface methodology (RSM) and the design of experiment (DOE) were used to plan and design the experimental work matrices for two EDM groups of experiments using kerosene dielectric alone, while the second was treated by the shot blast peening processes after EDM machining. To verify the experimental results, the analysis of variance (ANOVA) was used to predict the EDM models for high carbon high chromium AISI D2 die steel. The work piece fatigue lives in terms of safety factors after EDM models were developed by FEM using ANSYS 15.0 software. The results appeared that the experimental fatigue safety factors (at 10^6 cycles) decreased by (11 %) after EDM using copper electrodes compared with as-received material and this value is higher by (3.35 %) when using graphite electrodes. The fatigue strength at the same number of cycles was (0.88) and (0.84) times the fatigue strength of as-received material for copper and graphite electrodes respectively. While fatigue strength and safety factors increased after EDM when increasing shot peening time, at the higher shot peening time is by (19.1 %) when using copper electrodes and by (23.26 %) when using graphite electrodes.

Key words: electrical discharge machining, response surface methodology, analysis of variance, finite element method, die steel AISI D2, fatigue life.

تأثير معاملات التشغيل بطريقة التفريغ الكهربائي وقذف الكرات السفعي على عمر الكلال لصلب القوالب AISI D2

أ.م.د. احمد نايف الخزرجي
استاذ مساعد
الجامعة التكنولوجية - قسم الهندسة الميكانيكية

أ.م.د. سمير علي امين
استاذ مساعد
الجامعة التكنولوجية - قسم الهندسة الميكانيكية

م.د. سعد محمود علي
مدرس
جامعة كربلاء - قسم الهندسة الميكانيكية

الخلاصة

اهتم هذا البحث بدراسة تأثير معاملات التشغيل بطريقة التفريغ الكهربائي وقذف الكرات السفعي على عمر الكلال للمشغولات باستخدام أقطاب النحاس والجرافيت. وقداستخدمت منهجية استجابة السطح وطريقة تصميم التجارب لتخطيط

وتصميم مصفوفات العمل التجريبية لمجموعتين من التجارب بالتشغيل بطريقة التفريغ الكهربائي باستخدام الكيروسين العازل لوحده، في حين تمت معالجة المجموعة الثانية بطريقة قذف الكرات السفعي بعد التشغيل بالتفريغ الكهربائي.

وللتحقق من النتائج التجريبية، تم استخدام طريقة تحليل التباين للتنبؤ بنمذجة التشغيل بالتفريغ الكهربائي لصلب القوالبAISI D2العالي الكربون والكروم. كما ان عمر الكلال لمشغولات العمل قد تمت نمذجتها بعد التشغيل بالتفريغ الكهربائي بدلالة معاملات الامان وباستعمال طريقة تجزئة العناصر المحددة وبرنامج ANSYS15.0 . وقد بينت النتائج ان معامل الامان التجريبية للكلال (عند 10^6 دورة) تناقصت بمقدار (11%) بعد التشغيل بالتفريغ الكهربائي وباستخدام اقطاب النحاس مقارنة مع قيمها للمادة قبل التشغيل وهذه القيمة هي اعلى بمقدار (3.35%) وذلك عند استخدام اقطاب الكرافايت.

ان اجهادات الكلال عند نفس العدد من دورات الكلال اصبحت قيمها بنسبة (0.88) و(0.84) من قيمة الاجهادات قبل التشغيل لاقطاب النحاس والكرافايت على التوالي. بينما ازدادت قيم اجهادات الكلال ومعاملات الامان بعد التشغيل بالتفريغ الكهربائي عند زيادة زمن المعالجة بقذف الكرات ، وعند اعلى زمن معالجة ازدادت بمقدار (19.1%) عند استخدام اقطاب النحاس وبقدار (23.26%) عند استخدام الكترودات الكرافايت.

الكلمات الرئيسية: التشغيل بالتفريغ الكهربائي ، منهجية استجابة السطح ، تحليل التباين ، طريقة العناصر المنتهية ، صلب القوالب AISI D2 ، عمر الكلال.

1. INTRODUCTION

Electrical discharge machining is one of the most successful, practical and profitable non-conventional machining processes for machining newly developed high strength alloys and creating complex shapes within the parts and assemblies in the manufacturing industry that cannot be done by conventional machines, **Murray, et al., 2014** and **Majhi, et al., 2013**, with high degree of dimensional accuracy and economical cost of production, **Prabhu,** and **Vinayagam, 2008**.

EDM technique was progressed due to the growing application of EDM process and the challenges being faced by the modern manufacturing industries. New developments in the field of material science have led to new engineering materials that are hard, precise and difficult-to-machining metallic materials, composite materials, **Sundaram,** and **Rajurkar, 2011**, and **Klocke, et al., 2012,** and high tech ceramics, having good mechanical properties and thermal characteristics as well as sufficient electrical conductivity so that they can readily be machined by spark erosion **Gu, et al., 2012** and **Jahan,et al., 2012.**

AISI D2 die steel is recommended for tools requiring very high wear resistance, combined with moderate toughness (shock-resistance). This grade of tool steel was chosen because of its wide range of application in tooling and manufacturing sections **Atefi, et al., 2012** and **Majhi, et al., 2014**.

EDM components are commonly applied in high temperature, high-stress, and high-fatigue-load environments. Under such conditions, the cracks on the machined surface act as stress raisers and lead to a considerable reduction in the fatigue life of the component. Although a post-machining treatment can be performed to remove the recast layer to ensure the mechanical integrity of the component, this adds to the time and expense of the manufacturing operation. Accordingly, the current study conducts an experimental investigation of the economic and quick shot blast peening process to identify the optimal EDM machining parameters which suppress the formation of cracks in the recast layer for the longest lives under different fatigue loads.

Shot blast peening uses hard smooth hard steel balls with high velocities to yield a plastic deformation on the work piece surface layer. During the shot peening process, each piece of shot that strikes the material acts as a tiny peening hammer, imparting to the surface a small indentation or dimple. Shot peening is the most economical and practical method of ensuring surface residual compressive stresses. Compressive stresses are beneficial in increasing the fatigue strength, the wear resistance, endurance limit, the corrosion fatigue and to obtain better surface hardness and quality. Shot peening significantly improves the poor fatigue performance after EDM **Stráský, et al., 2013** and **Dmowska, et al., 2012**.

The improvements of the fatigue strength, the wear resistance, endurance limit by induced residual compressive stress are the main aims of using the shot blast peening processes. **Stráský, et al., 2013,** worked on multi-method characterization of combined surface treatment of Ti-6Al-4V alloy for biomedical use after EDM, acid etching and shot peening. Shot peening significantly improves poor fatigue performance after EDM. **Dmowska, et al., 2014,** presents the results of the influence of EDM parameters on surface layer properties. It was proved that the application of the roto-peen after the EDM resulted in lowering roughness height up to 70%. **Havlikova, et al., 2014,** presented an approach of surface treatment of electric discharge machining, chemical milling (etching) and shot peening resulting in significantly improves the favorable mechanical properties.

A considerable amount of work has been reported on the measurement of EDM performance using various designs of experiments (DOE) techniques especially utilizing the (RSM). **Mehdi et al., 2015**, used response surface methodology (RSM) to analyze the effect of EDM parameters for machining Al-Mg-2Si composite material on microstructure. The results show that voltage and current, and pulse on time are the most significant factors. **Santoki,** and **Ashwin, 2015,** studied the recent developments and effect of machining parameters on performance parameters in EDM. **Sabareesaan, et al., 2015,** developed a prediction model for material removal rate (MRR) for electrical discharge machining of Inconel X750 by RSM using Minitab software.

The present paper concerns with studying, analyzing the effects of EDM and shot blast peening on fatigue life for AISI D2 die steel and developing numerical models for verifying the fatigue tests results by using the response surface methodology (RSM) and the finite element method (FEM) with ANSYS version 15.0 software.

2. EXPERIMENTAL WORK

The work piece specimens were prepared with dimensions 89.9x30x4.25 mm, according to requirement of the plain bending fatigue testing machine type Avery 7305, as shown in **Fig. 1**. The specimens for chemical composition and mechanical properties tests were prepared on the bases of ASTM-77 steel standard for mechanical testing of steel products **ASTM A370, 1977.** The specimens' dimensions and shape for fatigue tests is shown in **Fig. 2**. Two groups were fabricated for fatigue tests, where the second experimental group was used for shot blast peening processes.

Two types of electrode materials were selected (Copper and Graphite). 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. The work pieces after EDM machining with the used copper and graphite electrodes are depicted in **Fig. 3**. The prepared electrodes were polished and examined for chemical composition properties. The average values of chemical composition of the selected work piece material and the equivalent values given according to ASTM A 681-76 standard specification for alloy and die steels **ASTM A681, 1976**, are listed in **Table 1**. The results of tensile test and Rockwell hardness tests are given in **Table 2**. The chemical compositions of the copper electrodes are listed in **Table 3**.

The main EDM selected parameters include the gap voltage V_p (140V), the pulse on time duration period T_{on} (40 and 120 µs), the pulse off time duration period T_{off} (14 and 40 µs), the duty factor (η =75%), and the pulse current I_P (8 and 22 A). Two side dielectric flashing with a pressure = 0.73 bar (10.3 psi).

The shot blast peening treatment processes were done on the drum type blast wheel (impeller) shot blasting machine shown in **Fig. 4** for experimental group (2), which is similar to group (1) in all EDM parameters used the kerosene dielectric alone. The experiments were divided into three subgroups. The first subgroup includes the specimens numbers (1, 4, 7, 10, 12, 15, 18 and 20), used a shooting time of (30) minutes. The second subgroup includes the specimens numbers (2, 5, 8, 11,13,16,19 and 21), used a shooting time of (45) minutes, while the third subgroup which includes the specimens numbers (3, 6, 9, 14 and 17), used a shooting time of (60) minutes.

In this work, (22) experiments were done for each group using the ACRA CNC-EB series EDM / Taiwan which is shown in **Fig. 5**, where a new set of work piece and electrode was used in each experiment. The first (11) experiments were conducted by using the copper electrodes, while the last (11) experiments were done by using the graphite electrodes. The selected specimens and both electrodes materials were prepared after grinding, polishing processes for obtaining better fatigue examining characteristics.

3. THE INFLUENCE OF EDM PARAMETERS ON SURFACE ROUGHNESS CHARACTERISTICS

The influence of EDM parameters on the surface roughness characteristics for each work piece and each electrode (copper and graphite electrodes) was done before and after EDM machining and after the shot peening surface treatments by using the portable surface roughness tester. **Fig. 6,** shows that SR values increase with increasing the pulse current and pulse on duration. The use of graphite electrodes gives SR values less (better) than using the copper electrodes because their higher thermal and electrical conductivity produce a uniform value of discharge energy at lower pulse current and time, works to minimize the defects resulting from increased discharge energy, such as electromechanical pits and decay formation which keep the producing surfaces with higher quality and fine roughness.

Fig. 7 shows the influence of EDM and shot peening parameters on the work pieces surface roughness (SR) indicates that the SR values are reduced with lower values of pulse current, pulse on duration time and longer shooting time. Increasing the pulse current and time producing high thermal energy generated that causes high melting with cooling accelerated cycles causing an increase in hardness and thus the lack of effect of shot blast peening process on the surface roughness. It is also noted that the surface roughness when using copper electrodes is higher than that of graphite electrodes due to high electrical resistivity of copper, which helps to generate high spark energy. When using lower values of pulse current and times, considerably less energy is generated and that will soften the metal causing a significant effect of the shot peening so improved surface roughness.

3. MODELING AND SIMULATION FATIGUE LIFE USING FEM

In this ANSYS fatigue analysis, the Von-Mises stress theory was used to compare against the experimental stress value. Fatigue strength factor is a modification factor to account the differences between the components in service from the as tested conditions.

The Multiphysics, static structural models domain loads, include the environment temperature, the fixing supported and the loading force. Setting the fatigue strength factor (Kf), which is equal to (1) and (0.72) for flat as received specimens and for EDM machining work pieces, respectively **Shigley,** and **Mischke, 2006**. The experimental fatigue results for both groups after EDM and shot blast peening processes are given in **Table 4** and **5**, respectively.

The experimental average values of fatigue strength at (10^6 cycles) and the experimental and numerical fatigue safety factor values for groups (1) and (2) are given in **Table 6** and **7**, respectively, where the fatigue safety factor values were calculated as the ratio of fatigue strength at (10^6 cycles) of the any experimental result with respect to the fatigue strength at (10^6 cycles) of the as received material which is equal to (270 MPa).

The S/N fatigue strength obtained at (10^6 cycles) curves after EDM machining are shown in **Fig. 8** and **9** using pulse current (8 A) and (22 A), respectively. These figures show that, copper electrodes gave fatigue life values higher than graphite electrodes, and fatigue life increasing with decreasing the pulse current and increasing the pulse on duration time. While, the fatigue lives values for experimental group (2) are increasing with the decrease of pulse current values and pulse on duration time and the increase of blast shot peening time and graphite electrodes gave fatigue life values higher than copper electrodes.

Three level factorial response surface methodology (RSM) and the design expert 9.0 software were used to analyze the obtained fatigue safety factor for each two experimental parametric subgroup. The (ANOVA) technique was used to analyze the significance of EDM process and the shot blast peening 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 and graphite electrodes and by using the inverse forward transform for two factorial models given in **Table 8**. The Model F-value of 8.35 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, it is corresponding to a 5% confidence. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B, C are significant model terms.

Table 9 shows the ANOVA analysis for group (2) experiments using copper and graphite electrodes after EDM machining and shot blast peening with linear reduced partial sum of squares transform model. The model F-value of 18.76 implies the model is significant. In this case A, B, C, D are significant model terms of estimated regression obtained as shown in **Table (7).**

The maximum fatigue life and safety factor obtained by the FEM and ANSYS solutions and simulations using the copper and graphite electrodes at the pulse current (8 A) and pulse on time (120 µs) are given in **Fig. 10** and **11** for group (1) and (2) using the copper and graphite electrodes at the same current value, the lower pulse on time (40 µs), respectively, and longer shot time for experimental group (2). Each of these tables shows two simulation figures for each of input parameters EDM sub-group. The right figures represent the numerical modeled fatigue safety factor. The figures in the left show the fatigue life model simulation and the fatigue strength at (10^6 cycles), which were obtained from the S/N curve of each experimental sub-group, the input EDM process parameters and the model loading force.

The final predicted empirical equation of fatigue strength (at 106 cycles) for actual factors obtained after EDM machining by using of copper electrodes for group (1) is:

$$\textit{Fatigue strength at } 10^6 \textit{ cycles} = +239.03571 - 1.28571 * \textit{Pulse current} + 0.087500 * \textit{Pulse on time } (T_{on}) \quad (1)$$

And, when using graphite electrodes is:

$$\textit{Fatigue strength at } 10^6 \textit{ cycles} = +228.53571 - 1.28571 * \textit{Pulse current} + 0.087500 * \textit{Pulse on time } (T_{on}) \quad (2)$$

For experimental group (2), the final predicted empirical equation after EDM machining and shot blast peening processes using copper electrodes is:

$$\textit{Fatigue strength at } 10^6 \textit{ cycles} = +274.27853 - 2.07020 * \textit{Pulse current} + 0.40494 * \textit{Shot blast peening time} - 0.14603 * \textit{Pulse on time } (T_{on}) \quad (3)$$

And, when using graphite electrodes is:

$$\textit{Fatigue strength at } 106 \textit{ cycles} = +281.09577 - 2.07020 * \textit{Pulse current} + 0.40494 * \textit{Shot blast peening time} - 0.14603 * \textit{Pulse on time } (T_{on}) \quad (4)$$

The analysis of results for fatigue safety factor for both experimental groups using the copper and graphite electrodes are shown in **Fig. 12** and **13**, respectively. While, the fatigue stresses at (10^6 cycles) are shown in **Fig. 12**and **13**, respectively.

Fig. 12 shows the fatigue safety factor analysis for group (1) using the copper electrodes, where the fatigue safety factor values are increasing with the decrease of pulse current values and the increase the pulse on duration time, reaching the maximum value as (0.85), experimentally (0.89) compared with the fatigue safety factor for as received material, which is equal to one, at a current value of (8 A) and a pulse time of (120 µs). Whereas, when using the graphite electrodes, the fatigue safety factor values reached the maximum value as (0.80), experimentally (0.86) at the same input current and time on period, as shown in **Fig. 13**. This means that the use of copper electrodes and the kerosene dielectric alone gives higher fatigue safety factor values by (3.35 %) when compared with the use of graphite electrodes.

Fig. 14 shows the analysis of fatigue strength at (10^6 cycles) using the copper electrodes, where these fatigue stresses values are increasing with the decrease of pulse current values and the increase of pulse on duration time, reaching the maximum value as (240 MPa) at a current value of (8 A) and pulse on time (120 µs). When using the graphite electrodes, these fatigue stresses values reached the maximum value as (232 MPa) at the same input current and time on period, as shown in **Fig. 15**. This means that the use of copper electrodes and the kerosene dielectric alone gives higher fatigue stresses (at 106 cycles) values by (3.45 %) when compared with the use of graphite electrodes and a pulse time of (120 µs).

These values of strength are equal to the ratios (0.88) and (0.84) for copper and graphite electrodes, respectively compared with the fatigue stresses (at 10^6 cycles) for the as received material, which equal to one. The high fatigue safety factors and fatigue stresses (at 10^6 cycles) levels obtained when using the copper electrodes are because the copper material has higher electrical resistivity and lower conductivity which produced lower heat discharges energy at the gap between the electrode and the work piece, especially with longer period of pulse on time, where the plasma channels are better arranged and then less unwanted metallurgical changing with brittle carbides formation will occur with less defects and lower white layer thickness. And, all these factors are strengthening the work piece against fatigue failure and then longer lives were obtained.

The using of graphite electrodes also produced higher unwanted carbides due to high heat formation and the carbon particles migration to the work piece as well as the carbon particles in the kerosene dielectric, where these brittle carbides especially in die steel grade with high carbon, high chromium and other added elements tend to form carbides, and then lower fatigue lives will be obtained.

The fatigue safety factor for experimental group (2) values using the copper electrodes are increasing with the decrease of pulse current values and pulse on duration time and the increase of blast shot peening time, reaching the maximum value as (1.22), experimentally (1.05) at a current value of (8 A), a pulse time of (40 µs) and longer shot time (60 min.). While, when using the graphite electrodes, the fatigue safety factor values reached the maximum value as (1.29), experimentally (1.06) at the same input current, pulse on time period and shot time, as shown in **Fig. 12** and **13**. This means that after EDM and shot blast peening processes, the use of graphite electrodes and the kerosene dielectric alone gives higher fatigue safety factor values by (0.95 %) when compared with the use of copper electrodes and higher by (19.10 %) and (23.26 %) when compared with the results of group (1) without using the shot blast peening and using the copper and graphite electrodes, respectively. Although the graphite electrode generates thermal energy more than that of copper, it works with the longer pulse time on annealing the work piece surface and on reducing the creation of martensitic structure, and that will lead to increasing the fatigue life.

The fatigue stresses at (10^6 cycles) analysis using the copper electrodes for experimental group (2) are increasing with the decrease of pulse current, the pulse on duration time and the blast shot time values, reaching the maximum value as (284 MPa) at a current value of (8 A), pulse on time (40 µs) and blast shot time (60 min.). Whereas, when using the graphite electrodes, these fatigue stresses values reached the maximum value as (287 MPa) at the same input current and time on period time, as shown in **Fig. 14** and **15**.

The reason of obtaining higher fatigue safety factor is because the use of low pulse current generates lower thermal energy, which cannot work to make large metallurgical changes in the crystalline structure of the work piece surface. Also, the abrasion process of EDM machining cannot accomplish its work completely due to the high amount of thermal energy necessary for melting the surface layer of work piece, and thus the abrasive phenomenon will work with less abilities required to remove the surface layers as well as the lack of interactions required for the generation of new carbides due to low level of energy generated.

This means that the use of graphite electrodes and the kerosene dielectric alone after EDM and blast shot peening processes fatigue stresses (at 10^6 cycles) gives higher values by only (0.35 %) when compared with the use of copper electrodes and yields a higher fatigue life than the situation when working without shot peening processes by (19.58 %) and (23.71 %) using the copper and graphite electrodes, respectively.

The values of these stresses are equal to the ratios (1.05) and (1.06) for copper and graphite electrodes, respectively compared with the fatigue stresses at (10^6 cycles) for the as received material. The high fatigue safety factor and fatigue stress (at 10^6 cycles) levels obtained when using graphite and copper electrodes are because the lower levels of current and pulse on time period produced a lower heat discharges energy at the gap between the electrode and the work piece. This means that less unwanted metallurgical changing with brittle carbides formation will be obtained due to lower level of carbon particles migration from the electrode to the work piece and also less defects and lower white layer thickness.

And, all these factors are strengthening the work piece against fatigue failure and then longer lives were obtained with the use of high effective techniques of shot blast peening, which is working on the conversion of tensile surface residual stresses to high level of compressive residual stresses and produced a new strength surfaces with preventing of micro cracks and other surface defects, especially at these low levels of input parameters. The work pieces surfaces are still soft, and a good surface hardening operation by the shot blast peening was gained, consequently a higher fatigue lives will be obtained.

4. CONCLUSIONS

1-The fatigue safety factor after EDM compared with as-received material and fatigue strength are increased with the decrease of pulse current and increase of pulse on time, except when using the shot blast peening or graphite mixing powder, with decrease pulse on time.

2-The experimental fatigue safety factors and fatigue stresses after EDM and kerosene dielectric alone reached (0.89) using copper electrodes, which is higher by (3.35 %) when using graphite electrodes.

3- The fatigue stresses at (10^6 cycles) are equal to the ratios (0.88) and (0.84) for copper and graphite electrodes, respectively compared with as received material, which equal to one, and reached the maximum value at a current value of (8 A) and pulse on time (120 µs). The use of copper electrodes gives higher fatigue stresses by (3.45 %) when compared with the use of graphite.

4-The fatigue safety factor and fatigue stresses after EDM and shot blast peening increased when using graphite electrodes, which increased by (0.95 %) compared with copper electrodes and higher by (19.10%) and (23.26%) when comparing with working without shot blast peening using copper and graphite electrodes, respectively.

5- A higher fatigue life were obtained than the situation when working without shot peening processes by (19.58 %) and (23.71 %) using the copper and graphite electrodes, respectively.

6- All fatigue stresses at (10^6 cycles) for the as received material ratio are close to those results of fatigue safety factors for the same input parameters, and this proves the accuracy of EDM and PMEDM models developed by FEM using ANSYS software.

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Table 1. The chemical compositions of work piece material.

SAMPLE Wt. %	C %	Si %	Mn %	P %	S %	Cr %	Mo %	Ni %	Co %	Cu %	V %	Fe %
Tested (Average)	1.51	0.174	0.264	0.014	0.003	12.71	0.555	0.158	0.0137	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 3.00	0.70 to 1.20	-	1.00 Max.	-	1.10 Max.	Bal.

Table 2. The mechanical properties of the selected materials.

Sample	Ultimate tensile stress N/mm²	Yield strength N/mm²	Elongation %	Hardness HRB
Average	704.25	415.25	18.125	90.75

Table (3). The chemical compositions of copper electrodes material.

Zn %	Pb %	Si %	Mn %	P %	S %	Sn %	Al %	Ni %	Sb %	Fe %	Cu %
0.006	0.001	0.011	0.0002	0.005	0.002	0.0005	0.007	0.004	0.005	0.007	99.96

Table 4. The experimental fatigue life results for experimental group (1) after EDM machining.

Exp. No.	Type of electrode	Pulse on time T_{on} (µs)	Pulse current (A)	Pulse off time T_{off} (µs)	Applied stress (σ) (MPa)	No. of cycles to failure (X1000)
1.	Copper	120	8	40	350.00	100.250
2.	Copper	120	8	40	300.00	239.750
3.	Copper	120	8	40	230.00	1260.500
4.	Copper	120	22	40	350.00	61.000
5.	Copper	120	22	40	300.00	133.500
6.	Copper	120	22	40	215.00	1273.250
7.	Copper	40	8	14	350.00	84.250
8.	Copper	40	8	14	300.00	199.750
9.	Copper	40	8	14	220.00	1157.500
10.	Copper	40	22	14	350.00	56.250
11.	Copper	40	22	14	210.00	1212.500
12.	Graphite	120	8	40	350.00	94.500
13.	Graphite	120	8	40	300.00	214.750
14.	Graphite	120	8	40	220.00	1319.000

15.	Graphite	120	22	40	350.00	45.250
16.	Graphite	120	22	40	300.00	87.250
17.	Graphite	120	22	40	200.00	1063.750
18.	Graphite	40	8	14	350.00	70.250
19.	Graphite	40	8	14	300.00	164.750
20.	Graphite	40	8	14	215.00	1201.500
21.	Graphite	40	22	14	350.00	51.250
22.	Graphite	40	22	14	200.00	1188.500

Table 5. The experimental fatigue life results for experimental group (2) after EDM machining and shot blast peening processes.

Exp. No.	Type of electrode	Pulse on time T_{on} (μs)	Pulse current (A)	Pulse off time T_{off} (μs)	Shot time (min.)	Applied stress (σ) (MPa)	No. of cycles to failure (X1000)
1.	Copper	120	8	40	30	250.00	864.000
2.	Copper	120	8	40	45	250.00	1008.000
3.	Copper	120	8	40	60	250.00	1242.000
4.	Copper	120	22	40	30	240.00	862.000
5.	Copper	120	22	40	45	240.00	902.000
6.	Copper	120	22	40	60	240.00	1016.000
7.	Copper	40	8	14	30	280.00	894.000
8.	Copper	40	8	14	45	280.00	942.000
9.	Copper	40	8	14	60	280.00	1205.000
10.	Copper	40	22	14	30	230.00	904.000
11.	Copper	40	22	14	45	230.00	973.000
12.	Graphite	120	8	40	30	260.00	836.500
13.	Graphite	120	8	40	45	260.00	1018.000
14.	Graphite	120	8	40	60	260.00	1204.000
15.	Graphite	120	22	4	30	240.00	954.000
16.	Graphite	120	22	40	45	240.00	1071.000
17.	Graphite	120	22	40	60	240.00	1178.000
18.	Graphite	40	8	14	30	280.00	933.000
19.	Graphite	40	8	14	45	280.00	1283.000
20.	Graphite	40	22	14	30	230.00	1036.500
21.	Graphite	40	22	14	45	230.00	1166.000

Table 6. The experimental average values of fatigue stress at (10^6 cycles) and fatigue safety factor for group (1) after EDM machining.

Exp. No.	Type of electrode	Pulse on time T_{on} (μs)	Pulse off time T_{off} (μs)	Pulse current (A)	Fatigue stress at 10^6 Cycles (MPa)	Fatigue Safety factor (experimental)	Fatigue safety factor (numericai)	Error in numerical mode %
1.	Copper	120	40	8	240	0.89	0.85	-4.5
2.	Copper	120	40	22	225	0.83	0.76	-8.4
3.	Copper	40	14	8	227	0.84	0.78	-7.1
4.	Copper	40	14	22	215	0.80	0.72	-10.0
5.	Graphite	120	40	8	232	0.86	0.80	-7.0
6.	Graphite	120	40	22	203	0.75	0.66	-12.0
7.	Graphite	40	14	8	223	0.83	0.75	-10.0
8.	Graphite	40	14	22	207	0.77	0.66	-14.3

Table 7. The experimental average values of fatigue stress at (10^6 cycles) and fatigue safety factor for group (2) after EDM and shot blast peening processes.

Exp. No.	Type of electrode	Pulse on time T_{on} (μs)	Pulse off time T_{off} (μs)	Pulse current (A)	Shot time (min.)	Fatigue stress at 10^6 Cycles (MPa)	Fatigue Safety factor Experimental	Fatigue safety factor Numerical	Error in numerical mode %
1.	Copper	120	40	8	30	243	0.90	0.94	+4.4
2.	Copper	120	40	8	45	250	0.93	0.96	+3.2
3.	Copper	120	40	8	60	257	0.95	0.98	+3.2
4.	Copper	120	40	22	30	235	0.87	0.87	0.0
5.	Copper	120	40	22	45	236	0.87	0.87	0.0
6.	Copper	120	40	22	60	241	0.89	0.89	0.0
7.	Copper	40	14	8	30	275	1.02	1.16	+13.7
8.	Copper	40	14	8	45	277	1.03	1.17	+13.6
9.	Copper	40	14	8	60	284	1.05	1.22	+15.1
10.	Copper	40	14	22	30	224	0.83	0.81	-2.4
11.	Copper	40	14	22	45	228	0.84	0.85	+1.2
12.	Graphite	120	40	8	30	254	0.94	1.00	+6.4
13.	Graphite	120	40	8	45	260	0.96	1.02	+6.3
14.	Graphite	120	40	8	60	265	0.98	1.04	+6.1

15.	Graphite	120	40	22	30	238	0.88	0.88	0.0
16.	Graphite	120	40	22	45	243	0.90	0.89	-1.1
17.	Graphite	120	40	22	60	246	0.91	0.90	-1.1
18.	Graphite	40	14	8	30	277	1.03	1.18	+14.6
19.	Graphite	40	14	8	45	287	1.06	1.22	+15.1
20.	Graphite	40	14	22	30	234	0.87	0.82	-5.7
21.	Graphite	40	14	22	45	238	0.88	0.83	-5.7

Table 8. The (ANOVA) table for the EDM machining input and response factors for group (1) experiments

Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-value Prob > F**	
Model	1.584E-006	3	5.279E-007	8.35	0.0338	significant
A-Pulse current (Ip)	1.127E-006	1	1.127E-006	17.83	0.0134	
B-Pulse on time (Ton)	4.409E-008	1	4.409E-008	0.70	0.0305	
C-Type of electrode	4.130E-007	1	4.130E-007	6.54	0.0429	
Residual	2.528E-007	4	6.319E-008			
Cor Total	1.837E-006	7				

Table 9. The (ANOVA) table for the EDM machining and shot blast peening inputs and response factors for group (2) experiments

Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-value Prob > F**	
Model	2.652E+006	4	6.631E+005	18.76	< 0.0001	significant
A-Pulse current (Ip)	2.045E+006	1	2.045E+006	57.83	< 0.0001	
B-Pulse on time (Ton)	1.580E+005	1	1.580E+005	4.47	0.0406	
C-Shooting time	2.772E+005	1	2.772E+005	7.84	0.0128	
D-Type of electrode	1.336E+005	1	1.336E+005	3.78	0.0497	
Residual	5.657E+005	16	35354.57			
Cor Total	3.218E+006	20				

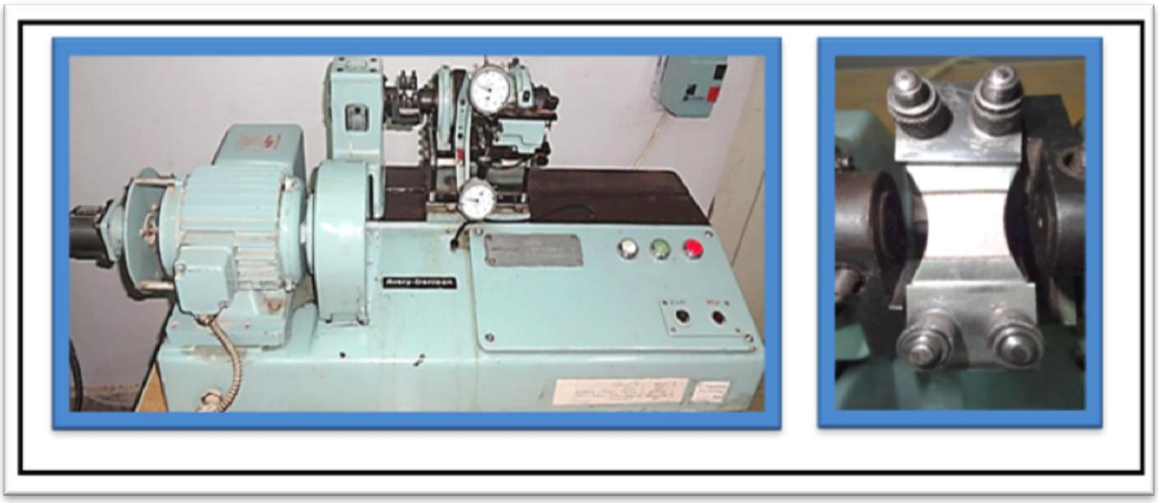


Figure 1. The Avery Denison plain bending fatigue testing machine type 7305, England.

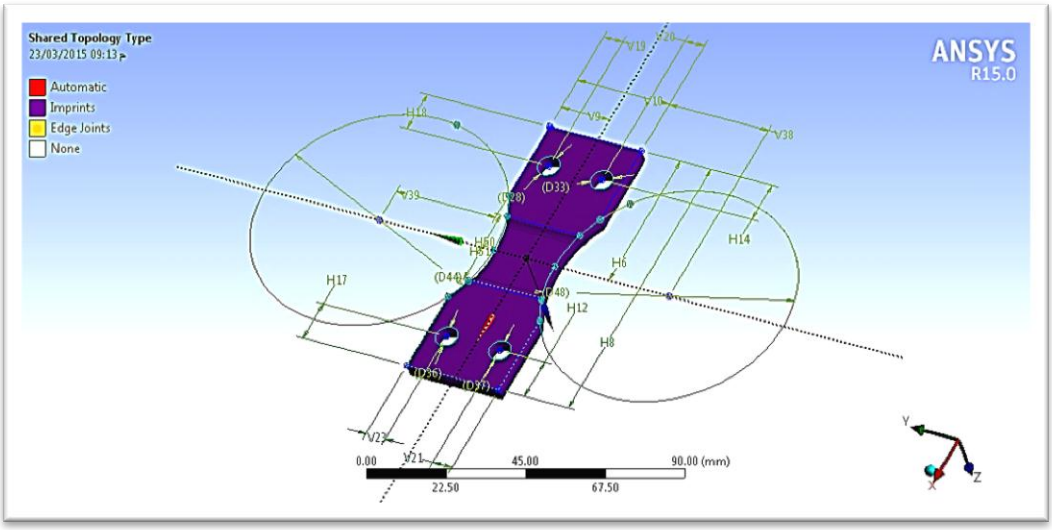


Figure 2. The specimen dimensions and shape for fatigue tests

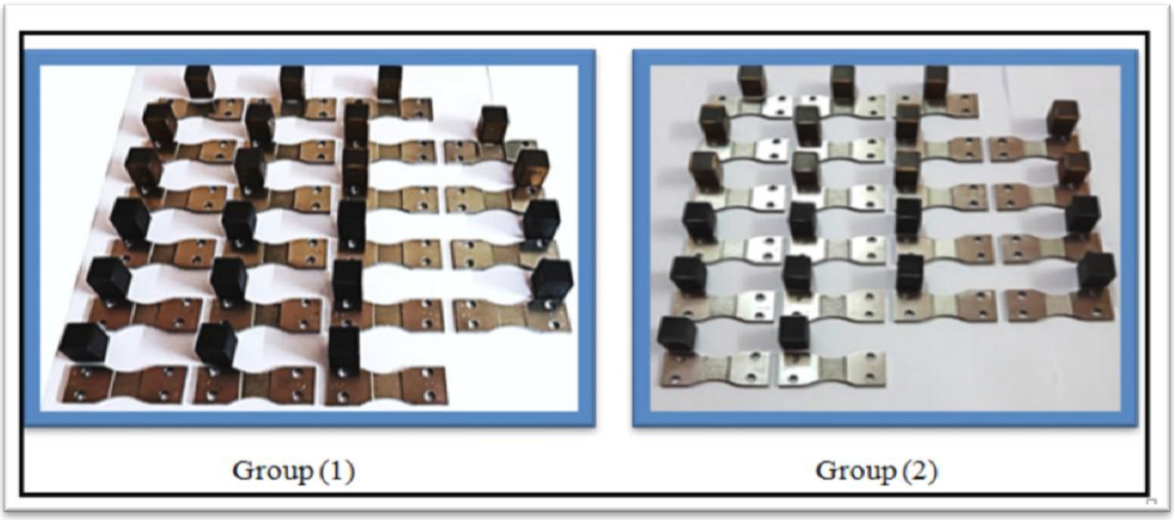


Figure 3. The specimens and the used copper and graphite electrodes for groups (1 and 2) experiments after EDM machining.

Figure 4. The drum type blast wheel (impeller) shot blasting machine.

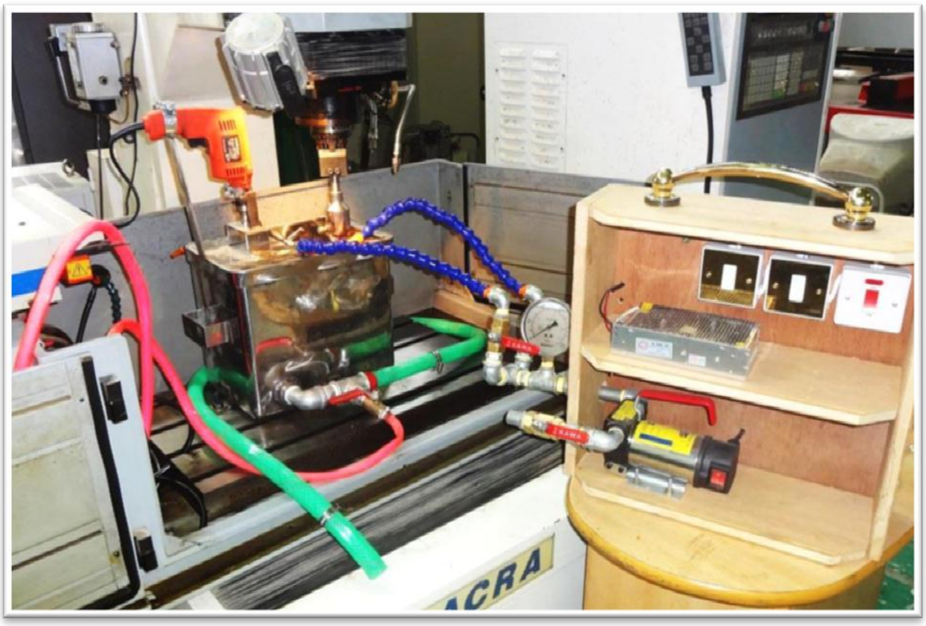
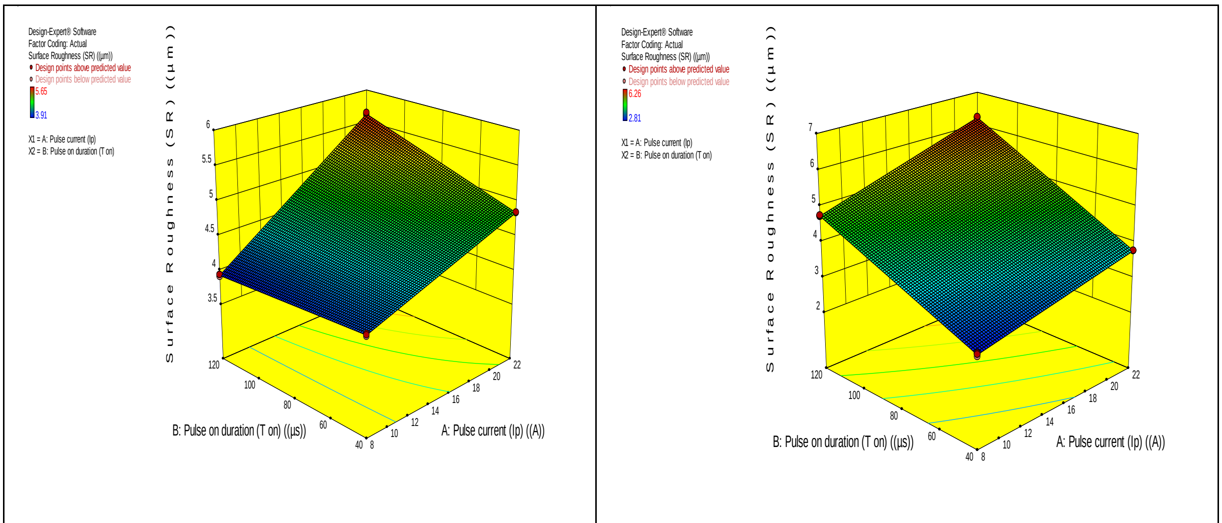


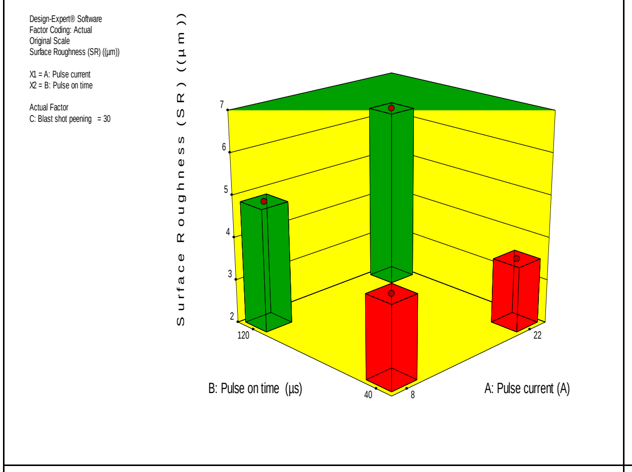
Figure 5. The used ACRA CNC EDM machine.



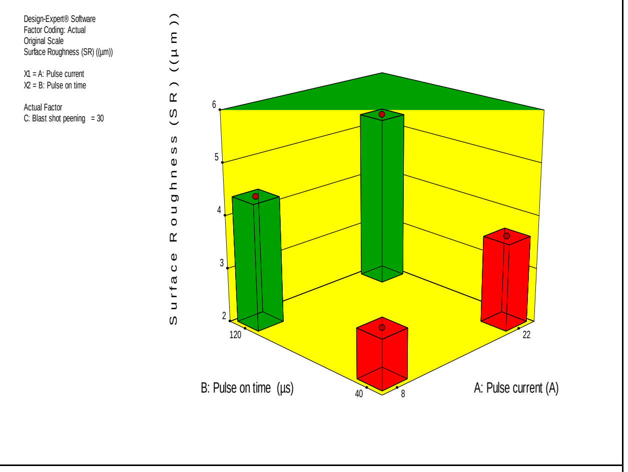
Copper electrodes	**Graphite electrodes**

Figure 6. The 3D graph models for the effect of EDM parameters on surface rouphness (SR) for experimental group (1)

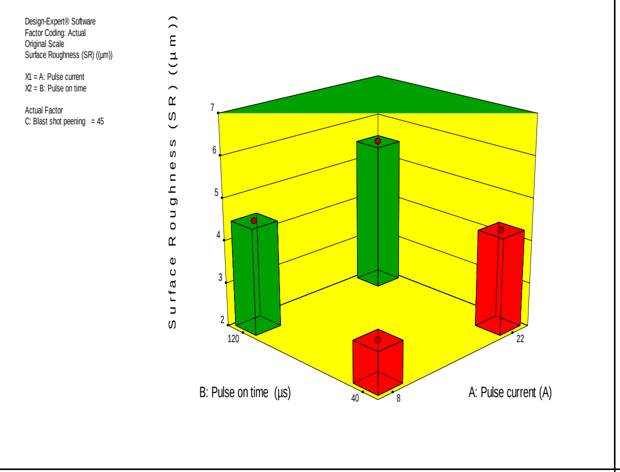
Copper electrodes / Shot blast peening time (30 min.)



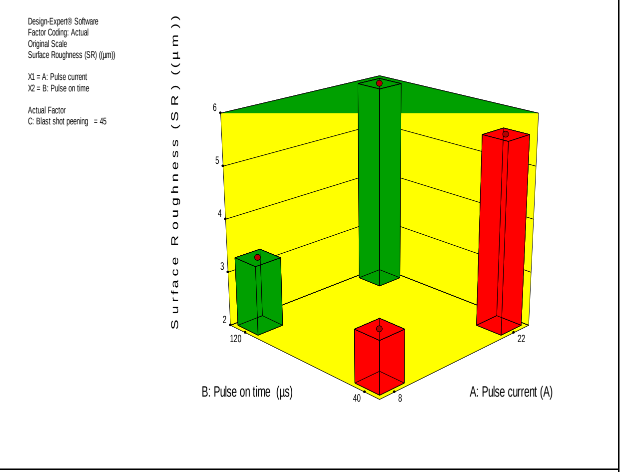
Graphite electrodes / Shot blast peening time (30 min.)



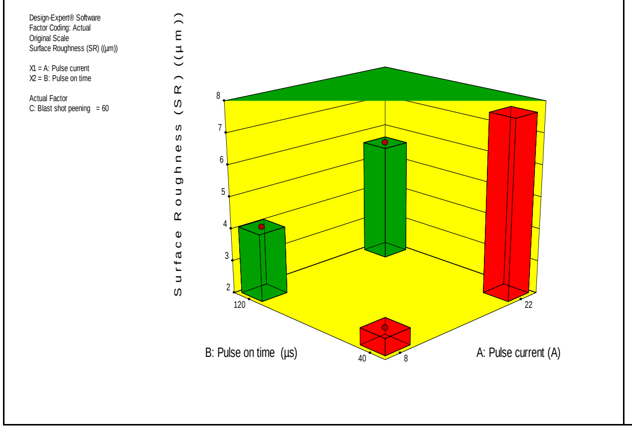
Copper electrodes / Shot blast peening time (45 min.)



Graphite electrodes / Shot blastpeening time (45 min.)



Copper electrodes / Shot blast peening time (60 min.)



Graphite electrodes / Shot blast peening time (60 min.)

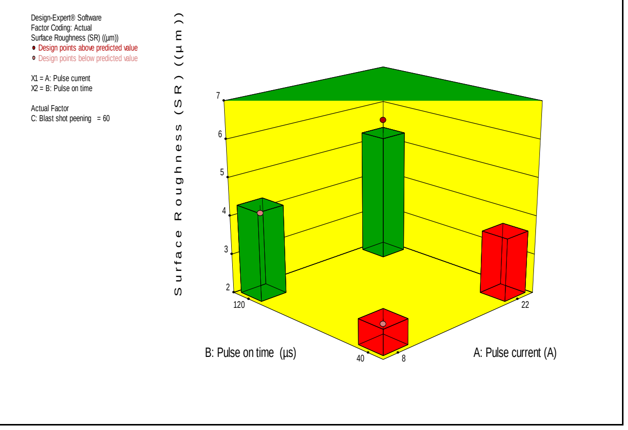


Figure 7. The 3D graph models of the effect of EDM and shot blast peening processes on SR for group (2)

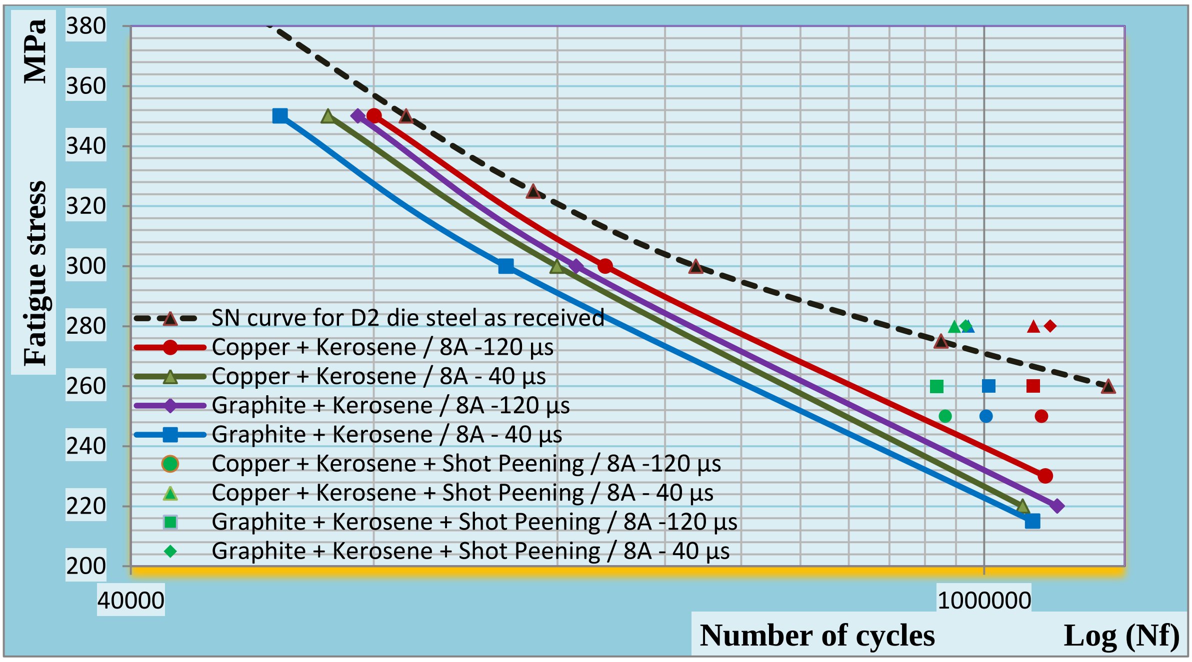


Figure 8. The S/N curves for both experimental groups after EDM and shot blast peening, using pulse current (8 A).

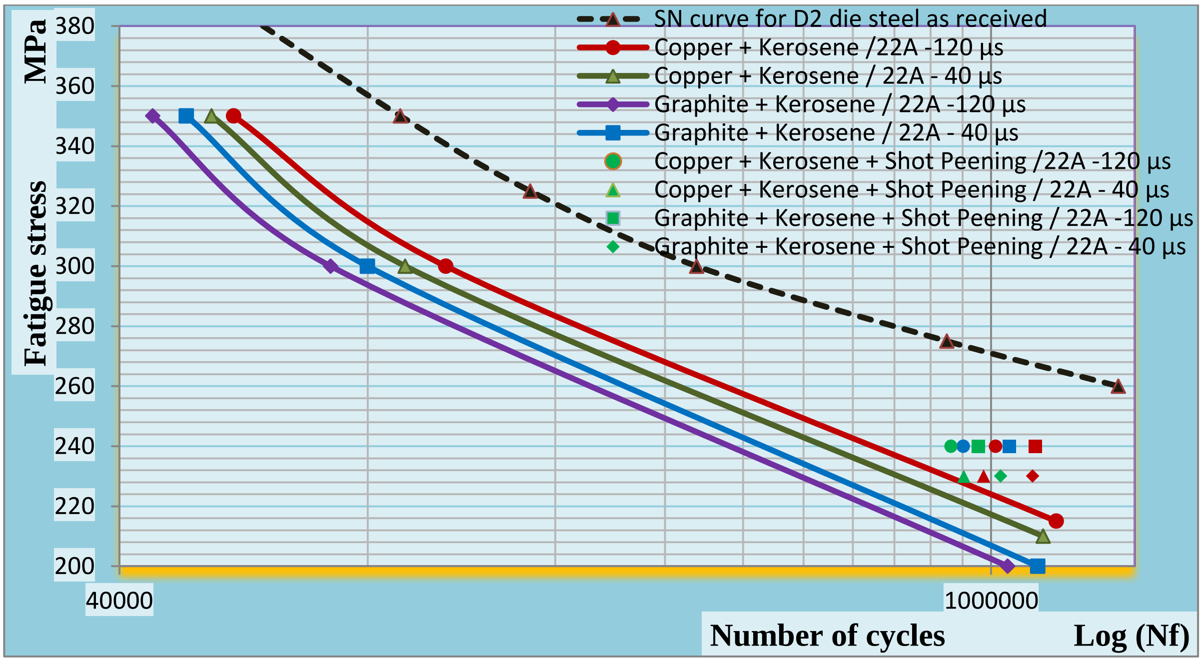
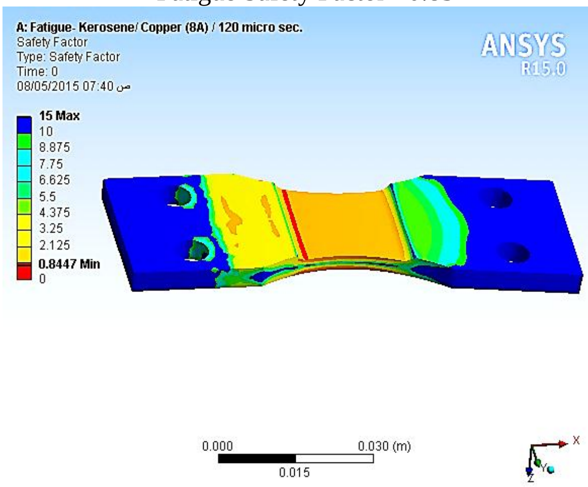


Figure 9. The S/N curves for both experimental groups after EDM and shot blast peening, using pulse current (22 A).

<table>
<tr><th>Exp. No.</th><th>Type of electrode</th><th>Pulse on duration Ton (μs)</th><th>Pulse Current (A)</th><th>Fatigue Safety Factor</th></tr>
<tr><td>1.</td><td>Copper</td><td>120</td><td>8</td><td rowspan="3">Fatigue Safety Factor =0.85

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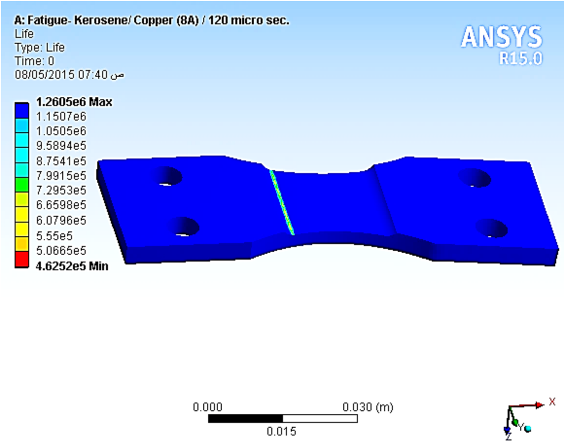
<tr><td colspan="4">Fatigue life=1.26E+6Cycles / σ_b=240MPa / F=168N</td></tr>
<tr><td colspan="4">
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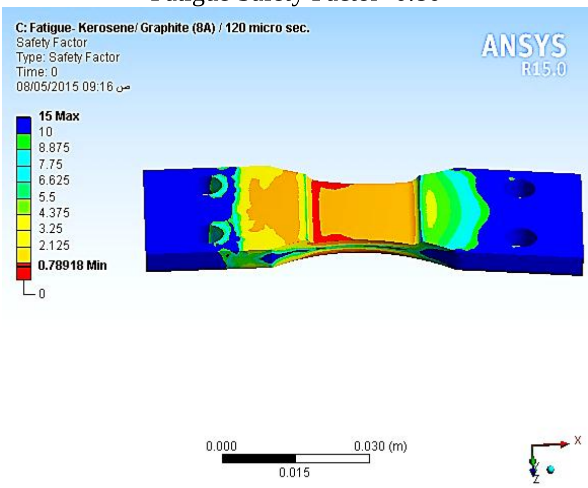
<tr><td>5.</td><td>Graphite</td><td>120</td><td>8</td><td rowspan="3">Fatigue Safety Factor=0.80

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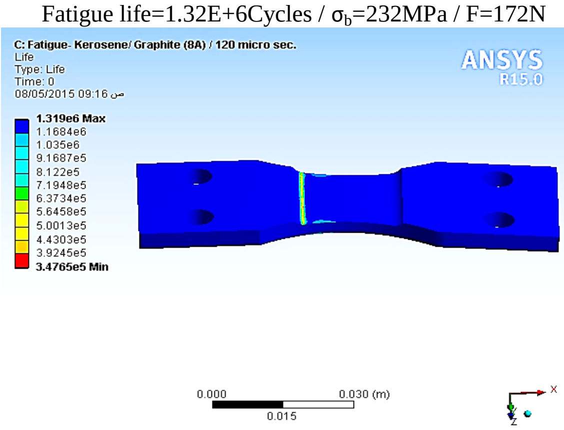
<tr><td colspan="4">
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Figure 10. The FEM fatigue life and safety factor Models for copper and graphite electrodes for experimental group (1).

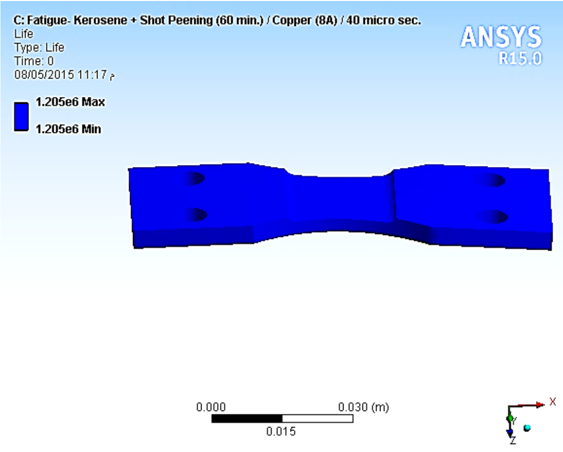
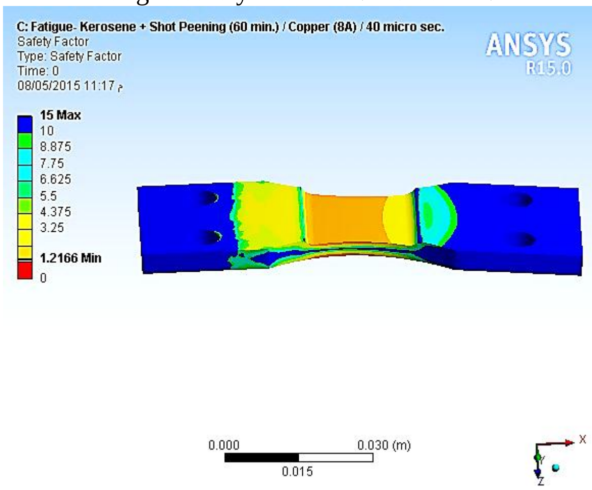
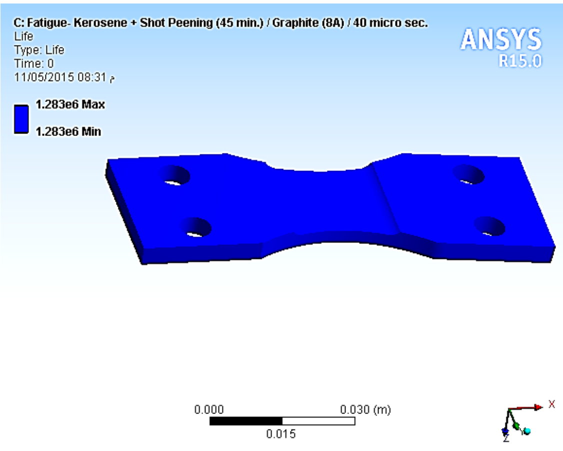
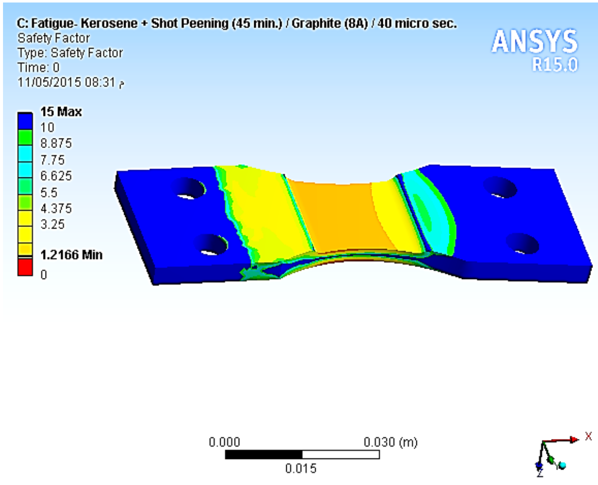
Exp. No.	Type of electrode	Pulse on duration Ton (μs)	Pulse Current (A)	Fatigue Safety Factor
9.	Copper	40	8	Fatigue Safety Factor =1.22 / 60 min.
Fatigue life=1.21E+6Cycles / σ_b=284MPa / F=148N 				
19.	Graphite	40	8	Fatigue Safety Factor=1.22 / 45 min.
Fatigue life=1.28E+6Cycles / σ_b=287MPa / F=142N 				

Figure 11. The FEM fatigue life and safety factor Models for group (2) after EDM machining and shot blast peening processes.

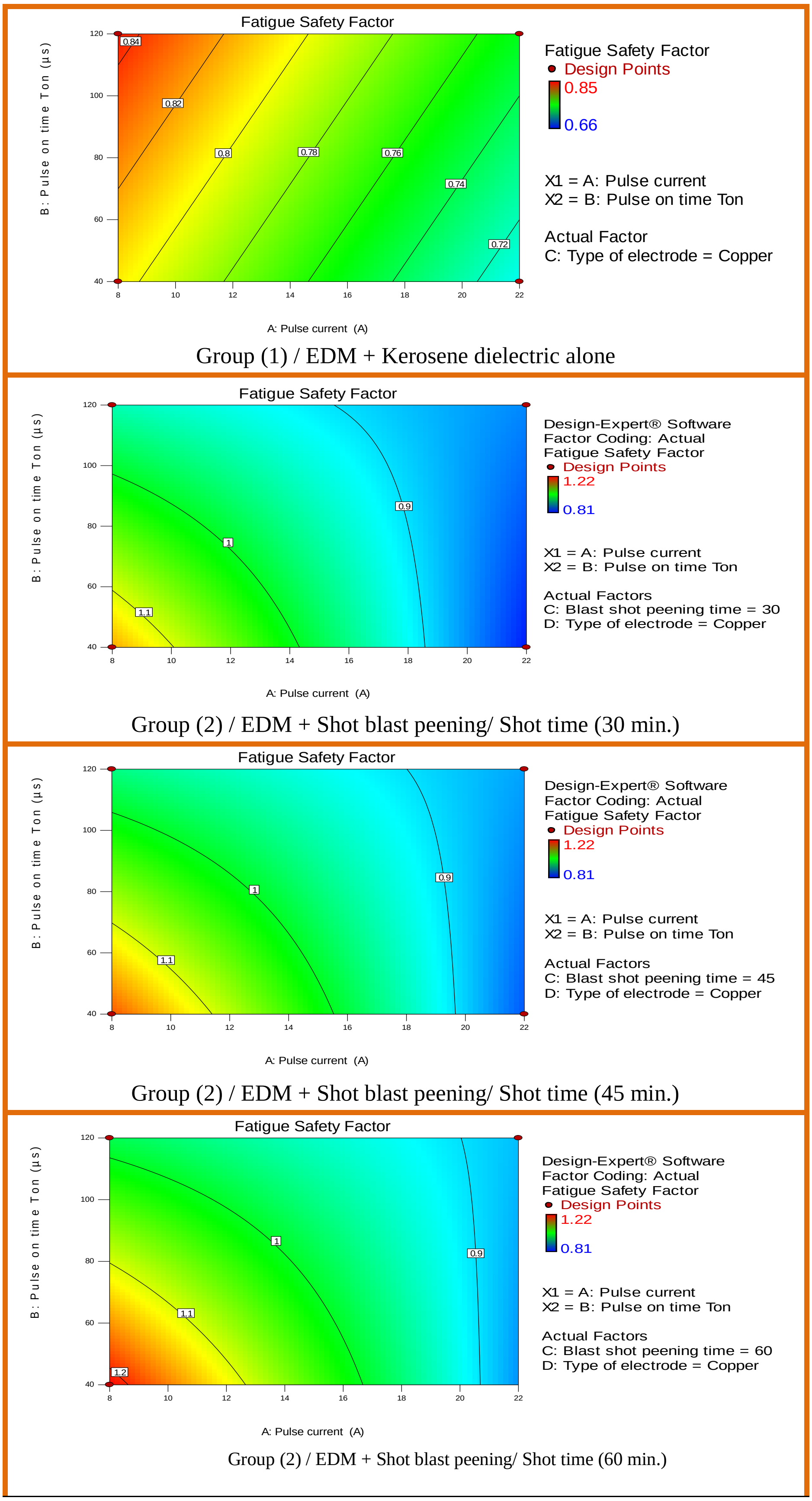
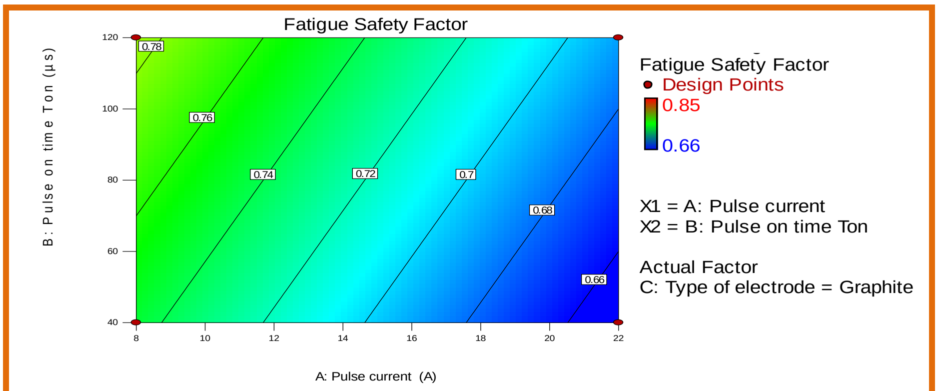
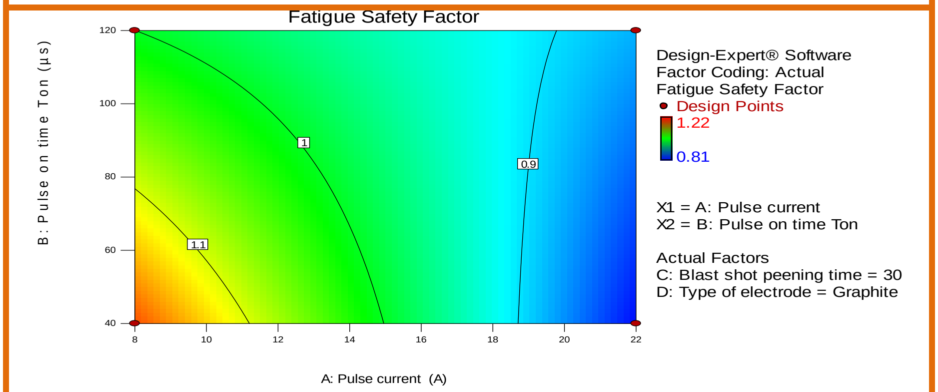


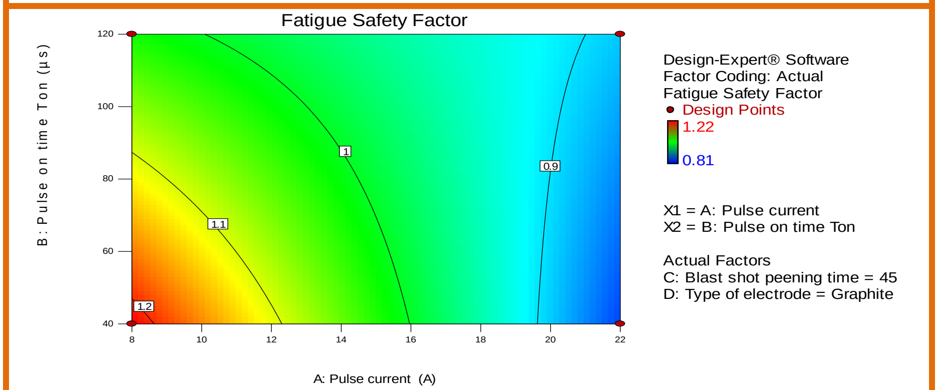
Figure 12. The fatigue safety factor for both groups after EDM and shot blast peening using copper electrodes.



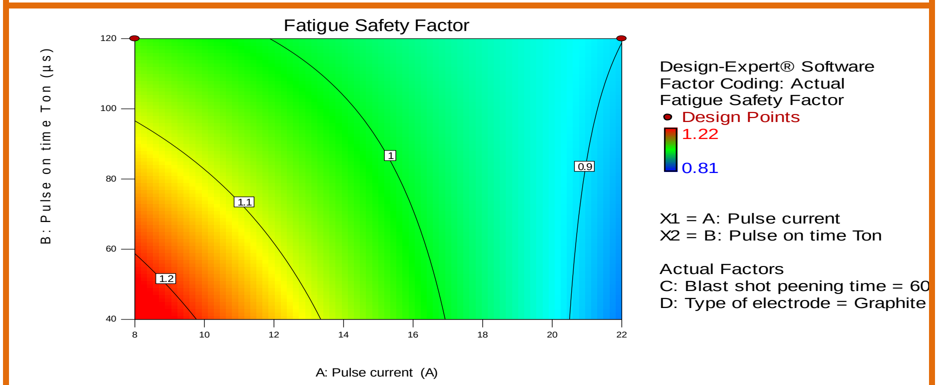
Group (1) / EDM + Kerosene dielectric alone



Group (2) / EDM + Shot blast peening/ Shot time (30 min.)



Group (2) / EDM + Shot blast peening/ Shot time (45 min.)



Group (2) / EDM + Shot blast peening/ Shot time (60 min.)

Figure 13. The fatigue safety factor for all experimental groups after EDM and shot blast peening using graphite electrode.

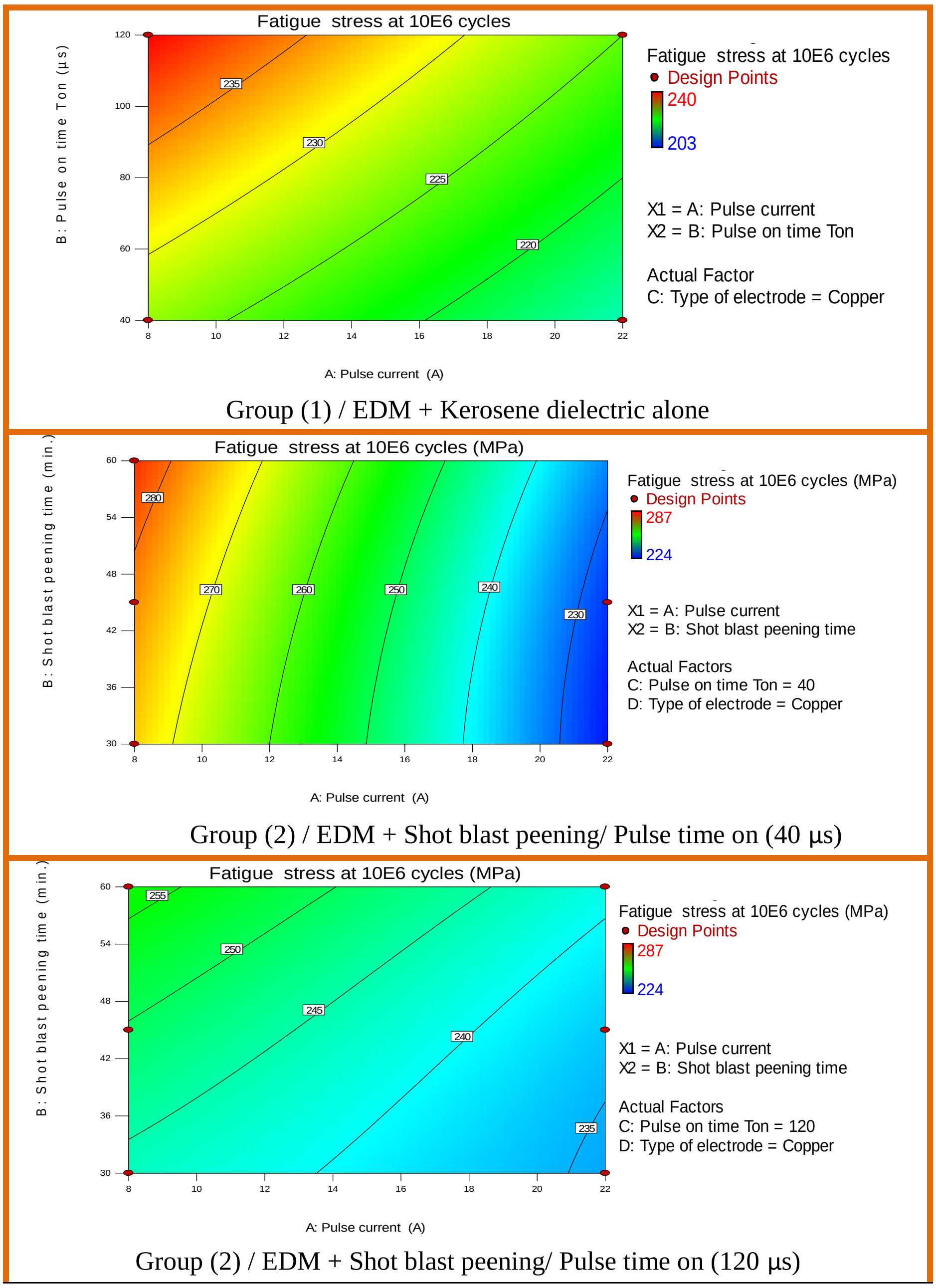
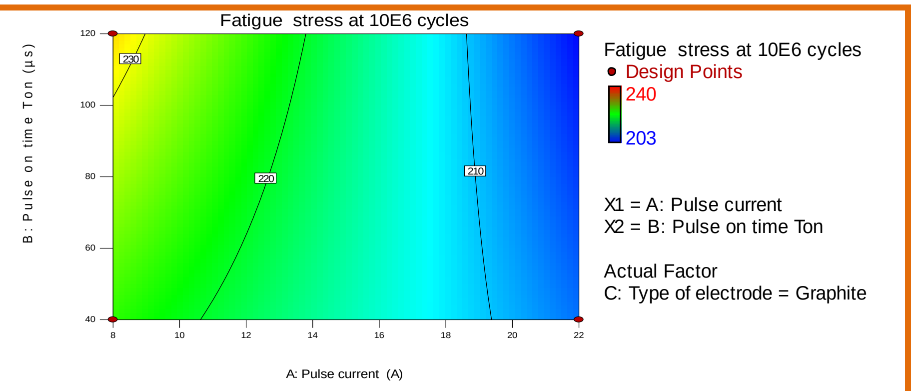
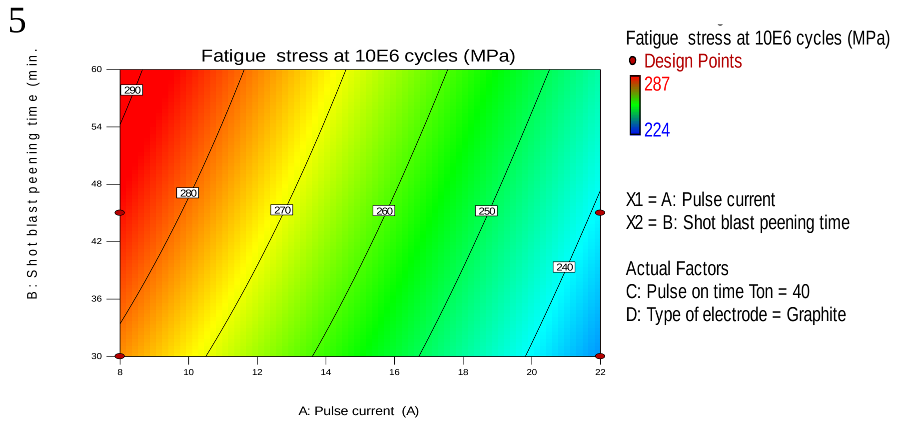


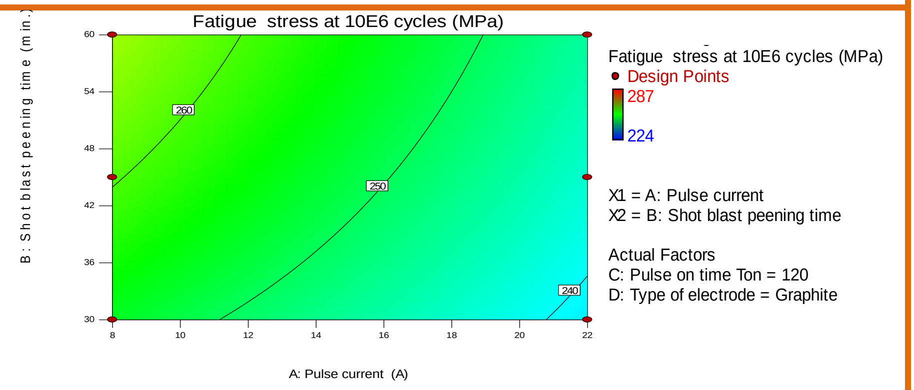
Figure 14. The fatigue strength at (10^6cycles) for all experimental groups after EDM and Shot blast peening using copper electrodes.



Group (1) / EDM + Kerosene dielectric alone



Group (2) / EDM + Shot blast peening/ Pulse time on (40 µs)



Group (2) / EDM + Shot blast peening/ Pulse time on (120 µs)

Figure 15. The fatigue strength at (10^6cycles) for all experimental groups after EDM and Shot blast peening using graphite electrodes.