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Morphological - Functional Aspects of Electro-Discharge Machined Surface Textures

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This study investigates a set of "non–common" surface topography parameters of Electro-Discharge Machined surfaces that give differing aspects of texture related to morphological characterization and possible tribological applications. The parameters considered are the Abbott (bearing) curve parameter at 10 % of the raw unfiltered and the roughness profile height $P_{tp10\%}$ and $R_{tp10\%}$, respectively, the also bearing curve oriented R_k family of parameters (ISO 13565-2:1996), the skewness R_{sk} and the kurtosis R_{ku} of the profile height distribution, the mean spacing R_{sm}, and the fractal dimension D. The correlation of the aforementioned parameters with pulse energy is examined to allow appropriate selection of machining conditions for producing functionally desirable Electro-Discharge Machined textures.

Keywords: electrical discharge machining, steel, surface topography, surface roughness

0 INTRODUCTION

Technological advances and high strength requirements have led to an increasing use of materials with improved mechanical properties in industrial production. In the machining of these materials, cutting processes exhibit several and serious shortcomings and are rivaled by the so-called "non-conventional" processes.

The most important advantage of Electrical Discharge Machining (EDM), one of the most widely applied non-conventional processes for high precision products is that its effectiveness is independent of the mechanical properties of the machined materials because that they are electrically conductive [1].

In EDM, removing material from a machined part, a series of repetitive spark discharges between the electrode and the workpiece causes local melting and/or evaporation of material in the presence of a dielectric fluid. The result is a surface characterized by overlapping craters and other topographic formations that are indicative of the intense thermal impact involved [2].

Besides the study of surface integrity changes (including surface topography) induced by EDM [2], the correlation of the surface topography parameters with machining conditions towards the advanced control and optimization of the EDM is of major interest. 2-D and 3-D profilometry together with the application of design of experiments methodology [4] and neural network models [5] are a promising tool for this purpose [3].

In previous works [2] and [6] to [7] the emphasis was on the relationship between multi-parameter analysis of the Electro- Discharge Machined surface texture and the process parameters and statistical regression models that were developed to correlate the machining conditions with the imparted surface finish characteristics.

The characterization and evaluation of engineering surface topography is essential for describing the functional behaviour, monitoring the quality of the products and to control the manufacturing process performed. The measurement of surface topography has constituted a challenging metrological problem over the years. Textures are complicated in form so to obtain a satisfying description at various levels many parameters have been proposed.

The establishment of the "M" (central line) system has facilitated the communication between laboratory and industrial practice but with more than one hundred parameters in view of literature too many have been proposed [1]. The ISO 4287: 1997 standard comprises thirteen parameters for surface roughness and the relevant surface waviness parameters. This is attributed to the usually complicated form of surface textures

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and the need for a suitable global description. As expected, numerous research papers focus on better manipulation of these parameters in various manufacturing processes and the impact of process factors on surface characteristics (indicative refs [3] and [4]).

Similarly to dies, moulds and other components are nowadays often manufactured by EDM with high precision requirements. Furthermore, classical surface roughness parameters like R_a, R_t or R_z are not sufficient for a morphological characterization of surfaces. The consideration of more roughness parameters would be more useful to measure surface characteristics because of the aforementioned overlapping craters over the surfaces and the nature of the irregularities which are completely different compared to conventional machining processes. Moreover, features of Electro-Discharge Machined surface profiles should be associated with functional characterization of the surface in case of experiencing contact used as machined or secondarily processed by a smoothening operation; to the authors' knowledge this topic has been to an extent overlooked in view of literature.

The present study is concerned with the investigation of a set of "non-common" surface topography parameters of Electro- Discharge Machined surfaces that describe differing morphological characteristics and are sensitive to profile shapes.

Surface analysis followed deals with three aspects: (a) correlation of bearing curve parameters with machining conditions and other surface texture parameters, (b) representation of the obtained bearing curves through polynomial fitting models and (c) description of bearing curves by the set of R_k parameters (ISO 13565-2:1996). The influence of the process variables on a number of amplitude (arithmetic and statistical) surface roughness parameters (R_a, R_{sk}, R_{ku}), and the spacing parameter R_{sm}, which also provides differing aspects of surface properties, is also examined.

1 THE EXPERIMENTS

1.1 Machining Conditions-Materials

Electro-Discharge Machining was performed on a HOSTEK SH-38GP (ZNC-P type) electro-discharge machine-tool with working voltage (V_e) of 30 V and open circuit voltage of 100 V. Experiments were conducted in a typical oil dielectric (BP250) with electrolytic copper used as the tool electrode (anode).

The pulse current i_e and the pulse-on time t_p were considered to be the main operational parameters that varied over a range from roughing to finishing i.e: i_e: 5, 10, 20, 30 A and t_p: 100, 300, 500 μsec, thus resulting in 12 discrete pulse energies. The pulse energy was calculated using the formula: $W_e = V_e\ I_e\ t_p$ ($V_e = 30$ V).

Specimens of plain carbon steel Ck60 and an AISI D2 tool steel (Sverker 21) in the form of square plates of dimensions 70x70x10 mm were used as workpieces (cathode).

Ck60 is a popular structural steel with sufficient hardness and AISI D2 is a tool steel characterized by high wear resistance and high compressive strength.

Their chemical compositions are accordingly:
Ck 60: 0.60 % C, 0.35 % Si, 0.80 Mn.
AISI D2: 1.50 % C, 11.50 Cr, 0.80 V, 0.75 Mo.

1.2 Surface Texture Measurements

The "non-common" texture parameters used in this study are incorporated in the DIN EN ISO 13565-2:1998 and ISO 4287:1997 standards, except the profile fractal dimension. R_a is considered for reference as it is widely used.

The definition of the arithmetic and statistical parameters used according to ISO 4287:1997 is briefly given, as follows:

- R_a (μm): average height of the profile,
- R_{sm} (μm): mean spacing of the profile peaks measured at the central line,
- R_{sk}: skewness (3nd order central moment) of the profile amplitude distribution,
- R_{ku}: kurtosis (4th order central moment) of the profile amplitude distribution.

The surface texture parameters related to Abbott (bearing) curve parameters expressed by the ISO 4287:1997 standard represent the material to void relation at 10 % of the raw (unfiltered) and the roughness profile height, and are $P_{tp10\%}$ and $R_{tp10\%}$, respectively. The raw parameter is used to provide an indicative description of integrated surface texture taking into consideration both roughness and waviness at the same time; the latter is neglected in several cases albeit it is functionally significant [22].

Naturally, a distinction must be made between corresponding Abbott curves for the raw and the roughness profile.

Alternatively, the evaluatation of the characteristics of Abbott curves of roughness is done through the "R_k" family of parameters defined in [8]. According to these standards, a group of five parameters characterizes the following three components of surface roughness (Fig. 1): a) core by R_k, which stands for the depth of the roughness core profile b) peaks by R_{pk} representing the top portion of the surface to be quickly worn away and MR1 that is the upper limit of the core roughness and c) valleys by R_{vk} describing the lowest part of the surface which has the function of retaining the lubricant, and MR2, the lowest limit of the core roughness.

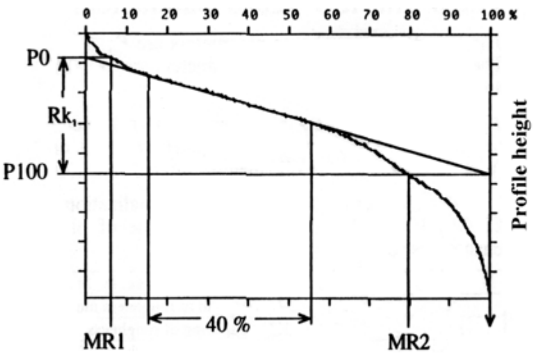

Fig. 1. *Definition of the family of "R_k" parameters*

In regards to the determination of profile fractal dimension D, an internationally standardized procedure has not yet been established.

The multi-parameter surface texture analysis was performed using a Rank Taylor-Hobson Surtronic 3+ profilometer equipped with the Talyprof software. The cut-off length was selected at 0.8 mm whilst 40 measurements were conducted on every specimen in random directions as it is known that Electro- Discharge Machining generates geometrically isotropic textures [9].

2 RESULTS AND DISCUSSION

2.1 Variation of Amplitude Parameters

Arithmetic average roughness (R_a) is by far the most commonly used parameter in surface finish measurement, for general quality and process control. Despite its inherent limitations it is easy to measure and offers a good overall description of height characteristics of a surface profile. The variation of average roughness, R_a with pulse energy is presented in Fig. 2. For Electro-Discharged Machined surfaces, the variation of R_a with process operational parameters follows well-known patterns [10]; it increases when the pulse energy increases at a gradually lower rate. For medium and high pulse energies ($W_e \geq 150$ mJ).

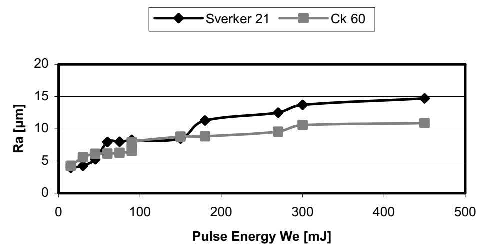

Fig. 2. *Variation of average roughness R_a, with pulse energy, W_e*

Electro-Discharged Machined surfaces of AISI D2 tool steel (Sverker 21®) are systematically rougher than the corresponding ones of Ck60. This observation can be correlated with differences in crater dimensions for certain pulse energies, which in turn are physically linked to corresponding alterations of the heat source, i.e. the plasma channel and the resulting melting isothermal and also with the thermal properties (conductivity, diffusivity) of the material being machined [11].

The skewness parameter (R_{sk}) is typically used to measure the symmetry of the profile about the mean line providing an implication of the "fullness" or "emptiness" of the profile and is sensitive to the existence of deep valleys or high peaks [12]. Surfaces with a positive skewness, such as turned surfaces have fairly high spikes that protrude above a flatter average. Skewness correlates with the load carrying capability of a surface and negative values for the former indicate pronounced bearing properties and favourable anti-wear behaviour, mostly for the running-in stage of function. The variation of skewness of EDMed surfaces with pulse energy is illustrated in figure 3; in general, it appears uncorrelated to the pulse energy. Judging from the measured skewness values, the EDMed profiles are "empty" of material as indicated from the relatively high positive values, excluding some lower pulse energies; at higher energies skewness is almost stabilized at positive values; see also [7].

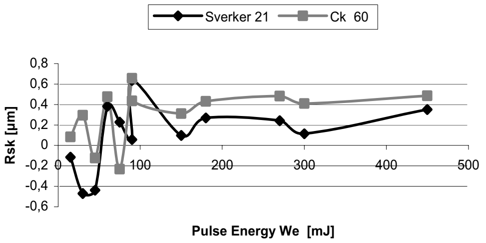

Fig. 3. *Skewness of the heights distribution R_{sk}, versus pulse energy, W_e*

Kurtosis (R_{sk}) typically describes the sharpness of the probability density of the profile [7] and [12]. Practically, low kurtosis values indicate strong bumpy peaks that increase bearing capability and wear resistance, but this must be viewed in association with skewness.

The measured values of this parameter are in the range of 2.5 to 3.5, see Fig. 4. They indicate randomly distributed high peaks and low valleys but show poor correlation to pulse energy. Note also that for both R_{sk} and R_{ku} parameters, higher values were measured for AISI D2 than the Ck60 specimens for the same medium and high pulse energies.

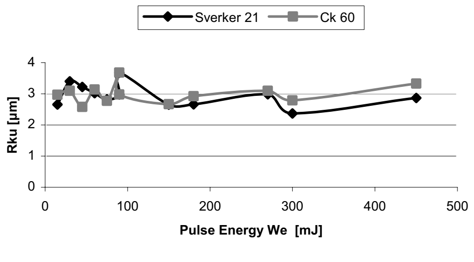

Fig. 4. *Kurtosis of the heights distribution R_{ku}, versus pulse energy, W_e*

2.2 Spacing Parameter

The spacing parameters measure the horizontal characteristics of the surface profiles. These parameters are of the utmost importance in sheet metal pressing since they influence the lubrication conditions and the avoidance of surface defects such as scoring.

During this study the mean spacing of the asperities (R_{sm}) was measured and the variation of this parameter with pulse energy is plotted in Fig. 5; it exhibits an increasing tendency. In combination with the number of the high spots of the profile, which decreases with pulse energy, it is concluded that EDMed surfaces processed at high pulse energies will permit a small number of contacts with a possible counterpart despite the increased roughness height.

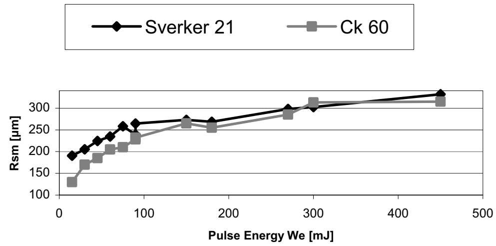

Fig. 5. *Variation of the mean asperities spacing, R_{sm} with pulse energy W_e*

2.3 Correlation of Bearing Curve Parameters with Machining Conditions

The Abbott (material ratio or bearing) curve is nowadays established as a means for providing a working representation of the portions of the surface at different depths, combining texture aspects related to contact area and contact mechanics, wear, lubricant retention and others [13]. Other views of the surface bearing capability can be provided by the skewness of the profile height distribution and the fractal dimension. These topographic parameters can, apart from connecting the EDM process to functional behaviour of the machined surfaces, also describe useful surface features and to generally give useful insights into the nature of roughness regarding the EDM process control.

$R_{tp\%}$ as a parameter refers to the bearing ratio at a specified height of the profile. The bearing curve parameters corresponding to the raw and the roughness profile were selected at 10% depth in order to be functionally significant, also considering waviness as an important component. The variation of $P_{tp10\%}$ and $R_{tp10\%}$ parameters with pulse energy is presented in Figs. 6 and 7, respectively. Both parameteres increase when the pulse energy increases, over a relatively wide range. This behaviour implies that when intensifying the machining conditions, the bearing capability of the surface becomes pronounced at the same level. Furthermore, similar trends shown by the unfiltered and the roughness profile Abbott curves indicate that besides roughness, to an extent waviness also contributes to the rise of surface bearing capability which is exhibited by an increasing pattern. This fact was also confirmed in ref. [7] and is attributed to an intensified vibration between the electrode and the workpiece

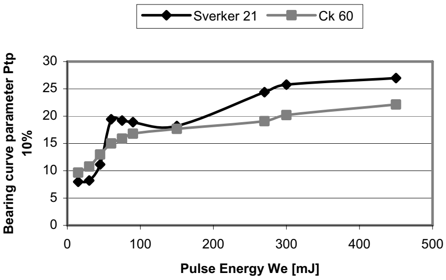

Fig. 6. *Variation of $P_{tp10\%}$ parameter of unfiltered profile with pulse energy, W_e*

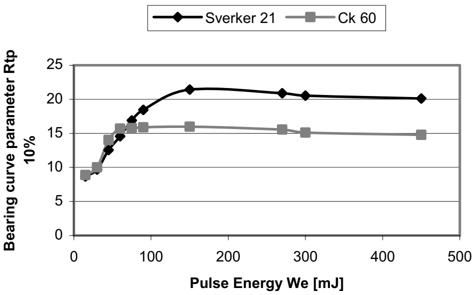

Fig. 7. *Variation of $R_{tp10\%}$ parameter of roughness profile with pulse energy, W_e*

It is noteworthy that for medium and high pulse energies, both $P_{tp10\%}$ and $R_{tp10\%}$ values measured for AISI D2 specimens are systematically higher than the ones measured for Ck 60; a trend similar to the one observed in R_a measurements.

A similar trend is followed if the Abbot parameters are considered with respect to R_a and R_{sk}. Note that R_{sk} (skewness) can be considered as a rough measure of the surface bearing capacity and as shown, it generally correlates with the R_{tp} (Abbot curve) parameter.

2.4 Representation of Bearing Curves through Polynomial Fitting Models

Preliminary analysis and previous research indicate that 3rd order polynomial fitting model gives a suceessful representation of bearing curves [13] and [15]. Given the mutual accordance, only the raw profile bearing curves fitting, for Ck 60 steel specimens, according to equation, $y = k_o + k_1x + k_2x^2 + k_3x^3$ is presented. Calculated fitting coefficients are shown in Fig. 8. An intense dropping trend of the cubic coefficient appears at high pulse energies. All these changes in the shape of the bearing curves are closely related to contact mechanics and wear behaviour [16].

2.5 Description of Bearing Curves by the Set of R_k Parameters

The R_k configuration is designed to divide the bearing ratio curve into three sections: the small peaks above the main plateaus, the plateaus themselves, and the deep valleys between plateaus; see Fig.1.

These parameters describe the shape of the relevant bearing (material ratio or Abbott) curves and permit the distinction between plateau and valley portions of the surface along with the core characteristic of the curve, which corresponds to the stable portion of material in the surface after initial wear. A linear approximation of the bearing curve is provided: the depth of profile below 40 % bearing area is taken to indicate the steady state wear status of the engine. They have been used in research [3] to [5]. The parameters were defined in paragraph 1.2. The functional behaviour may be predicted in this way and the control of the manufacturing process can be enhanced.

The variation of these parameters with pulse energy for all Electro-Discharge Machined specimens is plotted in Figs. 9 to 13. From these plots it is obvious that the ISO 13565-2:1998 standard suits EDM as the bearing curves are of a general "s"-shape, the correspondingly divided portions of the surface profile are distinctive and

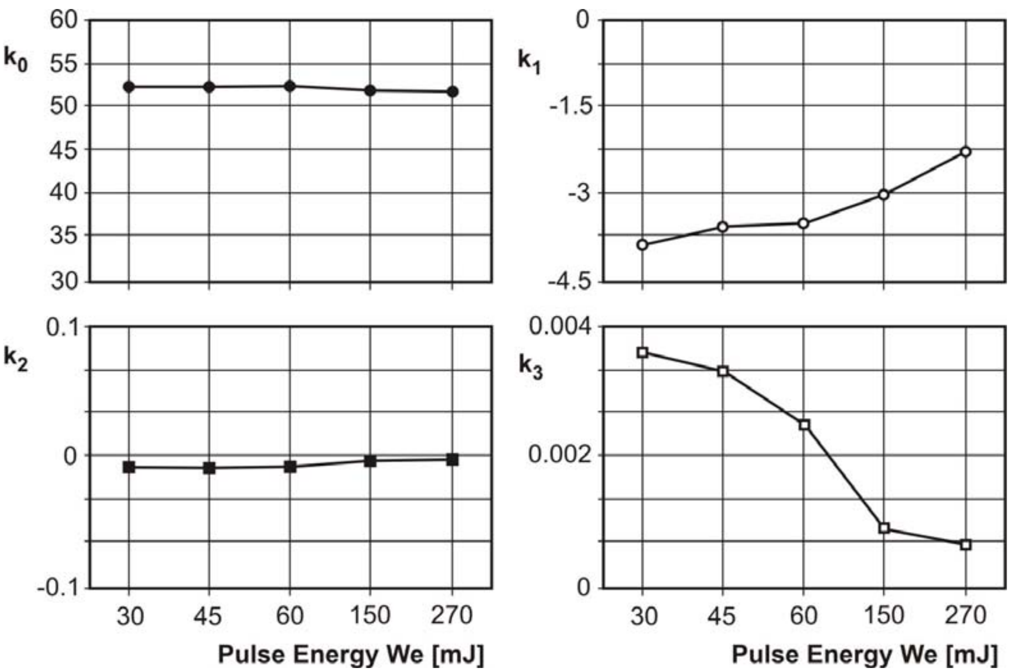

Fig. 8. *Polynomial fitting coefficient against pulse energy, W_e (k_o: constant, k_1: linear, k_2: square, k_3: cubic, material: Ck 60)*

the parameters vary in a monotonous way. The standard is successfully applied to "s"-shaped bearing curves in view of morphology because the profile statistical distribution does not markedly deviate from normality although this does not necessarily imply a stratified texture [20] to [23]. Note however, that this standard was originally formulated for stratified textures, therefore the present results need further clarification, e.g. through friction and wear test on a pin-on-disc tribometer.

From the plots presented in Figs. 9 to 13 it is evident that for low pulse energies ($W_e \leq 90$ mJ) measured values for the two steels are quite similar; for medium and high pulse energies measured values for AISI D2 tool steel (Sverker 21®) are systematically higher than the corresponding ones for Ck 60. This trend was identified for all five parameters of the R_k family. Moreover, for high pulse energies ($W_e \geq 270$ mJ) R_{vk}, M_{R1} and M_{R2} are almost constant and characteristic for each material, see Figs, 11 to 13, respectively.

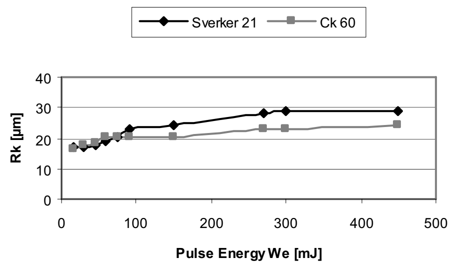

Fig. 9. *Variation of R_k with pulse energy, W_e*

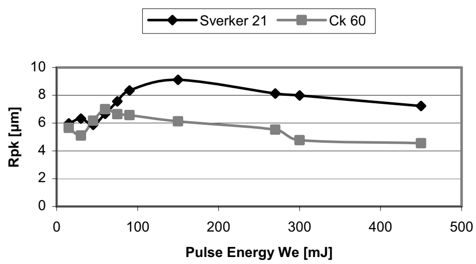

Fig. 10. *Variation of R_{pk} with pulse energy, W_e*

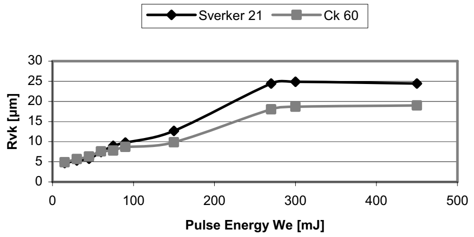

Fig. 11. *Variation of R_{vk} with pulse energy, W_e*

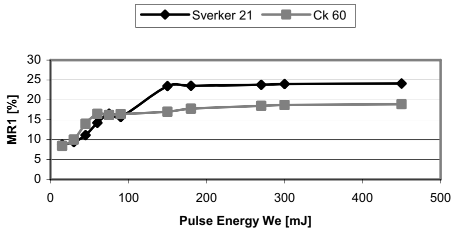

Fig. 12. *Variation of M_{R1} parameter with pulse energy, W_e*

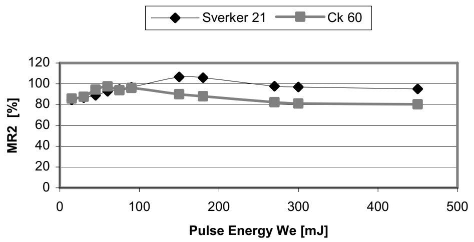

Fig. 13. *Variation of M_{R2} parameter with pulse energy, W_e*

2.6 Fractal Presentation

In addition to Abbot parameters, fractal-based methods for describing surface texture have attracted great interest as they can provide information that conventional surface roughness parameters cannot. Surface complexity can be represented under some hypotheses by fractal geometry. Fractal has been introduced to describe the micro roughness of surfaces generated by fracture, such as machined surfaces, in order to provide evaluation by one or two parameters only.

The main fractal parameters are fractal dimension D and topothesy L. As fractal dimension is established to correlate with machining conditions [14] and [24], it was the only fractal paprameter considered in this study.

The fractal dimension D is an intrinsic property of the surface, which is scale independent and reflects, as mentioned above, the "complexity" of the profile structure. High values for fractal dimension D are relevant to a higher complexity of the profile and as a consequence reinforce surface bearing capability.

A two dimensional self-affine fractal was assumed to represent the profiles of the EDMed parts and D was calculated via the power spectrum method. It appears almost insensitive to the pulse energy variation, except a rise at a low energy in the case of Ck60, see Fig. 14; such a phenomenon is consistent with the results reported in [14]. This shows that the degree of complexity of the EDMed surfaces is almost independent of the machining conditions employed and over a wide range of their variation.

The fractal dimension values are significantly higher for Ck60. Certainly, to clarify the applicability of fractal geometry analysis in Electro-Discharge Machining, more steel grades over a wider range of machining parameters have to be studied.

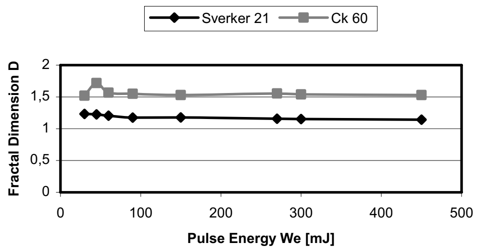

Fig. 14. *Variation of fractal dimension D with pulse energy, W_e*

3 CONCLUSIONS

A close correlation exists between the t_p bearing curve parameters of the raw, the roughness profile and the pulse energy regarded as the main machining variable. It was found that the P_{tp} and R_{tp} parameters increase monotonously with increase in pulse energy. Likewise, most of the R_k parameters exhibit a similar trend. R_{sk} and R_{ku} parameters appear uncorrelated to pulse energy. Moreover, the fractal dimension *D* appears insensitive to the pulse energy variation. Note that R_{sk} can be considered as a rough estimate of the surface bearing capability and as shown, it is generally correlated with the t_p (Abbot curve) parameters.

The bearing curves are represented by a 3rd degree polynomial model, which fits them satisfactorily. An intense falling trend of the cubic coefficient appears at high pulse energies. All these changes in the shape of the bearing curves are closely related to contact mechanics and wear behaviour of machined surfaces.

As far as the description of bearing curves by the set of R_k parameters defined in ISO 13565-2:1996 is concerned, it is indicated that these parameters can provide an adequate description of crucial portions of the resulted surface profile in relation to the machining conditions.

Regarding the correlation of the examined parameters with the machining conditions, the R_{sk}, R_{ku} and D appear uncorrelated over the whole range of machining conditions variation. This could indicate that these parameters are more or less insensitive to the process factors and they correspond to essential qualitative characteristics of Electro-Discharge Machined surface texture and could make up a representative set of morphology or function oriented parameters. However, in order to verify this statement, more evidence is required in terms of wider variation of machining parameters and workpiece materials.

The aforementioned parameters give insight to different features of the Electro-Discharge Machined surfaces, both topographically and functionally and are of particular interest in controlling and optimising EDM operations. It would be possible to manufacture parts with certain surface roughness requirements using the results instead of trial and error.

Even in case the requirements for a second processing by burnishing, grinding or other method exist, such findings will serve as inputs for a proper selection of process parameters.

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