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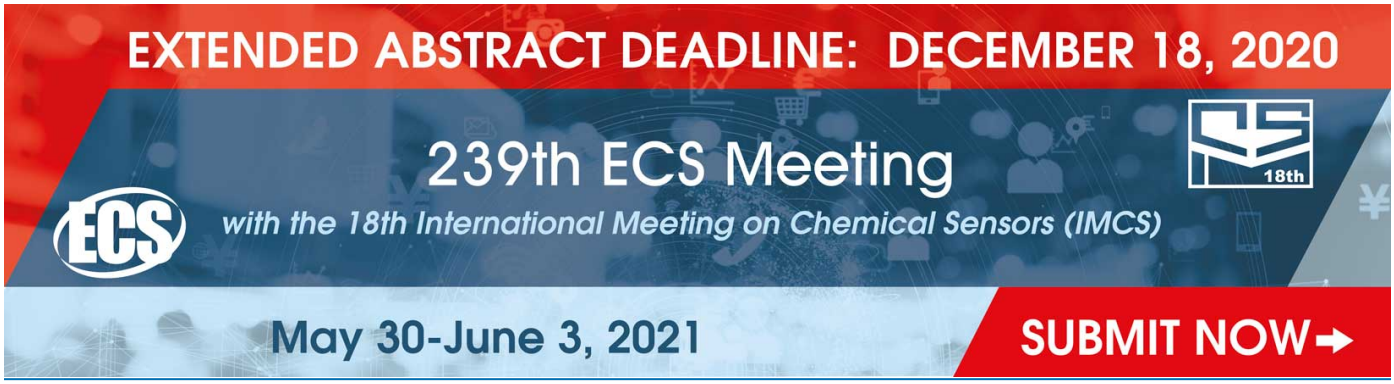

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Theoretical determination of the fatigue strength limit of electrical discharge machined (EDM) AISI 8740 steel

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Abstract. AISI 8740 is an alloy steel which is frequently preferred in plane and aerospace engineering. In this study, it was machined by electro-erosion and fatigue life of the surface structure is theoretically evaluated. For this purpose, AISI 8740 steel is processed with different processing parameters with EDM and the surface roughness and hardness of the produced surfaces are measured. Using these values in $\sqrt{area}$ fatigue model, the effect of surface structure on the fatigue endurance limit of the AISI 8740 steel was evaluated. It is the result of study that, surface roughness increases with increasing processing current and pulse duration and as a result fatigue strength limit decreases.

1. Introduction

EDM is a contactless manufacturing technique used in forming electrically conductive metals. The surfaces machined with EDM are formed by thousands of electric sparks falling randomly on the workpiece. The surface appearance is a cratery structure formed by the overlapping of the hemisphere pits. The machining mechanism is based on partial melting and evaporation of the region by falling down of electric sparks through plasma channel formed between the tool and the workpiece.

There are some important studies to investigate the effect of EDM machined surfaces on fatigue life. In a study, the fatigue life of EN X160CrMoV12 alloy specimens prepared by EDM and evaluated by the Wöhler diagrams in which the fatigue life is determined by high cycle tensile fatigue test. In the study, the fatigue strengths of specimens processed only with EDM, cleaned with a wire brush and micro-cracked white layer after EDM, surfaces with only polishing and polishing both with EDM and wire brush were examined. The highest fatigue lives were obtained on the surfaces obtained by “EDM+brushing+polishing”, “EDM+polishing”, “EDM+brushing” and “pure EDM” [1]. In another study, researchers were machined the Ti6Al4 alloy with grinding and WEDM separately, and the bending fatigue lives of both surface structures were compared. Although the roughness of the EDM treated specimens is high, it has been found to exhibit higher fatigue strength [2]. In a study of fatigue tests at loads ranging from 1470 to 2401 N with the aim of determining the fatigue lives of steel specimens treated with EDM SKD11 [3]; A fatigue test was also performed for comparison of the surface polished SKD11 sample. The results indicated that increasing the current and decreasing the waiting time of the pulses reduced the surface cracking probability. In general, the present results show that four samples taken in the fatigue test can be ranked according to their fatigue life decreasing order: the polished sample, samples with thin recast layer and without surface crack, with thick recast layer and no cracks and structure with surface cracks. In another study [4], the effects of surface integrity on fatigue life were researched on the fatigue life of AISI D2 tool steel, and the specimens were coated with physical vapour deposition (PVD) of titanium nitride (TiN) after processing with

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EDM. Experimental results have shown that only EDM process reduces the fatigue life but TiN coating increases the fatigue life due to the increase of hardness and decreases the surface residual stresses. Furthermore, TiN coating has been proposed as an effective method to improve the fatigue life of the tool steel subjected to the electrical discharge treatment. Fractographic analysis was carried out to investigate the fatigue fracture mechanisms in which the electrical discharge machined SiC particle reinforced A356 Al at 15% volume [5]. Researchers evaluated the effects on the surface quality of the and the performance under monotonic and fatigue loading conditions. And as a result, it was noted that the surface roughness formed by random sparks, significantly increased in EDM and caused a slight subsurface softening under the outer surface layer of the microstructure. Moreover, the fatigue strength is significantly reduced in processing with EDM and as the MRR increases more, this reduction in fatigue reaches even further levels as surface crater sizes increase with increasing current. Consequently, the crater roughness pattern on the surface is different from other manufacturing methods and it is thought that the white hard layer material formed after EDM processes has the effect of increasing the fatigue life of the material.

2. Experimental and theoretical study

In this experimental works, AJAN brand "50 AS 200" type electric erosion machine was used. The processing system used in the operation is schematically shown in Figure 1. Experiments were carried using AISI 8740 steel plate have 10mm thickness with dimensions of 30X50 cm. Copper bars with 10x40 cross-sectional area are used as the tool. Workpiece surface roughness measurements were made with a portable detector tip surface roughness tester with a Mutitoyo surface roughness tester SJ-210. Sampling length and measurement length were chosen from standard tables as 0.8 mm. Ra, Rz



Figure 1. Die sinking EDM machine used in experimental machining's.

Table 1. Experimental parameters.

Experiment parameters	Values
Discharge current (I_d) [A]	6, 12.5, 25
Pulse on Time (Ton) [µs]	3,48,99,201
Pulse off Time (Toff) [µs]	6,9,12,24
Dielectric flusting method	Lateral flushing
Release time [sn]	0,1
Polarity	Electrode (+), Workpiece (-)
Waiting time (t_p) [µs]	12,5
Dielectric	Kerosene
Workpiece	AISI 8740 Steel
Electrode (tool)	Copper
Machining depth [mm]	0,5

(DIN) and Sm surface roughness parameters were recorded. Roughness measurements were made on the machined surface of the workpiece in the direction of the dielectric fluid flushing from ten different points. The averages of the measurements taken in the study were used.

2.1. Surface roughness parameters

The maximum peak-to-valley height is defined as Rti for each sampling length. Rz(DIN) is expressed as the average of all Rti values in the measurement length (Figure 2). Sm is the average of the distances between consecutive peaks on the average line along the measurement length (Figure 2).

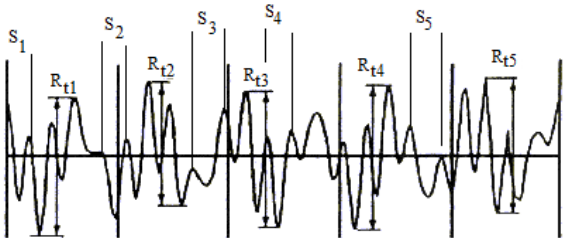

Figure 2. Largest peak-valley heights in the profile (crater depth) Rt and Profile peak distance (crater diameters) Sm.

$$R_z\left(DIN\right)=\frac{\left(R_{t1}+R_{t2}+R_{t3}+\ldots+R_{tn}\right)}{n}=\frac{1}{n}\sum_{i=1}^{n}R_{ti} \tag{2.1}$$

2.2. MURAKAMI's fatigue strength approach due to the surface roughness

Murakami defined and expressed four factors effecting on fatigue strength: (***1***) surface roughness as a stress inducer, (***2***) residual stresses occurred after machining, (***3***) work hardening or softening which occurred after plastic deformation, (***4***) microstructure change after plastic deformation. And he also stated that, these four factors normally affect the fatigue life together, but it is difficult to theoretically evaluate the fatigue strength together with these four factors [6] (Murakami et.al.; 2002). In his first studies carried out, performed tensile and compression fatigue tests using Maraging steel (HV=715). And he presents a parameter model in which the surface roughness is expressed as a shallow constant pitch and depth in a periodic notch which called "area$^{1/2}$" [7] (Murakami;1996).

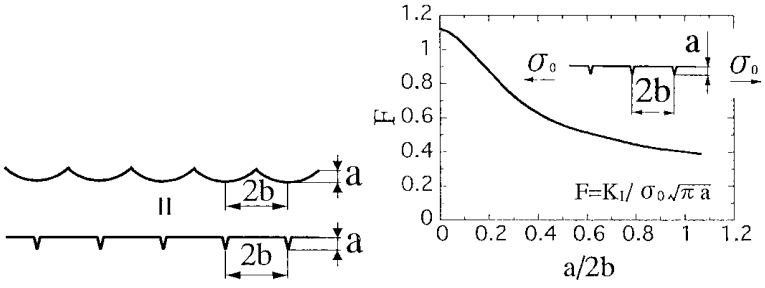

Figure 3. Stress intensity factor for periodic surface roughness notches [6].

Figure 3 shows the stress intensity factor K_t, for periodic surface roughness pitches on machined surface. The term F is a geometric correction factor which depends upon the depth and pitch of cracks, and K_t is defined by the following equation as a function of HV:

$$K_{th}=\left(3.3\right)10^{-3}\left(\mathrm{HV}+120\right)\cdot\left(area^{-1/2}\right)^{1/3} \tag{2.2}$$

Murakami proposed a prediction equation which takes into account the effect of mean stress should be based on the equation for R=-1 (stress ratio), that is Eq. 2.3. For R=-1the equation should reduce to Eq. 2.5.

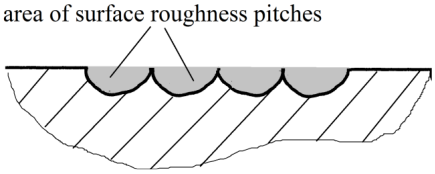

Figure 4. Area of surface roughness notches in 2 dimension.

$$(area)^{1/2}_{R} / 2b2.97(a/2b) - 3.51(a/2b)^{2} - 9.74(a/2b)^{3} \text{ for } a/2b < 0.195 \quad (2.3)$$

$$(area)^{1/2}_{R} / 2b0.38 \text{ for } a/2b > 0.195 \quad (2.4)$$

$$\sigma_{w} = \frac{1.43(H_{v}+120)}{(\sqrt{area})^{1/6}}\left[\frac{1-R}{2}\right]^{\alpha} \quad (2.5)$$

Using this $(area)^{1/2}_{R}$ equations for R =-1 in eq. 2.5; it can be used to predict the fatigue limit of the specimens with surface roughness and of those with an average notch (Sm) and pitch (Rz(DIN)). "σ_w" is the allowable stress amplitude equation for theoretical estimating and evaluation of materials with surface roughness. Here "α" stress sensivity factor and defined as;

$$\alpha = 0.226 + HV \times 10^{-4} \quad (2.6)$$

$$R = \frac{\sigma_m - \sigma_w}{\sigma_m + \sigma_w} \quad (2.7)$$

Here "σ_m" is mean stress value. In this study, all equations (2.3)-(2.7) were used for predicting the fatigue life of the electrical discharged machined AISI 8740 metal which have crater surfaces after machining. The average of surface roughness values is taken. Because, during EDM processing, getting the probability of each crater formed by the spark in same sizes as diameter and depth are very small.

3. Results and discussion

Surface roughness parameters were measured in accordance with the fatigue life model for the roughness of the machining surface. These values are "Rz(DIN)" for the factor "a" in the fatigue model and "Sm" for the factor "2b". For roughness values, three measurements were taken from each treated surface and the average was calculated. These values were used in the calculation of √area values and the results are presented together with the measured values in Table 1. As the spark discharge energy increases with increasing current flow in the processes, faster and more volumetric material removal is realized. This situation means removal in short time and so in other words it is the deepening and expansion of the craters. Hence, the smallest Ra, Rz(DIN) and Sm values were measured at I=6A. The highest values were obtained at I=25A. The power level and arc interval (steady state) were steady, and when the arc duration (pulse on time) was increased, the roughness values increased, especially to Ton=99μs. At Ton=201μs, the roughness values decreased as the cutting speed decreased. This is because, if the arc duration is increased above the optimum value, the discharge energy does not break the chip. This may be due to the plasma channel expansion during long pulse durations and the fact that the heat cannot be concentrated to the workpiece surface in a narrow channel. Thus the surface of the workpiece and the dielectric are heated unnecessarily.

Table 2 also shows the results of $\sqrt{\textbf{area}}$ calculations. This value is the size of the roughness peak-valley gap area, which at the same time which also produces fatigue notch discontinuity that's depending on the machining current and the increase in Ton=99μs. After exceeding this value; the shallower and narrower craters were formed due to the undesirable energy spread described above. Hence the $\sqrt{\textbf{area}}$ values are reduced. Table 3 shows the threshold stress intensity factor (ΔK_{TH}) and fatigue limit stress values. The ΔK_{TH} values are an expression of the stress concentration depending on

Table 2. Processing parameters, measured roughness values and calculated $(area)^{1/2}$ values.

Exp. No	Current (A)	Pulse on Time-Ton (□s)	Pulse off Time-Toff (□s)	Ra (□m)	Rz(DIN) (□m)	Sm (□m)	$\sqrt{area}$
1	6	3	6	2,8	19,35	563,47	54,91487
2	6	48	9	3,5	24,19	714,34	68,69888
3	6	99	12	3,8	26,26	803,71	74,70755
4	6	201	24	3,34	23,08	728,94	65,75724
5	12,5	3	6	3,12	21,56	644,27	61,26561
6	12,5	48	9	3,9	26,95	817,83	76,63928
7	12,5	99	12	4,2	29,03	872,21	82,51447
8	12,5	201	24	4,7	32,48	981,83	78,62378
9	25	3	6	3,28	22,67	679,67	64,43018
10	25	48	9	4,4	30,41	944,45	86,57377
11	25	99	12	4,8	33,17	1019,95	94,38687
12	25	201	24	4,32	29,86	918,75	84,97064

the geometry in the discontinuity region that will initiate the fatigue. Therefore, surface structure obtained after the processes, involves a lot of small areas of the peak-to-valley roughness which occurs in small current and pulsed processes, and therefore ΔK_{TH} is small. This means that as the roughness decreases, the stress accumulation which will trigger the formation of micro cracks is also decreasing. This is clearly seen in Figure 5. After Ton = 99μs, ΔK_{TH} is decreased because of roughness and $\sqrt{\mathbf{area}}$.

Table 3. $\sqrt{area}$ fatigue model results.

Exp. No.	Current (A)	Ton (μs)	ΔK_{TH}	Fatigue Limit Stress (Mpa)
1	6	3	5,4	204
2	6	48	5,8	196
3	6	99	6	193
4	6	201	5,8	196
5	12,5	3	5,6	200
6	12,5	48	6	192
7	12,5	99	6,2	190
8	12,5	201	6,3	189
9	25	3	5,7	198
10	25	48	6,3	188
11	25	99	6,5	185
12	25	201	6,3	189

The change in the fatigue limit value tends to decrease with increasing surface roughness, and increase with decreasing tendency. This is clearly indicated that the cross-sectional area of the craters on the surface affects the stress at the beginning of fatigue, and ultimately the value of the stress that will bring the damage. Small currents mean low roughness values and high fatigue strength stress. On the other hand, in the case of high flow and high flow, the opposite situation occurred. In Figure 6, fatigue limit stress decreased with the increase of current and pulse duration. This value has increased due to the decrease in roughness after Ton=99μs. At the highest σ_w=204MPa, I=6A and Ton=3μs, the lowest σ_W=185MPa, I=25A and Ton=99μS, respectively.

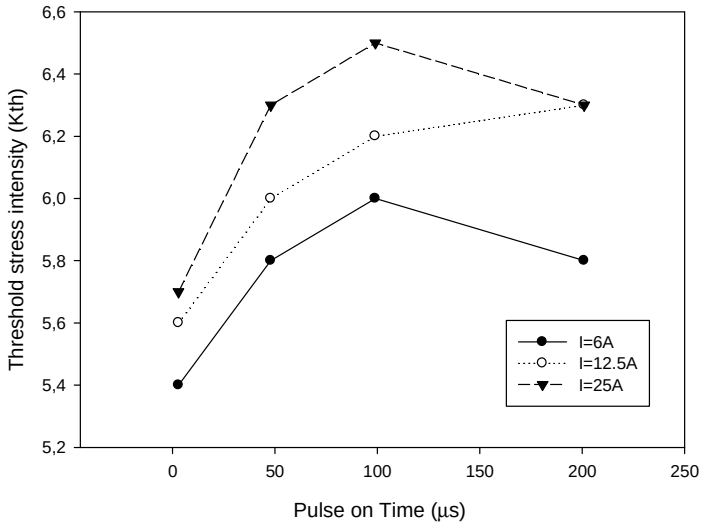

Figure 5. Changing of threshold stress intensity (K_{th}) due to the T_{on} and I.

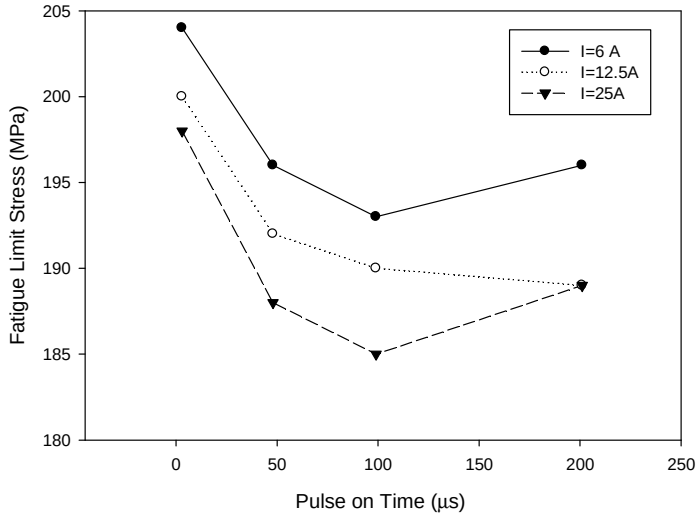

Figure 6. Changing of fatigue limit stress due to the T_{on} and I.

4. Conclusion

In this study, AISI 8740 steel was machined in various machining parameters by sinking EDM. Fatigue limit stresses were calculated by using Rz(DIN) and Sm roughness parameters of the cratered surface structure in the fatigue lifetime model. The Rz(DIN) and Sm roughness parameters are the best values for this calculation. It has been understood that there is an ideal value of current and pulse duration in processes. So with the continuous increase of these machining parameters, there is no increase in roughness and in MRR. And a decrease with the same reduction of machining parameters. Ton=99µs pulse duration was determined as the threshold change point. The increases after this value decreased the roughness and the value of $\sqrt{\mathbf{area}}$ depending on it. The roughness peak-valley area has been identified a very effective predictor of the fatigue life of machine elements after manufacturing. The increased pulse on time and the current increased the ΔK_{TH} value in these areas, which are considered to be the starting points of the fatigue damage, and decreased the fatigue stress limit value. Thus, in manufacturing with EDM, the crater size on the surface was important in understanding the initial stress value of the fatigue damage. After all, it should be taken into consideration that the service life of the machine elements will change according to the type of the selected manufacturing type.

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