On machining of Calmax steel by EDM: an experimental study

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Abstract: Electrical Discharge Machining (EDM) is a non-conventional machining process in which the material removal occurs by utilizing thermodlectric energy. EDM's inherent properties render it a feasible method in machining hard-to-cut materials, like tool steels. The current study presents an experimental study regarding the machining of Calmax, a chromium - molybdenum - vanadium alloyed steel, with EDM. The control parameters are the pulse-on current, the pulse-on time and the open-circuit voltage, while the machining performance was estimated in terms of the Material Removal Rate (MRR), the Tool Wear Ratio (TWR) and the Arithmetic Average Roughness (Ra). The experiments were carried out based on Taguchi DOE and an L16 orthogonal array design. Finally, for the aforementioned performance indexes, Analysis Of Variance (ANOVA) was performed to determine how the machining parameters impact the process' results.

Keywords: EDM, Calmax steel, Taguchi DOE, Non-conventional machining process.

1. Introduction

Electrical Discharge Machining (EDM) is a thermoelectrical process characterized by material removal through electrical discharges between the working electrode and the workpiece. As the spark rises, the workpieces' temperature (both of the tool and the electrode) surpass the melting temperature even up to the boiling point. The shape and geometry obtained after machining depend mainly on the tool's geometry [1,2]. EDM is commonly employed in machining difficult-to-cut materials such as hardened steel, titanium, and nickel alloys, which typically require special cutting tools for machining with conventional methods.

Many researchers carried out experimental studies to define the optimal process parameters in order to achieve the maximum MRR and better Surface Quality (SQ). Kiyak and Çakır [3] investigated the machining parameters of EDM and their influence on a 40CrMnNiMo864 tool steel's surface roughness. The Experimental results revealed that lower and relatively higher pulse-on time (T_on) and pulse-on current (I_p) respectively produced better surface quality. Dewangan, Gangopadhyay and Biswas [4] applied fuzzy TOPSIS, and sensitivity analysis on surface integrity of AISI P20 Steel machined with
EDM. The conducted research study investigated the influence of the machining time, the $I_p$ and the $T_{on}$ on the Surface Crack Density, White Layer Thickness and the Surface Roughness (SR). Chandramouli and Eswaraiah [5] performed an optimization study in order to achieve higher MRR with lower SR on a 17 PH steel by EDM. The Analysis of Variance showed that the pulse-on time has a higher contribution on the SR (76.6%) and the MRR (58.3%). Ubaid et al. [6] also applied an optimization study in machining AISI 304 steel with EDM using fuzzy logic. In their study, the ANOVA results indicated that the pulse off time ($T_{off}$) and pulse-on current mainly affect the machining performances. Straka et al. [7] used a composite electrode SF-CU to optimize the Heat Affected Zone (HAZ) of X32CrMoV12-28 tool steel after the machining with EDM. The statistical analysis showed that, for the roughing conditions, the HAZ thickness varies from 120 to 180 µm and finishing varies from 60 to 100 µm. The influence of the EDM parameters on stainless steel 316L was investigated by Singh et al. [8] and authors deduced that the lower SR was 0.443 μm for $I_p$ of 20 A. At the same time the higher MRR came up with an increase of almost 32% in SR. Another optimization study was conducted by Straka and Hašová [9] to investigate the MRR and the Tool Wear Ratio (TWR) in a die-sink EDM of EN X210Cr12 tool steels. It was concluded that TWR is strongly related with the $I_p$, while increase of $T_{on}$ resulted a decreased of TWR. Finally, Nguyen et al. [10] employed a Taguchi–Grey Relational Analysis for EDM optimization of a high chromium tool steel. They used several responses such as average SR, microhardness, average WLT and, the MRR to identify the optimal machining parameters with $I_p$ 5 A, $T_{on}$ 18 µs and, pulse-off time 34 µs.

In the current study, an experimental investigation regarding the machining of Calmax steel by EDM is presented. Calmax is a chromium – molybdenum – vanadium alloyed steel, of high toughness and good wear resistance, which is commonly utilized in a wide range of applications like manufacturing cold-extrusion dies with complex geometries, prototype tooling, and moulds for the plastic industry. Although EDM is included in the non-conventional processes that are usually employed in machining of Calmax steel, a limited experimental investigation has been carried out concerning the machining of this specific alloy with EDM. The control parameters are the pulse-on current ($I_p$), the pulse-on time ($T_{on}$), and the open-circuit machining Voltage ($V_o$). The productivity of the process is calculated based on the Material Removal Rate and the Tool Wear Ratio. Moreover, the machined Surface Roughness is estimated according to surface Arithmetic Average Roughness (Ra). Finally, for the performance mentioned above, indexes Analysis of Variance (ANOVA) was performed.

2. Materials and Methods

The experiments were carried out on a Roboform 350sp die-sink EDM in the presence of kerosine as a dielectric medium. The selected workpiece material was a 60CrMoV18-5 (Calmax) austenitic tool steel used for injection moulds, dies and cold forming tools with complex shapes. This steel alloy offers excellent flame and induction hardenability (up to 58HRC) and wear resistance, resulting to low tooling costs per produced part. In table 1, the chemical composition of the workpiece material, along with its major thermophysical properties are listed. A copper rectangular electrode with nominal dimensions of 14×20 mm was utilized, and the cutting depth was set to 0.5 mm in order for a fully developed surface to be formed. Copper was chosen as electrode material due to its high electrical and thermal conductivity, its high strength, and the high degree of machining safety. Additionally, and in contrast with graphite or powder-metallurgy electrodes, its cost is significantly lower, render copper an economically viable solution. Prior to the experiments, a number of tests was carried out in order the repeatability of the process to be ensured, along with the necessary consistency of the results. Moreover, the machining time, according to the machining parameters combinations, varied from 15 min up to 7.5 h for each experiment, hence, the obtained data and measurements can be considered representative. The control parameters were the pulse-on current, the pulse-on time and the open-circuit voltage, while the close-circuit voltage, the duty factor and the dielectric flushing pressure were constant. In table 2, the experimental parameters are listed in detail. In the current series of experiments, each control parameter had 4 levels, aiming to a wide range of machining power and per pulse energy to be covered.
In order to limit the number of experiments, the Taguchi DOE method was employed, adopting an L16 orthogonal array design; thus, 16 experiments were conducted in total.

### Table 1. Chemical composition of work piece material Calmax (Uddeholm).

| Typical analysis % | C   | Si  | Mn  | Cr  | Mo  | V  |
|--------------------|-----|-----|-----|-----|-----|----|
|                    | 0.6 | 0.35| 0.8 | 4.5 | 0.5 | 0.2|

| Physical Properties |
|---------------------|
| Density [kg/m³]     | 7770|
| Thermal Conductivity [W/mK] | 27  |
| Specific Heat [J/kgK] at 293K – 473K – 679K | 455 – 525 – 608 |

### Table 2. Experimental parameters.

| Machining Conditions | Level 1 | Level 2 | Level 3 | Level 4 |
|----------------------|---------|---------|---------|---------|
| Discharge current $I_p$ [A] | 5 | 9 | 13 | 17 |
| Pulse on-Time $T_{on}$ [μs] | 12.8 | 25 | 50 | 100 |
| Open circuit voltage $V_o$ [V] | 80 | 120 | 160 | 200 |
| Close circuit voltage $V_c$ [V] | 30 |
| Duty Factor           | 0.5   |
| Dielectric            | Synthetic hydrocarbon fluid |
| Dielectric Flushing   | Side flushing with pressure |
| Dielectric Flushing Pressure [MPa] | 0.7 (Constant under the whole conditions) |

The MRR and TWR were calculated according to eq. 1 and 2, respectively [1]:

$$MRR = \frac{W_{st} - W_{fin}}{t_{mach}} \cdot \frac{1}{\rho_w}$$  \hspace{1cm} (1)

$$TWR = \frac{E_{st} - E_{fin}}{W_{st} - W_{fin}}$$  \hspace{1cm} (2)

with MRR in mm³/min, TWR in gr/gr, $\rho_w$ the workpiece material density in gr/mm³, $t_{mach}$ the machining time in min, $W_{st}$ and $W_{fin}$ the workpiece weight before and after the machining in grams, while $E_{st}$ and $E_{fin}$ the electrode’s weight before and after the machining, respectively, in g. For the samples weighing, a scale with precision of 1mgr was utilized. Finally, the surface roughness was evaluated according to the Ra, which was measured utilizing a Keyence VHX-7000 optical microscope, and based on Focus Variations technology. The digital microscope is equipped with specialized lenses which can reproduce entirely focused images with 20-2000X magnification and according to ISO 4287: 1997. For the specific Ra values the cut-off length was defined at 0.8 mm.

### 3. Results and discussion

In table 3 the experimental results are presented. During EDM, complex physical phenomena are taking place, which also interact with each other, resulting to a non-linear system. Competitive mechanisms occur, and thus, the MRR and TWR do not compulsorily increase for higher machining power and/or per-pulse energy (i.e., higher $I_p$, $T_{on}$ and $V_o$). More specifically, as the plasma channel expands, e.g., for higher pulse-on times, it absorbs and consumes significant amount of energy affecting the process efficiency. Moreover, the decomposed carbon coming from the dielectric fluid, bonds on the electrode's and workpiece's surfaces, forming a shielding layer. This layer protects the electrode from wear, but, at the same time, acts detrimentally for the MRR. The MRR is also negatively affected by the debris concentration between the electrode and the workpiece. These debris, which, from a point and after cannot be efficiently flushed away, consume energy as they re-melt, while they also destabilize the process by causing arcing conditions. This brief theoretical analysis has to be taken into consideration...
in the following analysis of the results.

Table 3. Experimental results.

| # | Ip [A] | Ton [μs] | Vo [V] | MRR [mm³/min] | TWR | Ra [μm] |
|---|---|---|---|---|---|---|
| 1 | 5 | 12.8 | 80 | 0.34 | 0.354 | 1.37 |
| 2 | 5 | 25 | 120 | 0.95 | 0.448 | 2.56 |
| 3 | 5 | 50 | 160 | 0.43 | 0.033 | 2.25 |
| 4 | 5 | 100 | 200 | 0.30 | 0.022 | 2.56 |
| 5 | 9 | 12.8 | 120 | 1.29 | 0.189 | 2.33 |
| 6 | 9 | 25 | 80 | 0.75 | 0.267 | 2.39 |
| 7 | 9 | 50 | 200 | 1.03 | 0.071 | 2.28 |
| 8 | 9 | 100 | 160 | 0.72 | 0.065 | 2.93 |
| 9 | 13 | 12.8 | 160 | 5.42 | 0.342 | 3.59 |
| 10 | 13 | 25 | 200 | 3.93 | 0.1 | 3.77 |
| 11 | 13 | 50 | 80 | 5.52 | 0.068 | 4.75 |
| 12 | 13 | 100 | 120 | 4.35 | 0.031 | 4.67 |
| 13 | 17 | 12.8 | 200 | 7.03 | 0.331 | 2.69 |
| 14 | 17 | 25 | 160 | 5.51 | 0.215 | 3.22 |
| 15 | 17 | 50 | 120 | 7.98 | 0.1 | 6.13 |
| 16 | 17 | 100 | 80 | 4.03 | 0.103 | 5.63 |

In figure 1, the Main Effects Plot and the Interaction Plot for MRR are presented. From the Main Effects Plot it can be deduced that the pulse-on current significantly affect the MRR, with its increase, leading to higher mean MRR. Namely, as the Ip increases from 5 to 17A the mean MRR increases approximately by 1126%. On the contrary the pulse-on time and the open circuit voltage have a fuzzy effect on MRR. For a more in-depth analysis, the Interaction Plot has to be studied. It is observed that for 5 and 9A all combinations of Tons and Voc result to almost the same MRR, and a significant deviation is occurred for pulse-on currents of 13 and 17A. This differentiation between low and high machining conditions is also noticed in the open-circuit voltage, where the 80 and 120V have similar trends, as also the 160 and 200V. Hence, it is concluded that in the machining of Calmax with EDM the combination of the process parameters is of major importance, while, at the same time, low and high machining power and per-pulse energy follow dissimilar patterns and have different responses.

The TWR, by its definition, consists of the percentage comparison of the electrode and workpiece wear. Thus, it is directly related to the machining efficiency and the process' economic feasibility and
viability. In figure 2, the Main Effects Plot and the Interaction Plot for TWR are presented. Unlike MRR, TWR is mainly affected by the pulse-on time, while the pulse-on current and the open-circuit voltage have a vague impact on it. Namely, as the Ton increased from 12.8 to 100 μs, the TWR decreased approximately by 81.9%. Considering that the Ton had a fuzzy effect on the MRR, the reduction of TWR can be reasonably attributed to the lower relative electrode wear, which renders the process more effective and efficient. By analysing the interaction plot, some interesting conclusions can be also deduced. Firstly, for pulse-on times 50 and 100 μs, the TWR for all machining parameters combinations is almost the same, regardless the employed pulse-on current or the open-circuit voltage. Moreover, it has to pointed out that those machining combinations that result to similar MRR, may have a significantly different TWR. More specifically, in experiments 9 and 11 the MRR is approximately 5.5 mm3/min while their TWR is 0.342 and 0.068, respectively. This indicates the importance of selecting the optimal process' conditions during the machining planning to achieve not only a high MRR but also low electrode wear.

The SR also depends on the machining conditions. The plasma channel and the subsequent removal of the molten material, form tiny craters with different geometrical characteristics depending on the utilized machining parameters. As a general rule of thumb, it can be said that increased pulse-on current, results to deeper craters, while higher pulse-on time mainly affects craters' width. Nevertheless, it has to be taken into consideration that the total material removal is the accumulative result of successive sparks and therefore the obtained roughness is resulted by the superposition of successive craters. Simultaneously, during the process, molten material that has not been removed may flow and re-solidify, affecting the surface roughness. Hence, and considering the process' chaotic nature, any result regarding the Ra has to be carefully deduced.

In figure 3, the Main Effect Plot and the Interaction Plot for Ra are presented. From the Main Effect Plot, it can be concluded that the increase in pulse-on current results to higher mean Ra, while when higher open-circuit voltage is utilized, the mean value of Ra is decreased. As the Ip is increased from 5 to 13 A, the mean Ra is increased by 91.86%. Intentionally, the 17 A are not included in this comparison, since, according to the Interaction Plot, for 17 A, the Ra has a significant deviation between low and high values, thus, the mean value that is presented in Main Effect Plot is not representative. Similarly, for low Vo, i.e., 80 and 120 V, high deviation in Ra is observed, while, for the high open-circuit voltages, i.e., 160 and 200 V, the Ra values converge and become lower. Finally, the Ton uncertainly impacts the SR and depending on the employed Vo and Ip. Especially for the higher pulse-on times, i.e., 50 and 100 μs, a clear differentiation between the low and high values of Ip and Vo respectively, can be noticed, forming "groups", each of which follows a different trend and pattern. It can be said, in conclusion, that up to 13 A increase in pulse-on current, almost certainly leads to higher Ra, while the high open-circuit voltage acts beneficially regarding the Ra.
As has been aforementioned, only a proportion of the melted material is removed from the surface. Simultaneously, the rest of it, is re-solidified, forming an amorphous layer, well known as White Layer. The surface's morphological characteristics are directly related to the machining parameters and the efficiency of the molten material flushing. In figure 4, SEM images of the machined surfaces are presented, where typical characteristics can be observed, along with some major differences, according to the employed machining conditions. In figure 4(a), where lower machining power and per-pulse energy has been utilized (I_p 5 A, T_on 12.8 µs, and V_o 80 V), the surface is relatively smooth, while islets of multiple layered remelted material have been formed. Moreover, a significant proportion of the surface is covered with pockmarks, which can be considered as micro-porosity, a characteristic that impacts material's erosion resistance. For the more intense machining conditions (i.e., I_p 17 A, T_on 100 µs and V_o 80 V - figure 4(b)), the surface seems rougher, a conclusion that is totally in line with the Ra values; Ra values are 1.37 and 5.63 µm, respectively. The pockmarks and the microporosity are now more intense, while, along with the multiple layers of re-solidified material, debris depositions are also existing. These depositions are spheroidal and most likely come from ablated material that remained close to the surface and then is rapidly cooled down and subsequently re-attached on the machined surface. Finally, the absence of cracks has to be pointed out, a characteristic that is favourable for material's mechanical properties and erosion resistance. The surface cracks, which are commonly developed after EDM, are resulted from high gradients in temperature and pressure. Hence, it is of major interest and importance that the Calmax surface seems resistant to cracking after the machining with EDM.

Figure 4. SEM images of the machined surfaces for a) I_p 5 A T_on 12.8 µs and V_o 80 V and b) I_p 17 A T_on 100 µs and V_o 80 V.
4. Conclusions

In the current paper, an experimental study of machining Calmax steel with EDM has been presented. Although Calmax steel is utilized in numerous applications, only limited experimental investigation has been carried out regarding its machining with EDM. The current study, by covering a wide range of machining parameters, aims, not only to be scientifically interesting, but also to have a practical value as well. The control parameters were the pulse-on current, the pulse-on time and the open-circuit voltage, while the machining performances were estimated in terms of MRR, TWR and Ra. The experiments were conducted based on Taguchi DOE. For the performance mentioned above, indexes ANOVA was performed to determine the control parameters’ impact on the machining results. From the current study it was deduced that:

- The pulse-on current is the parameter that majorly affects the MRR, while the pulse-on time and the open-circuit voltage have a vaguer impact on MRR.
- On the contrary with MRR, the TWR is mainly affected by the pulse-on time, while for high Tons the TWR was almost constant. The stabilization of TWR for high pulse-on times is of major importance in the process planning, in order to become economically viable.
- The Ra is mainly affected by the pulse-on current, whilst, for 17 A, a significant deviation on Ra values observed depending on the machining parameters combination.
- By SEM microscopy, typical characteristics of EDMed surfaces were observed, like islets of remelted material and re-depositions, pockmarks, and micro-porosity. In comparison with other steel alloys, Calmax surfaces were almost free of cracks.

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