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Research Paper

Predicting the Influence of Electrical Discharge Machining (EDM) Parameters on the Finished Work Surface in CK45 Steel

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Abstract

CK45 steel is a suitable material for the manufacturing of forging dies. This paper investigates the influence of electrical discharge machining (EDM) parameters including voltage, current, on-time and off-time on the microstructure of the machined surface of this material. The process induces thermal stresses that in turn result in the generation of widespread micro-cracks on the surface of the part subjected to spark EDM. The influence of EDM parameters on the quality of the machined surface is explored by performing an extensive experimental program. The impact of EDM parameters on the surface roughness and the intensity of micro-cracks have been evaluated quantitatively using the test results and regression analysis. Predicting the relationship between EMD parameters and the surface quality provides practical means to appropriately decide on the adjustment of process control parameters to their optimum values and hence to achieve the desired surface quality at reasonable manufacturing times and cost.

Keywords

Micro-crack, Surface Roughness, EDM Parameters, CK45 Steel, Forge Die

1. Introduction

Electrical discharge machining (EDM) is a very efficient machining process widely used in manufacturing components of complicated geometry [1-5]. Based on its nature, i.e. material removal by electric discharge, the process induces thermal stresses that in turn result in the generation of widespread micro-cracks on the surface of the machined part. Due to its superior advantages, i.e. material removal from hard materials, EDM has turned into a practical technique in manufacturing forging dies at a reasonable cost. The process works based on metal conductivity to remove the material with great accuracy and control from the work piece material. One common application is in the manufacturing of forging die components from hard materials such as high alloy steels using “Spark” EDM. Spark machining as a type of EDM due to its unique characteristics has turned into a rapidly growing manufacturing process. A thorough description of modern manufacturing techniques including spark EDM is provided by McGeough [6-10]. The technique is based on electric discharge between the two electrodes in a controlled manner. The negative pole, the machining electrode tool is moved to a set distance typically within the range of

0.01 to 0.5 mm from the positive pole, the workpiece surface. The process takes place in a saturated environment of dielectric fluid that plays a key role in the generation of a finely channeled electric beam, termed “the spark”. A pulse-type shift in electric voltage introduced between the two electrodes turns the dielectric fluid into a narrow conductive plasma channel, typically around 20 μm in diameter, bridging the short distance between the poles. The very high temperature generated by the intense electric beam is well beyond the melting point of all known metals. However, the high pressure in the plasma channel prevents
the metal from vaporization. Instantaneous disconnection of the impulsive current removes the pressure that subsequently results in the occurrence of the bulk boiling phenomenon allowing the material removal from the workpiece surface [6].

During the EDM process, the workpiece material experiences a spontaneous increase in temperature as a result of electric discharge followed by the cooling function of the dielectric fluid. A study of the microstructure changes due to EDM was carried out by Kruth [11]. They suggested that during the thermal shock experience, besides changes in surface properties, the material initially having reached the “red” point temperature exhibits changes in microstructure such that three distinct layers may be recognized. The top layer consists of molten spherical drops of the workpiece material and the EDM electrode tool. The second layer in white appearance is the reformed metal with a hard Martensitic microstructure that is developed as a result of phase transformation that occurred during the re-solidification of metal at the molten cavern. As a consequence of the rapid change in temperature residual thermal stresses induced in the work piece generates surface micro-cracks with substantial intensity. Finally, the third layer noted by McGeough is a transition from the hardened layer of the softer base material. From the research work illustrated above, it can be concluded that the formation of a hard surface layer on a flexible base would improve the resistance of a forge die against fatigue failure. The Formation of these layers during the spark EDM machining leads to the desired properties to the surface such that there would be no need for further surface hardening treatments for the forge die after EDM. The three layers described above are shown schematically in Figure 1[12].

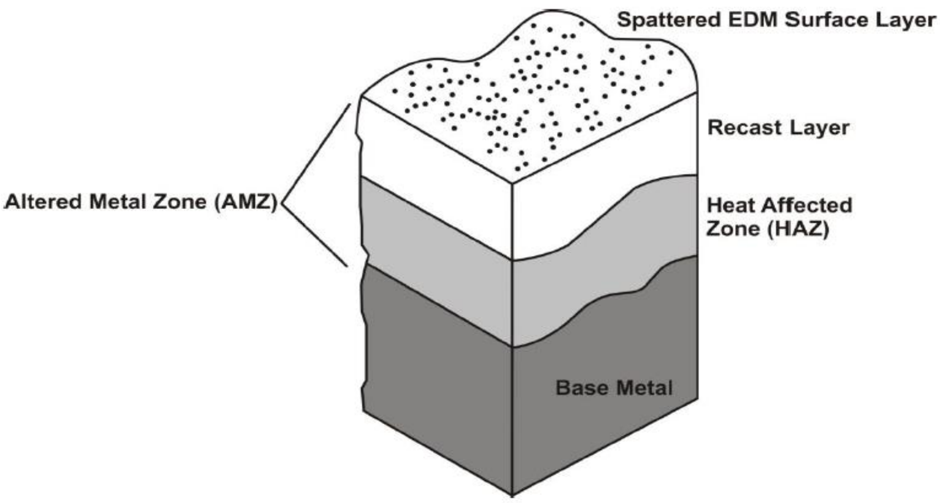

Figure1. Surface layers after EDM [2]

Thermal stresses on the machined surfaces are often harmful. These stresses on the surface of the "brittle" re-molten layer result in the generation of micro-cracks. The relationship of the EDM parameters with the intensity of micro-cracks may be used as a guide in setting the parameters in the manufacturing of the forging dies. During the forging operation as the part is hammered into the internal surfaces of the forging die are also loaded in compression by the part. However, on the die surfaces manufactured through the EDM operation, the thermal stresses and hence the micro-cracks are formed in the recast layer only. The heat affected zone (HAZ) is softer than the remolten layer. Subjecting this surface to compressive loading puts the recast layer in compression and HAZ in tension. As a result cracks under compression tend to closure. Ekmekci studied the development of micro-cracks during the EDM process on the surface of micro alloy steel and concluded that the thermal impact of the loci of electric discharge, i.e. the molten cavern around the spark, plays a significant role and acts as a characteristic factor that is responsible for the generation of surface micro-cracks. They also argued that the EDM region undergoes compressive thermal stresses whereas the micro-cracks experience localized tensile stress fields [12].

As the expanded molten metal within the process zone rapidly cools down, it tends to retain its original volume, but the high rate of solidification prevents this from happening. Therefore, tensile stresses act from the edges towards the center of the spark affected region which means that the zone undergoes compressive stresses and hence the micro-cracks should appear on the boundaries. If the forces acting on such surfaces are compressive they tend to close the micro-cracks that are beneficial to the forge dies. Variation of the pulse energy during the EDM process changes the heat affected zone that in turn alters the stress level generated at the machined surface. As a result, the machining parameters that change the pulse energy level become more significant.

Using an atomic force microscope (AFM), Guu investigated the effects of EDM machining on the surface of AISI D2 tool steel samples. He could provide 3D images of the machined surface and hence clearly represented the built-up surface micro cracks with great details. Based on this study it was further suggested that to achieve a good practice of the machining process for the finishing stage it is essential to reduce the pulse energy level. This is because both the quality of the surface finish and the depth of micro-cracks are directly related to the energy level used during the process. The work also used the micro crack depth information obtained from the AFM images to adjust the machining parameters for the AISI D2 tool steel to appropriate values [4].

A Variation of the energy imposed onto the process zone depends on the level of electric current as well as its action time i.e. the pulse duration. The time interval during which there is no current consists of the washing time and the process zone cooling time. The effect of this interval on the machined surface should be carefully studied. The voltage affects the quality of the generated spark and hence influences the level of the energy absorbed by the component. Guu used the information obtained from the AFM magnification and only considered one spark affected zone in his study. Surface roughness is estimated as an averaged value based on the summation of up and downs measured over the surface. Moreover, although by increasing the input energy the intensity of micro-cracks in the spark affected zone increases, the number of sparks within a unit surface area decreases. Therefore, considering a larger area for the study is recommended.[12,13]

One important issue in the manufacturing of forging dies is the quality of the metallurgical properties of the recast layer. This is because the use of lubricants during the forging process and the surface friction influence the load required and the desired load level plays a significant role in the overall cost in the forging process. An investigation on the effect of the EDM machining process on TiCN alloy was performed by Manoj Kumar, who focused on the study of the behavior of the alloy components in the process zone. They prepared samples and used scan electron microscopy (SEM) to explore the influence of machining process parameters of the alloy components. This study also looked at the mechanisms involved in the process of transfer of base metal from the machining zone to the machining tool during the EDM operation [14].

Manoj Kumar also measured the alloy elements on the part surface before and after the formation of the recast layer. The presence of Carbon in the dielectric liquid used in their study resulted in the penetration of Carbon in the recast layer that affects both the strength and the surface roughness of this layer. The heat conduction coefficient of the dielectric used in the process influences the metallurgical properties of the recast layer. The impact of metallurgical changes in the intensity of microcracks is evident, but this was not considered in their investigation.[15]

In the present work, the influence of EDM machining characteristics on the surface microstructure in CK45 alloy steel has been explored. An extensive experimental program has been designed and performed for this purpose. A description of the experimental program is presented in the next section. This is followed by explaining the test procedures. The results obtained from the study are then analyzed and discussed in great details and the role of EDM parameters has been evaluated quantitatively using regression analysis. Finally, the paper is closed by highlighting the significant results of the investigation.

2. Description of the experimental program

All specimens used for the study were prepared from one block of CK45 and with the same initial conditions. The test pieces were then subjected to a range of EDM processes with changing one parameter of machining for each set of experiments. Using optical microscopy the surface roughness and the intensity of micro-cracks on the machined surfaces were then quantified for each set of test specimens.

2.1 The material

The alloy tool steel used in the experimental program is known as CK45 in the DIN standard that is considered equivalent to 1045 steel in the AISI coding system. The chemical composition of the material is shown in Table 1. Good response to thermal treatment has made CK45 a suitable candidate that is widely used for fabrication of forging dies.

Table1. Typical material composition of the CK45 steel

CK45	C	Mn	P	S
Composition	0.45	0.65	0.04	0.05

2.2 The EDM generator

The EDM generator provides the required electric voltage and electric current throughout the manufacturing process. A servo-electric motor is responsible for controlling the vertical positioning of the tool holder along the vertical “z” axis such that the distance between the tool and the work piece surface, the “gap”, is continuously maintained at an appropriate level for spark generation. This automatically controlled tool ensures that during the EDM process the system performs an ideal machining action and any “short circuit” due to short distance or “no spark” due to far distance is avoided throughout the process.

In brief, the spark action completes within a three-stage process, known as three time intervals described as follows:

1. The discharge time, t_d, that is the time spent for the generation of an electric field and hence the transformation of dielectric into ions within the “gap”
2. The time corresponding to the construction of ionic channel and formation of plasma, termed “on-time”, t_{on}
3. The time during which the channel is cut and the molten bits are removed from the spark zone. This is called “off-time”, t_{off}

The above three-steps representing the process are shown schematically in Figure 2. The type of generator used for the experimental program was an “ISO PULSE” type generator that- using an electronic control system independent of t_d controls and maintains the real spark time at a constant level. Therefore, by allowing the adjustment of the “real” on-time and off-time intervals it provides the continuously controlled spark energy throughout the EDM machining [6].

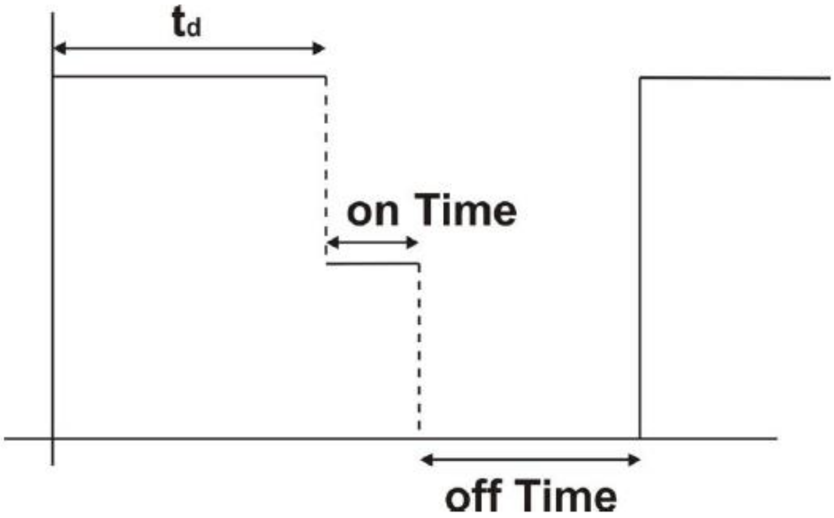

Figure 2.The three-step time intervals associated with the EDM process

3. Experimental procedures

3.1 General procedures

According to the instructions provided by the manufacturer for spark machining at high current a minimum machining surface of 7 Cm^2 is required. Test samples of CK45 steel with a diameter of 3 cm were therefore prepared for the study. The machining electrode tool (negative pole) used in the study was a conventional tool made of 99.98 % pure copper with a cross-section of 3 Cm^2. The dielectric fluid used in all experiments was gasoil that is commonly used in EDM. The machining parameters set for the experiments, including the electric Voltage, the on-time, and the off-time in the experimental program was those recommended for spark EDM in standardized tables that are widely used in general practice in the manufacturing industry. The other key parameter, the electric

Current, was adjusted based on experiments by Descoeudres. This parameter was set to the level at which the diagram for variation of current versus surface roughness indicates a change in the slope. Although in their experiments both the work piece and the electrode tool materials were different from those used in the current investigation, change in the slope of variation of current with surface roughness occurs at the same current levels. The values of electric current corresponding to the point of change of slope were therefore used as the basis in this study. The machining parameters used in the experimental program are summarized in Table 2.

Table2. The selection of machining parameters used in the experimental program

Current (A)	0.33	1	2	3	4	6	8	12	16	25
On- time µsec	12	25	50	100	200	400	800	1500	-	-
Off- time µsec	6	12	25	50	100	200	400	800	-	-
Voltage(V)	30	40	45	-	-	-	-	-	-	-

3.2 Design of experiments

The test samples were prepared for the experiments using the same procedures to ensure that the initial conditions on the surface of the specimens were almost identical. For each set of EDM test pieces, one parameter was chosen to vary, whereas the remaining parameters were kept constant. The only parameter that was automatically controlled by the ISO PULSE generator during each machining experiment was the “gap”, the distance between the electrode tool head and the work piece surface.

Throughout operating the controller unit continuously adjusted the distance, using the information received from the process zone to ensure the ideal spark was generated. The experiments were performed on test specimen sets with a similar sample size by varying one of the machining parameters, electric current, on-time, off-time, and voltage respectively for each test set.

The next stage of the experimental study was to investigate the effect of spark EDM operation of the surfaces for all test samples. At this stage, the surface roughness was measured at three arbitrary chosen points on the machined surface of each specimen using the $\mathbf{R_a}$ technique. The equipment used for these measurements was a “TIME TR100” apparatus. Regression analysis was the procedure used to process the measurement data and approximate equations describing the correlation of surface roughness with the corresponding machining parameter were obtained independently. The diagrams of these relationships were plotted using the measured data and the approximated equations for all EDM parameters.

The following stage was to prepare appropriate images of the machined surfaces that could be used for the measurement of surface micro-cracks. The images obtained from optical microscopy proved to be sufficiently adequate for this purpose. The images were therefore used and measures of the length and the surface width of micro-cracks were obtained from all test specimens. For each specimen, the erosion zone of a spark was approximated with a circular shaped area of measurable diameter and three erosion zone circles on each specimen surface were selected for the measurements. The average diameter of the three circles was used as the reference diameter. Then the total area of surface micro-cracks was measured approximately by using the width and length for the micro-cracks within the circular areas that represented the spark erosion zones. Theses information was analyzed and approximate equations describing the relationship between the micro crack surface and the average diameter were obtained using conventional regression analysis available in most data processing commercial software. These relationships were then used to estimate the total micro-crack surface area within a specified reference surface (500 µm ×400 µm) of the specimen concerning the intensity of the spark erosion zones within the reference surface. This procedure led to the determination of independent relationships between various machining parameters with the quality of the spark erosion zones on the work surface. Hence the influence on the intensity of the sparks on the work piece surfaces for various spark EDM parameters could be predicted.

4. Results and Discussion

4.1 Surface roughness

Variation of average roughness, $\boldsymbol{R_a}$, with the process control parameters, voltage, current, on time, and off-time are presented in Figures 3 to 6 respectively, for the range of parameters used in the experiments during the spark machining process. The results shown in Figure 3 suggest that increasing the current would initially increase the surface roughness at a rather high rate. A further increase in current would still lead to an increase in the roughness, but at a much lower rate. The slope of the variation of roughness continues to reduce so that increasing the current from 12.5 A by 100% to 25 A, increases the roughness by only 10% (from 3.8 to 4.2 µm). The decreasing impact of current on roughness is consistent with the results of metallographies examinations that indicated current had less influence on reducing the diameter of the spark erosion zone on the work piece surface than the other process controlling parameters. In contrast with the current, increasing the voltage has resulted in a reduction in the surface roughness with a slightly reducing negative rate. A comparison of the results shown in Figure 4 with the results in Figure 3 suggests that the impact of voltage on roughness follows a rather smoother rate of variation. This observation can be explained by noting that an increased voltage provides higher stability of the plasma channel during the process of arc formation. As a result, the erosion zone of the spark on the work surface is associated with less deviation from the corresponding erosion zone on the machining tool leaving a smoother work surface.

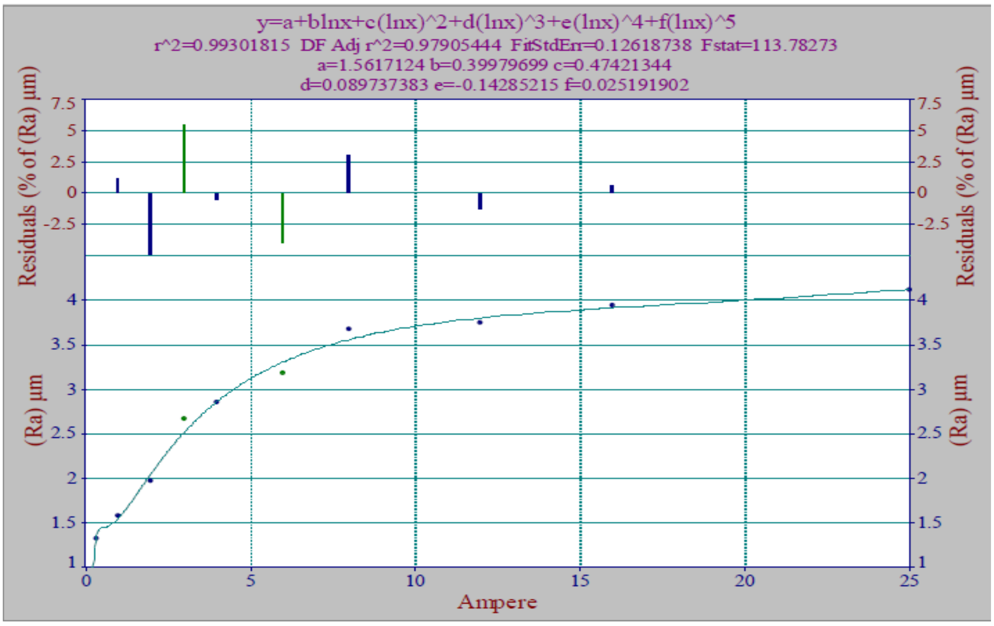

Figure3. Variation of surface roughness with current parameter (including errors)

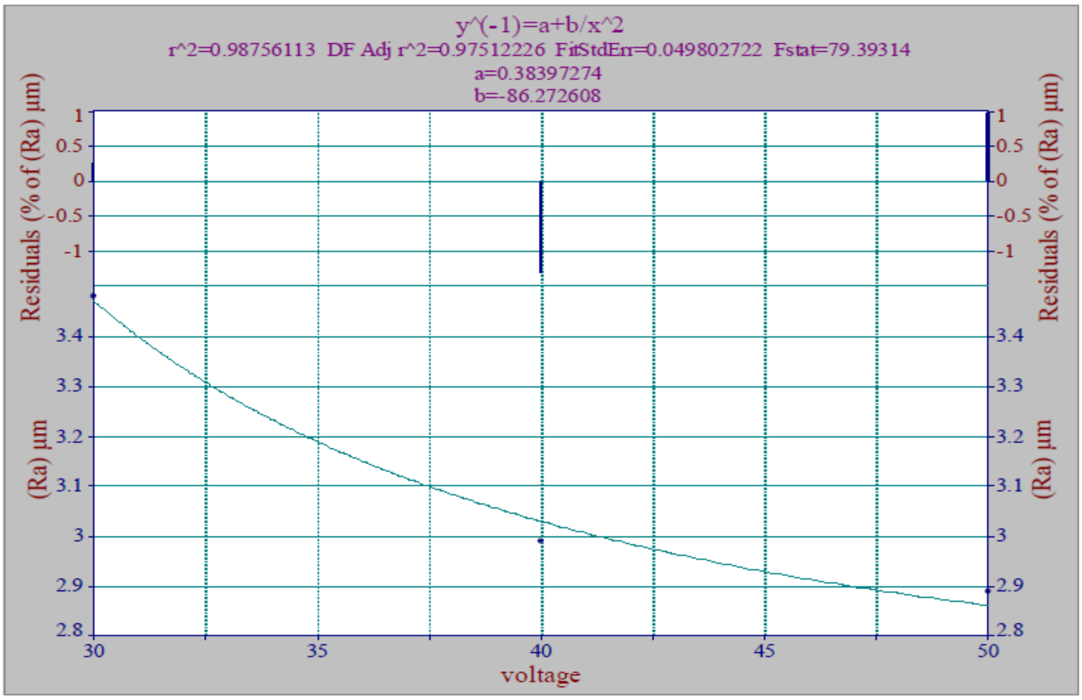

Figure 4. Variation of surface roughness with voltage parameter (including errors)

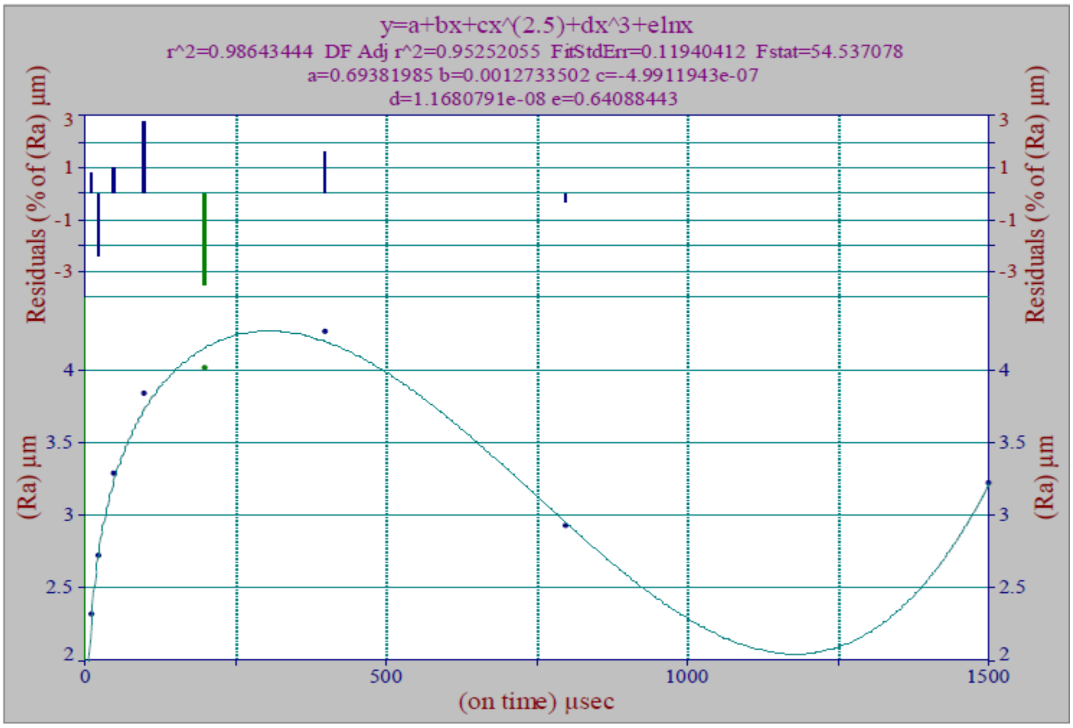

Figure5. Variation of surface roughness with on-time parameter (including errors)

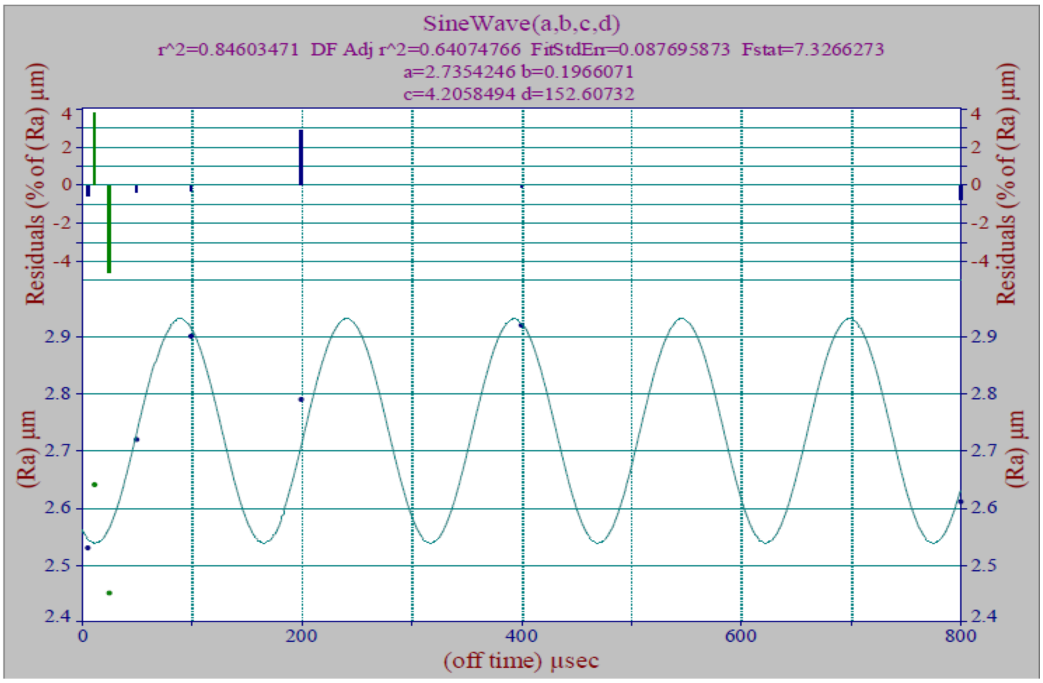

Figure6. Variation of surface roughness with off-time parameter (including errors)

Figures 3 to 6 suggest that the “current” and “on-time” parameters exhibit a more significant impact on the surface roughness. The reason for the sign shape behavior of the surface roughness with the on-time parameter seen in Figure 5 is linked with the generation of an electric resistance carbon bridge that is itself a result of the decomposition of the dielectric fluid. To conclude, one may consider the combined effect of the two parameters on the surface roughness using regression analysis which is shown in Figure 7.

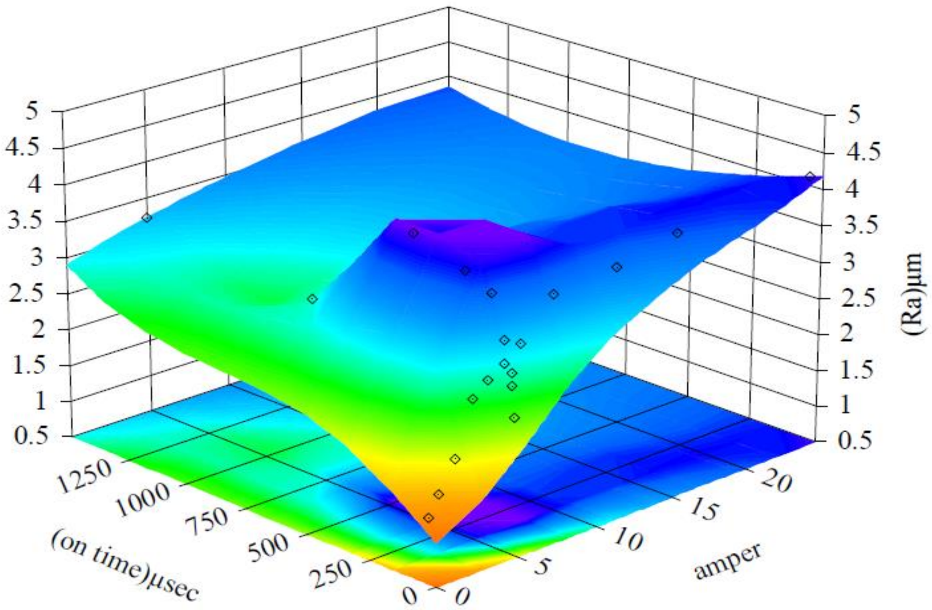

Figure7. Combined effect of “current” and “on-time” parameters on $\mathbf{R_a}$

This figure may be used as a guide in setting the parameters to achieve the desired surface quality or to predict the obtained surface roughness from the combination used in the spark machining of CK45 tool steel. Furthermore, it helps provide a general outline for the overall influence of machining parameters on the quality of the finished work surface.

4.2 Micro cracks

As shown in Figures 8 and 9 are micro scale images of machined samples obtained using an optical microscope. These pictures were used for quantifying the intensity of microcracks on the machined surface. This was achieved by measuring the ratio of the total surface of the micro-cracks to the diameter of a circle representing the erosion zone. As Figures 8 and 9 indicate it was found that within the spark erosion zone the intensity of micro-cracks as well as their lengths and widths were directly affected by the input energy level during the EDM process. However, the size of the erosion zone also increased with increasing the input energy. These two contrasting effects lead to the conclusion that in comparison, for low input energy machining, due to the presence of a higher number of spark erosion zones within a specified surface, the surface of cracks could be higher than in high energy machining.

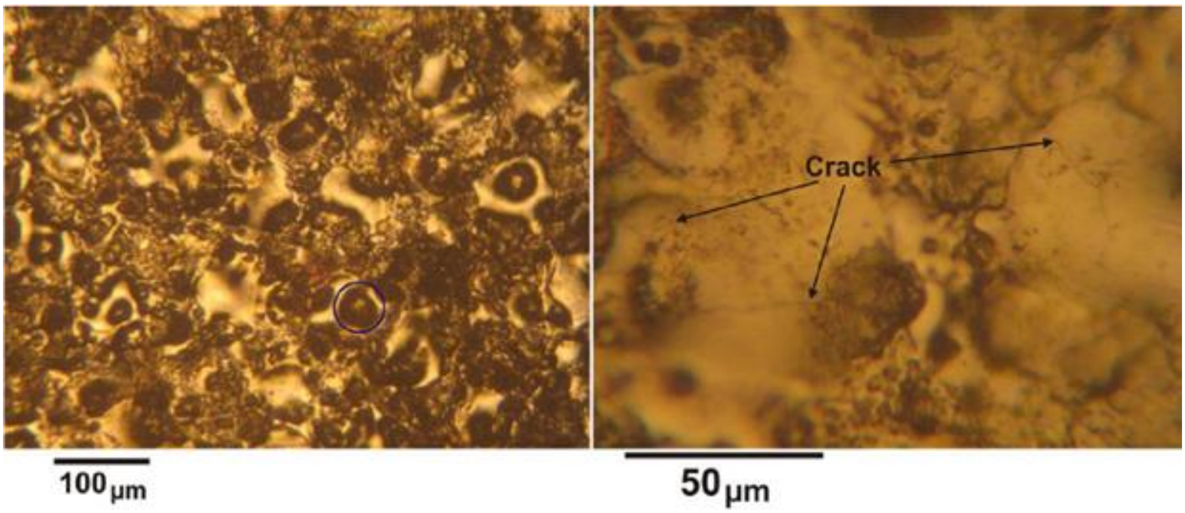

Figure8. Machining effect on samples with parameters set as, on-time = 50µs, off-time= 50µs, current (I) =1 A and voltage (V) =40 V, Right: observation of micro cracks, Left: circle surrounding a spark erosion zone

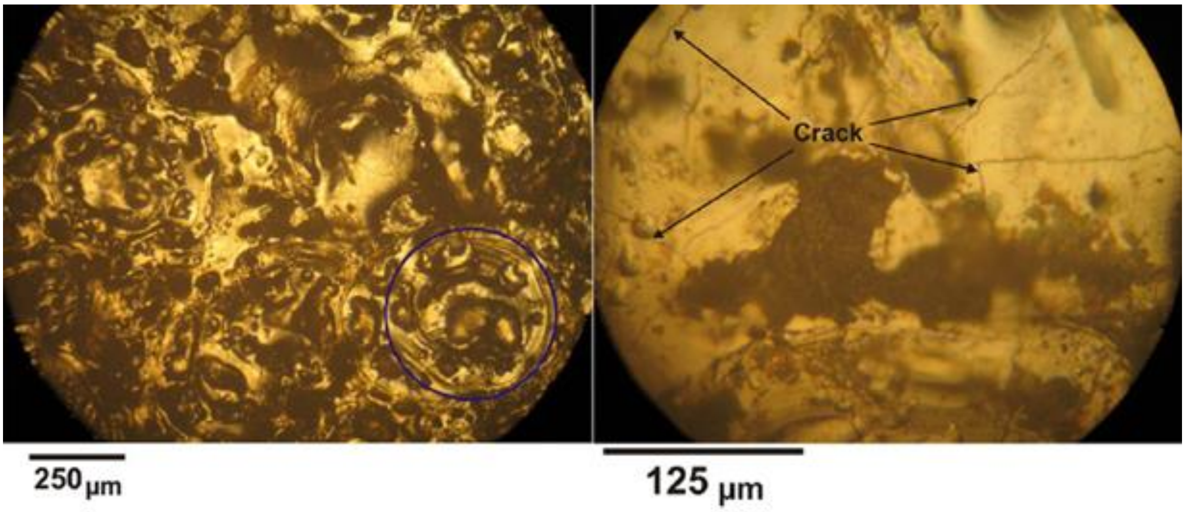

Figure9. Machining effect on samples with parameters set as, on-time = 800µs, off-time = 50µs, current (I) =5 A and voltage (V) =40 V, Right: observation of micro cracks, Left: circle surrounding the spark erosion zone

Figures 10 and 11 describe the relationship between the crack surface and change in diameter of the spark erosion zone on the machined surfaces.

The reason for this behavior concerning the on-time parameter may be found in Figure 9. As seen once the on-time parameter exceeds a specific level the material within the spark erosion zone would no longer be fully vaporized. Hence part of the spark energy increases the temperature in a neighboring zone surrounding the center of the spark effect. At a farther distance from the spark center, the available thermal energy is no longer sufficient to cause vaporization and can only melt the material. Reducing temperature through heat transfer then results in the formation of solidified material shaped as co-centric layers around the spark center as Figure 9 indicates. This behavior may, therefore, be described by the mechanism within which the molten material around the boundaries of micro-cracks undergoes re-solidification (also referred to as localized welding).

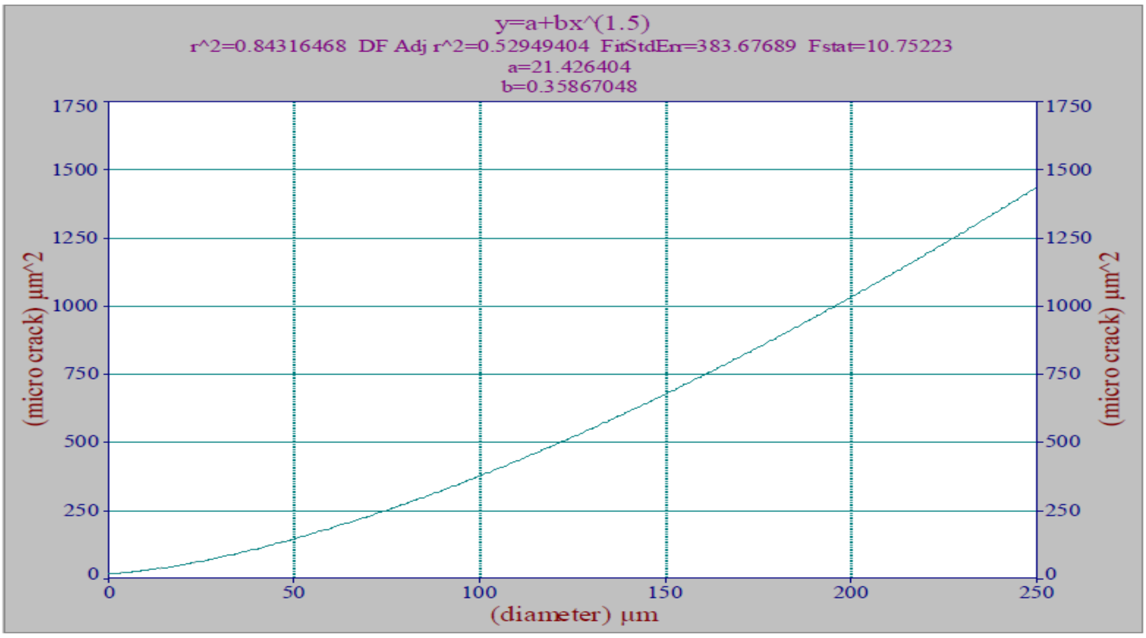

Figure10. Variation of the total surface of micro-cracks with the average grain diameter for varying off-time, voltage and current parameters

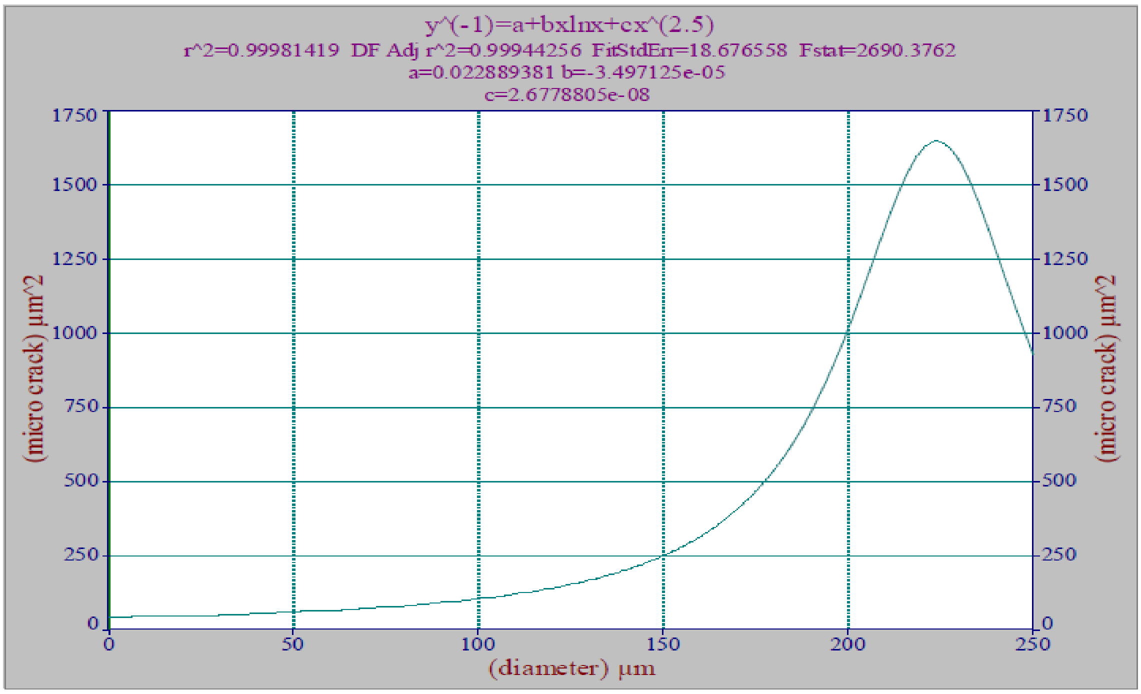

Figure11. Variation of the total surface of micro-cracks with average grain diameter for variable on-time parameter

Using the information obtained from Figures 10 and 11 as described earlier in experimental procedures, the surface of micro-cracks within the reference machined surface of 200000 μm^2 was plotted for various machining parameters independently. These are shown in Figures 12 to 14 for current, off-time, and on-time respectively. These figures suggest that current and on-time are the two key parameters most affecting the surface of micro-cracks on the machined samples. Therefore the conclusion is that one may correlate the surface crack intensity to these parameters by considering the simultaneous impact of the combined current and on-time parameters using regression analysis. This procedure has been followed for the test samples and the outcome is plotted in Figure 15. Using this figure the intensity of micro-cracks generated during the spark EDM manufacturing process can be predicted.

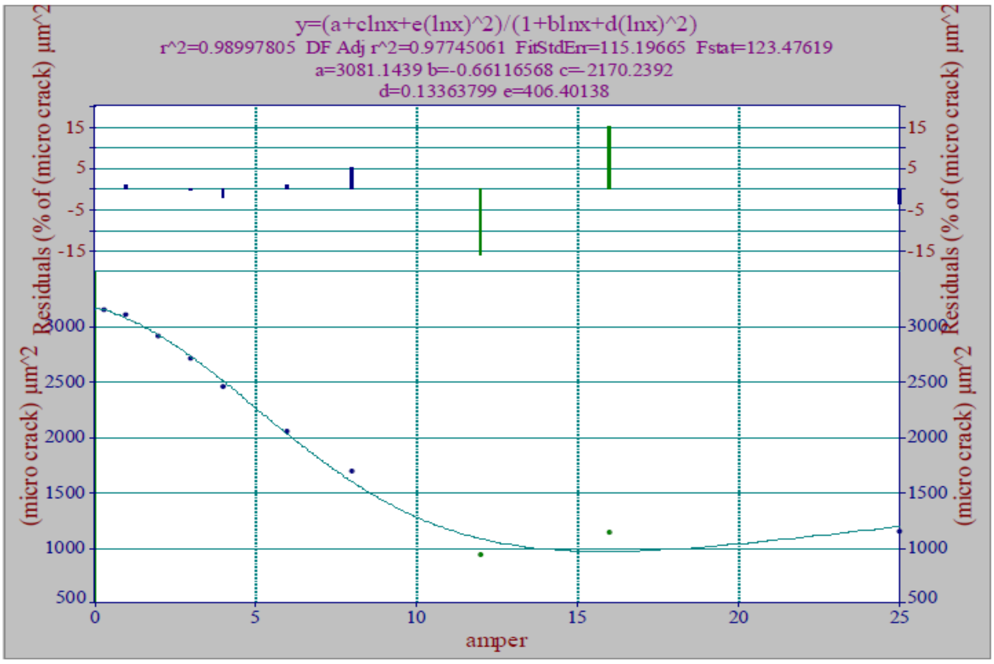

Figure12. Relationship between the variation of current and the total surface of micro-cracks on the work piece surface

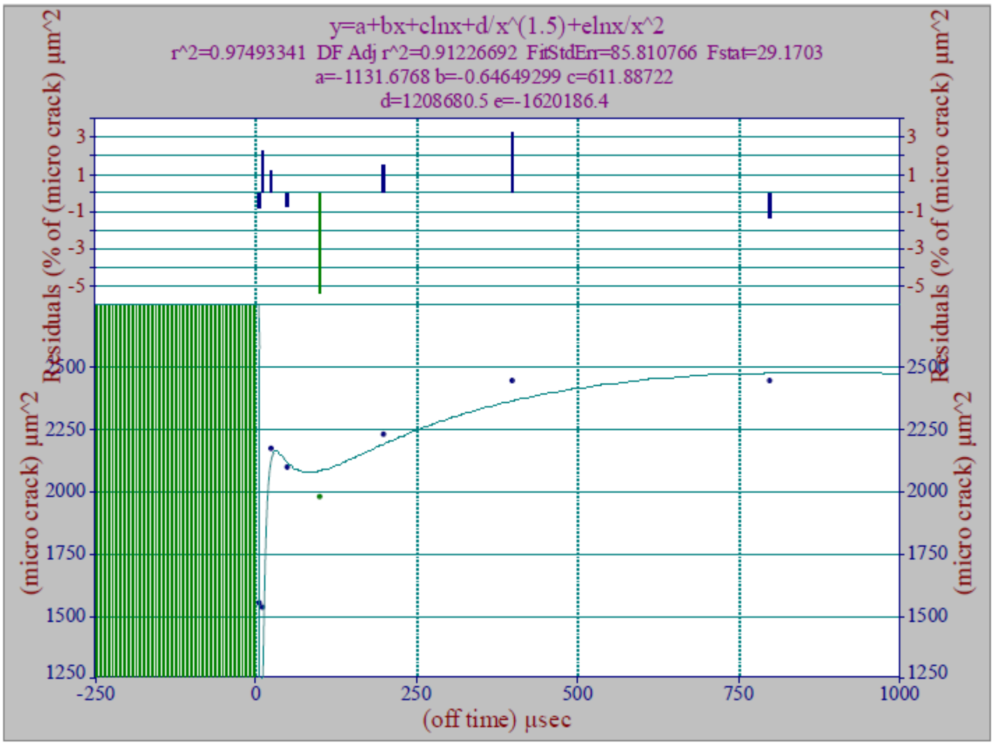

Figure13. Relationship between the variation of off-time parameter and the total surface of micro-cracks on the work piece surface

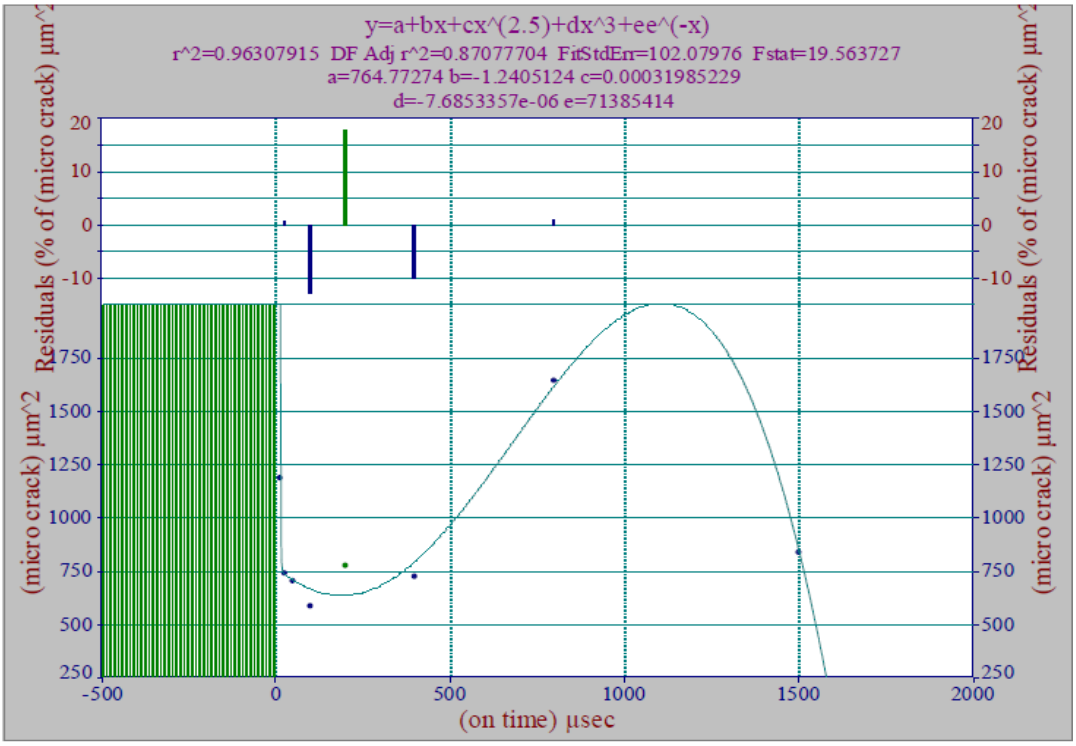

Figure14. Relationship between the variation of on-time parameter and the total surface of micro-cracks on the work piece surface

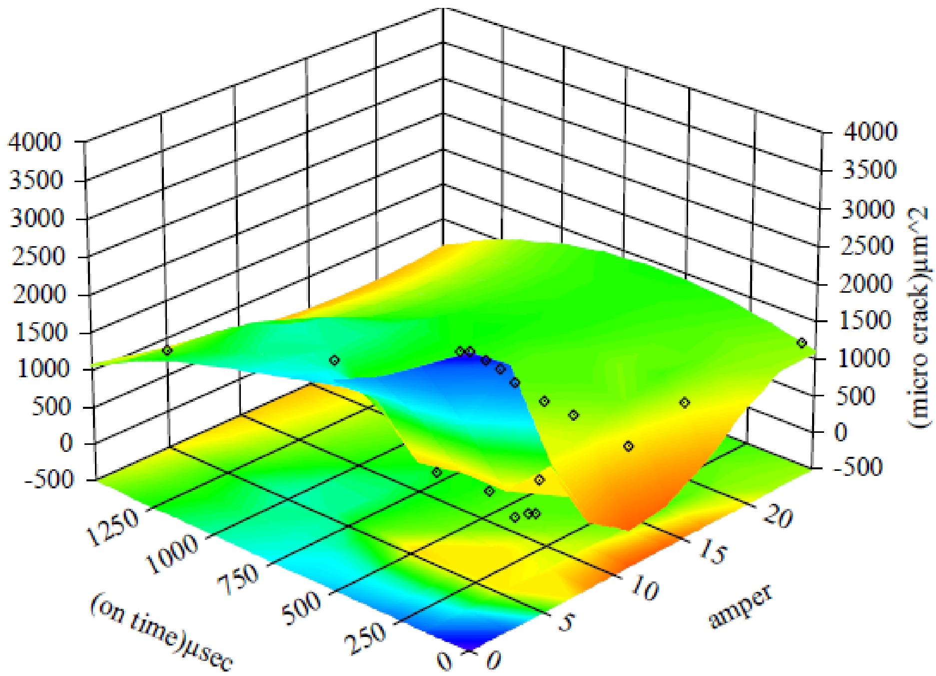

Figure15. The relationship between current and on-time parameters with the surface of micro-cracks measured on a reference surface of 200000 µm^2

5. Conclusion

1. The surface roughness and the intensity of surface micro-cracks were introduced as the measure of the quality of the spark machined surface.

2. "Current" and "on-time" were identified as the two main parameters affecting the quality of the final surface obtained by spark EDM process using the "Iso-pulse" generator.
3. The relationship between the intensity of micro-cracks and the characterizing diameter of the spark erosion zone in the spark EDM process was examined for a range of varying on-time parameter. It was found that within the early stage of the on-time parameter the relationship is similar to those obtained for the current, voltage, and off-time parameters. Increasing the on-time parameter, however, results in the reduction of the intensity of micro-cracks as a consequence of heat transfer that is linked to the prolonged duration of the on-time parameter.
4. The good response of CK45 tool steel to water quenching as a heat treatment results in a relatively uniform distribution of micro-cracks on the machined surface.
5. A "bi-directional" behavior was observed for the impact of the "on-time" parameter on the surface quality as pointed in remark 3. It was forecasted that this phenomenon would become more significant for the materials with higher heat transfer coefficient than CK45. In contrast, this behavior should become less evident for lower coefficients of heat transfer.
6. Finally, it is predicted that the use of a dielectric fluid with significantly higher heat transferability would resolve the bidirectional behavior of the on-time parameter.

6. Acknowledgments

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