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Fundamental Analysis of High Frequent Electrical Process Signals for Advanced Technology Developments in W-EDM

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Abstract

Technology development in EDM is very time consuming especially for the application of new materials or in the case of unfavorable machining conditions. Due to the large number of influencing factors and their interdependencies it is not possible to predict the machining conditions only by interpretation of the used generator parameters. Therefore it is difficult to link the machining results directly to the parameter setting. As a consequence a large number of test series are typically performed in a trial and error approach to find the ideal set of parameters for each machining task. But in this case the resulting technology is limited to the machining of the same material, geometry and the used machine tool.
For an intelligent model based technology development the direct influence of the generator parameters on the actual process conditions need to be identified. In this paper the actual physical values for current and voltage as well as pulse on- and off-time of each discharge is determined by monitoring the electrical process signals. By tracking these values over time the quality of the whole process is evaluated by determination of the actual discharge frequency, the percentage of misdischarges and the resulting duty cycle. These parameters are then linked to the output variables cutting rate and surface roughness. Using this approach the specific influence of the machined material as well as other special machining conditions on the EDM process can be identified. With this fundamental knowledge the needed test series for future developments can be reduced and the transferability of the resulting technology will be improved significantly.

Keywords:EDM; Wire-EDM; Monitoring

1. Introduction

Due to the contact free and virtually force free characteristics EDM is a powerful alternative for the machining of very hard and temperature resisting materials. The development of machine tools especially in terms of generator technology in the recent years has boosted the competitiveness of EDM further.

By implementing up to date power electronic components the effectiveness of Wire-EDM (W-EDM) was improved significantly. Using these devices high current signals can be handled with high frequency to create discharge pulses between 50 and 2000 ns with a peak current of up to 1 kA [1]. Since the material removal ratio between the cathode and anode is time dependent these pulses have a significantly reduced tool wear ratio [2]. Consequently more electric power can be induced into the process without causing a wire breakage, which is the main restriction of W-EDM.

Local wear phenomena are the main reason for wire breakage demonstrating the need for a fast and adaptive process control of the machine tool. Therefore another main advantage of the power electronic components is the capability to alter the discharge form according to the process condition in a very short manner. Thus process instabilities can be detected by monitoring the discharge delay time which showed to be more efficient compared to the mean gap voltage which is mainly used to control the feed rate of the wire [3]. By adapting the generator parameters to suite only temporarily occurring unfortunate gap conditions the overall stability of the process can be increased and wire breakage avoided

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without having to reduce the discharge energy over the whole process.

Due to the complexity the control is mostly limited to a reduction of discharge energy in case of a temporary instability and not for optimization purposes. For a maximum in material removal rate, which is the main goal of the main cut, the parameters of the generator as well as the parameters of the control still need to be optimized.

Despite decades of research in EDM technology development for new materials or special geometries is still very time consuming and therefore expensive. Due to the complex physical events and their dynamic nature there is still no holistic model of the continuous EDM process. The formation of each discharge is significantly dependent on the characteristics of each component of the discharge circuit including the thermo-physical properties of the electrode materials and the gap condition [4]. The dielectric strength is dependent on the electric properties of the used dielectric but is also influenced to a great extent by discharge particles, the degree of ionization and the aggregation state of the dielectric. Besides the discharge itself especially the interval time as well as the flushing parameters and conditions influence the amount of debris inside the gap. Every discharge is therefore influenced by the previous set of discharges concerning its location, electrical properties as well as the resulting thermal impact. Since every input parameter has a direct or indirect influence on the gap condition the resulting EDM process is always the sum of all parameters and influences. A technology optimized for cutting speed is typically very sensitive to small changes and only effective for a single material combination, geometry and machine tool setting. As a result technologies are significantly different for every machining height, wire material and especially different machine tool suppliers.

Due to the large number of influences the resulting discharge characteristics cannot be predicted from the chosen generator parameters alone, especially if these are adjusted during machining by the above mentioned process control. Therefore it is not possible to link the machining results directly to the technology parameters. As a result the machining process is mostly analyzed with a statistical approach. But due to the complex interdependencies of the input variables the number of needed experiments for a significant result is very high.

In this paper the actual current and voltage signals are analyzed to determine the influence of each input parameter. Process parameters are defined and monitored to characterize the actual machining conditions as an approach for a model based advanced technology development for EDM.

2. Experimental Setup

In this paper all experiments were conducted on a Sodick AQ537L W-EDM machine tool with up to date generator technology and linear drives. The current and voltage signals of the machining process were recorded using a Tektronix digital oscilloscope DPO 7104 C which has a bandwidth of 1 GHz and a sampling rate of up to 10 GS/s using three channels. To minimize the interference of the measurement setup on the high frequent electrical signals the current was measured directly at the contact points between the generator and the machining table using 2 contactless current clamps with a bandwidth of 15 MHz (Tektronix TCP 305A). The signals of the two probes were added by the oscilloscope. The according voltage signal between the wire electrode and the machining table was measured using a differential probe with a bandwidth of 50 MHz (Tektronix P5200A).

Due to the very short duration of the analyzed discharges between 0.5 and 2 µs a sample rate of 50 MS/s was used to ensure a correct reproduction of the discharge characteristics. For each experiment the signals were recorded for 20 ms at three different time slots distributed at random during the machining process. Due to a typical cycle time of the used machine tool in the range of 10 µs up to 2000 discharges are possible per recording. For the analysis of each discharge an algorithm was implemented using the Labview platform. By this algorithm each discharge is characterized by the duration of the different phases of the discharge, as shown in Figure 1. The voltage offset is caused in this case by the Sodick anti-electrolysis generator. Apart from the discharge duration the electrical energy of each discharge was determined by calculating the integral of the product of current and voltage.

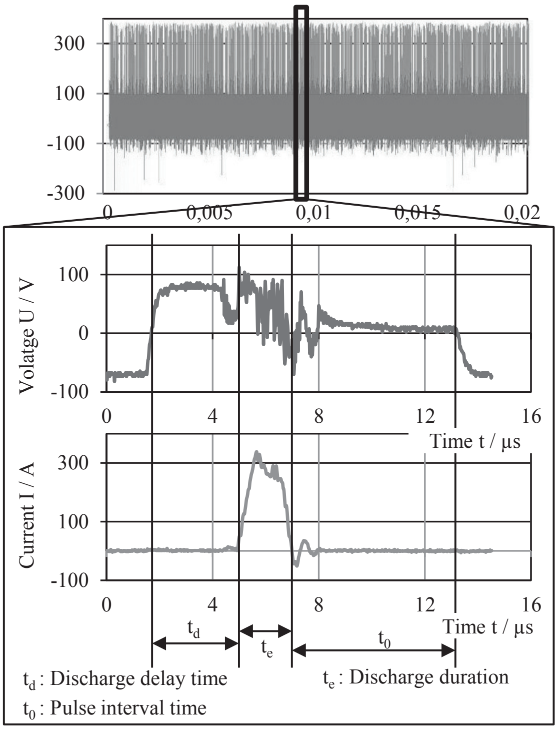

Figure 1: Extraction of a single discharge and assignment of parameters

To ensure that the change of process characteristics are caused by the change in generator parameters, only experiments with constant machining conditions were considered. As workpiece material the tool steel HS6-5-3 and the magnesium alloy AZ91 were compared due to their significantly different thermo-physical properties, as summarized in Table 1. For the sake of clarity the influence of the generator parameters on the process conditions will only be shown for one material at first.

Table 1: Excerpt of the physical properties of AZ91 and HS6-5-3

Material	Density ρ (g/cm³)	Electrical resistance ρ_s (Ωmm²/m)	Melting temperature T_m (°C)	Thermal conductivity λ (W/mK)
HS6-5-3	8	0.54	1400	19 - 28
AZ91	1.81	0.143	470 - 595	51

As basis for the experiments a standard technology for the machining of steel was chosen which was provided by the machine tool supplier Sodick (Table 2). All experiments were performed under constant flushing conditions. In case of the Sodick specific technology table no physical representation or precise definition is given to indicate the meaning of these parameters which further demonstrates the incomparableness of different machine tools.

Table 2: Excerpt of the steel technology for a workpiece height of 40 mm [5]

ON	OFF	IP	MAO	SV	V	WK	WT	WS	WP
16	13	2215	327	30	8	25	130	150	63

ON: Pulse Duration
MAO: Process control parameter
OFF: Pulse interval time
IP: Maximum discharge current
V: Open circuit voltage
SV: Servo reference voltage
WK: Wire properties
WP: Water pressure
WT: Wire tension
WS: Wire speed

3. Analysis of the process signals

A first analysis of the recorded data showed that observed discharges can be divided into two main categories. The two types of discharges differ in the discharge duration and consequently in the resulting electrical energy, as seen in Figure 2. Due to the very small deviation of the two discharge forms the separation is clear. It can be assumed that long discharge times are desired and the process control only reduces the time in case of poor gap conditions. In the following the desired forms will be referred to as normal discharges and the short discharge form as misdischarges.

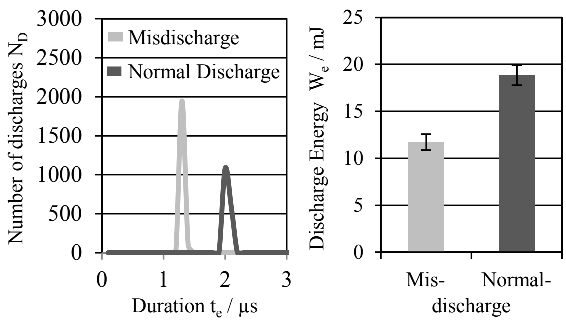

Figure 2: Differentiation between normal- and misdischarges

Furthermore the analysis showed that due to the multiple influences and their interdependencies two different parameter settings can lead to the same cutting rate as shown in Figure 3.

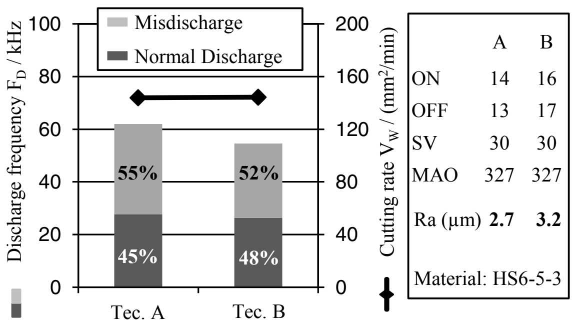

Figure 3: Comparison of two technologies leading to the same cutting rate

A first conclusion which can be derived by the simple count of discharges is that the discharge frequency is significantly lower than the maximum of about 100 kHz. It can therefore be assumed that the difference in discharge frequency, as well as a different ratio of normal- to misdischarges and their difference in electrical energy is the cause of the identical cutting rate. Evidence for the different discharge energies is also a different mean surface roughness which stresses the need for a more detailed analysis of the actual process conditions for an effective model based technology development. In the following the main discharge parameters are varied to investigate their influence on the actual process conditions. In a first step the parameters ON, OFF and SV will be linked to actual physical quantities.

3.1. Variation of the main discharge variables ON and OFF

The analysis of the data shows that a change from 10 to 16 of the ON-parameter represents an increase of the mean duration of the normal discharge from 0.7 µs to 2 µs resulting in an increase of electrical energy of 15 mJ in total, as seen in Figure 4.

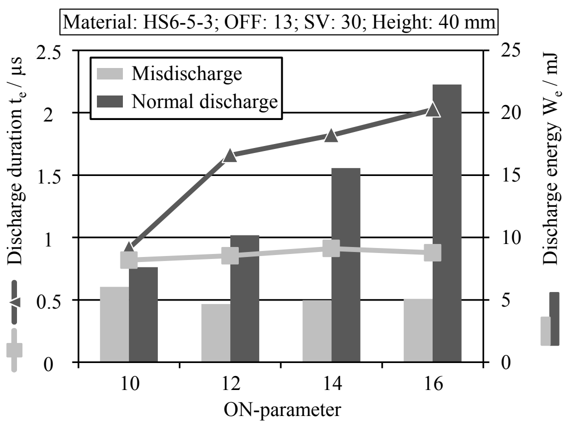

Figure 4: Resulting Discharge duration and electrical energy after variation of the ON-parameter

In contrast to the normal discharges the characteristics of the misdischarges are almost unchanged. The values seem reliable due to a standard deviation of all values below 2%.

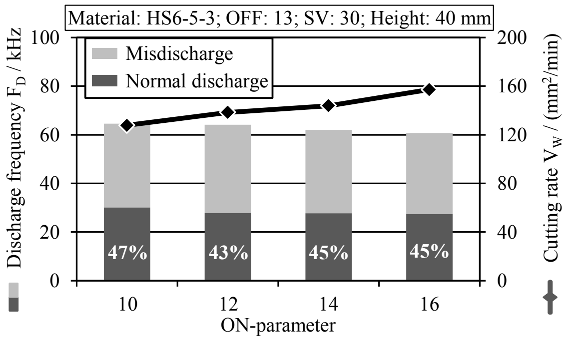

Figure 5: Influence of the ON-parameter on the discharge frequency and the cutting rate

The influence of the ON-parameter on the process conditions is shown in Figure 5. Due to the extended discharge duration the discharge frequency of the normal discharges as well as the misdischarges decreases. This trend is not a direct consequence of the extended cycle time since the overall discharge frequency is significantly lower compared to the maximum achievable frequency as stated above. The percentage of normal discharges decreases only marginal demonstrating that there is room for improvement, due to the fact that for stability reasons only a moderate SV-parameter of 30 was chosen as reference value for the feed rate of the wire axis. In case of ON = 12 in which the percentage drops noticeable the misdischarges almost evens the decrease of the overall discharge frequency. The observed process condition is therefore a resulting equilibrium between the effectiveness in material removal of the discharges, the resulting gap condition and the set SV-parameter.

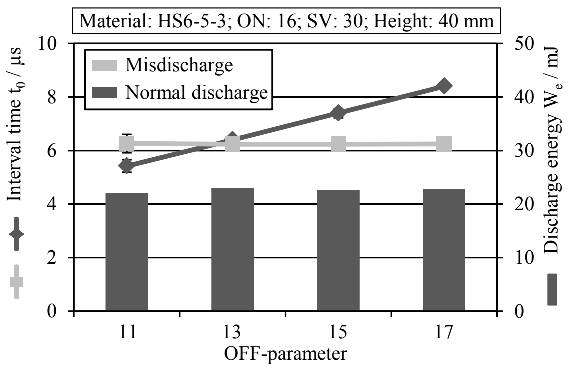

Figure 6: Resulting pulse interval time and electrical energy after variation of the OFF-parameter

The decrease in percentage of normal discharges can be explained by the higher concentration of debris inside the gap due to the increase of discharge energy. In total the extended effective discharge duration leads to an increase in cutting rate although the overall discharge frequency decreases. The observed increase in cutting rate despite the constant SV-parameter can be explained by the small ratio of the discharge time compared to the cycle time. Since the interval time is constant the reduction of discharge frequency combined with an increase in energy for the normal discharges results in a higher cutting rate.

The effect of a variation of the discharge interval time is shown in Figure 6. Similar to the variation of the ON-parameter only the interval time of the normal discharge change when the OFF-parameter is varied. If small values are chosen even smaller pulse interval times can be reached compared to the misdischarges. Since the interval time does not influence the actual discharge form the energy remains unchanged.

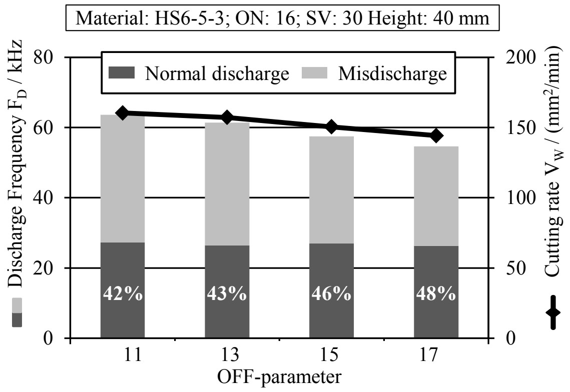

Figure 7: Influence of the OFF-parameter on the discharge frequency and the cutting rate

By extending the discharge interval time the cycle time is increased and consequently the discharge frequency is reduced, as seen in Figure 7. Due to the improved gap conditions the percentage of normal discharges increases until the equilibrium according to the set SV-parameter is reached. Better flushing conditions accompanied with an extended pulse interval time and a lower discharge frequency lead to an increased percentage of normal discharges. Since the overall discharge time is reduced despite the higher percentage of normal discharges the cutting rate decreases accordingly. It becomes obvious that a higher percentage of normal discharges dos not necessarily lead to a higher cutting rate.

3.2. Variation of the servo reference value SV

The SV-parameter is a reference value which is compared to the overall mean voltage of the process. The mean voltage is high if the open circuit voltage is reached often and a voltage drop resulting from a discharge is seldom. The desired value of the mean voltage is reached by variation of the feed rate of the wire axis to reach the above mentioned equilibrium. A decrease of this value therefore aims for a more aggressive technology setting by minimizing the time in which the open circuit voltage is reached, increasing the actual erosion time and decreasing the pulse interval time respectively. The course of the mean voltage for different SV-parameters is shown in Figure 8.

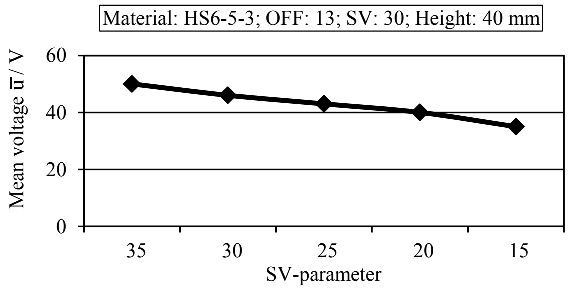

Figure 8: Measured mean voltage for different SV-parameters

A reduction of the SV-parameter has a direct influence on the discharge frequency because the time in which the gap is too wide for a discharge is reduced by a faster movement of the wire axis. A consequence of a higher discharge frequency is a higher concentration of debris in the discharge gap leading to an increase of misdischarges rather than normal discharges, as described in Figure 9. Despite the reduced percentage of normal discharges the cutting rate increases almost linear. Partly this is due to the fact that only stable machining conditions were investigated. Further reduction of the SV-parameter led to a decrease of cutting rate mostly because of instabilities which could not be handled by the process control anymore and finally led to a wire breakage.

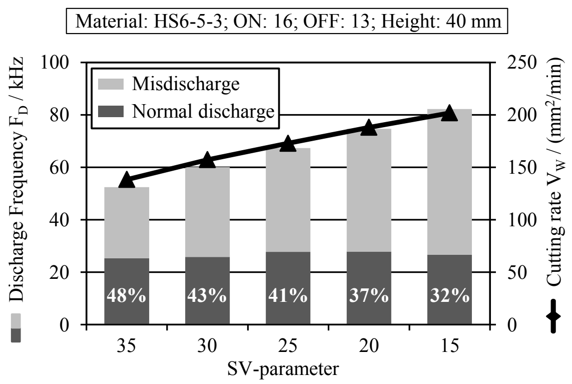

Figure 9: Influence of the OFF-parameter on the discharge frequency and the cutting rate

3.3. Variation of the MAO parameter of the process control

Since the resulting machining condition of the parameter setting is a result of normal and misdischarges the parameter of the process control will be analyzed in the following. The MAO parameter is actually a combination of three parameters. Parameter M is a reference value for the detection of instabilities. In case of a detected instability the A-parameter extends the pulse interval time and parameter O shortens the discharge duration. The analyzed data suggest that the process control distinguishes stable and instable gap conditions according to the discharge delay time. In Figure 10 the course of the maximum t_d time of the misdischarges as well as the minimum t_d time for the normal discharges is shown depending on the chosen M-parameter.

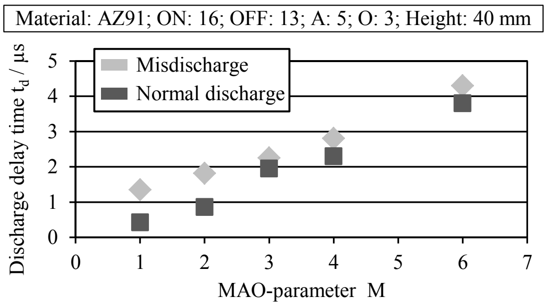

Figure 10: Maximum t_d time of normal discharges and minimum t_d for midischarges for different M-parameters

With increasing M-parameter the discharge duration for a higher number of discharges is reduced leading to a more stable process while decreasing the cutting rate despite an increase in discharge frequency.

Very similar to the ON- and OFF-parameter for the normal discharges the characteristics of the misdischarges can be selected by variation of the value for A and O of the MAO-parameter, as seen in Figure 11. With these parameters again a compromise between stability and material removal needs to be found for an optimum of cutting rate.

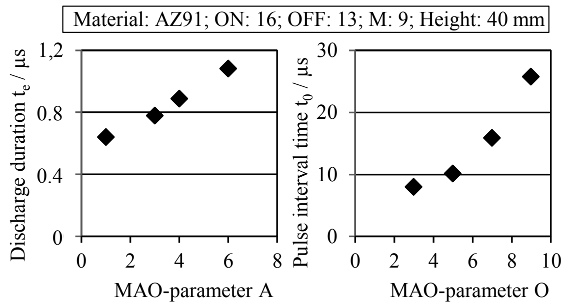

Figure 11: Variation of the parameters A and O

3.4. Evaluation of the process conditions

An outcome of the analysis is that the characteristics of both discharge categories can be selected by choice of the generator parameters and the process control parameter MAO precisely and separately. Due to the opposing trends a change of each parameter in combination with the complex interdependencies between material removal per discharge, frequency and stability it is very difficult to find a global optimum for the cutting rate. Therefore criteria need to be found to rate the quality of a process and to provide a goal for the technology development.

In Figure 12 the set duty cycle is compared to the resulting cutting rate. As expected a higher duty cycle has the tendency to lead to a higher cutting rate but not necessarily to the highest value. This again can be explained by the percentage of normal and abnormal discharges as well as the actual discharge frequency that is reached. It can also be seen that certain duty cycles lead to a wire breakage while higher values still lead to a stable process.

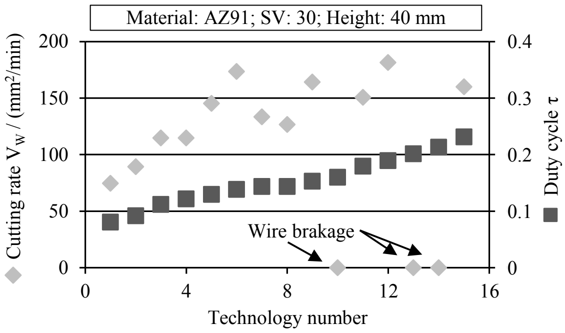

Figure 12: Comparison of cutting rate and the actual duty cycle

Therefore the actual discharge frequency and the discharge duration of each discharge need to be considered. These values combined in the induced electrical energy per minute showed a high resemblance to the resulting cutting rate with a deviation of the proportionality factor below 6%.

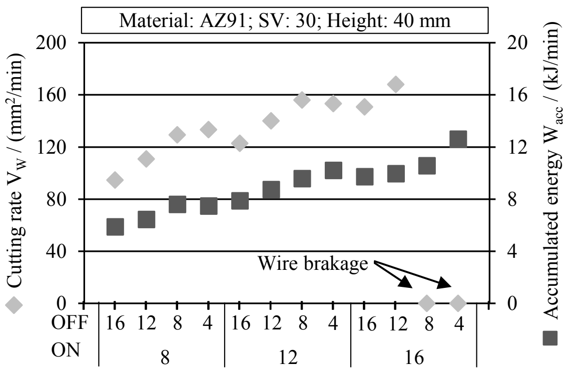

Figure 13: Comparison of cutting rate and the accumulated electrical energy per minute

One consequence of the observed relationship is that the needed discharge energy to remove a certain volume of material is constant under the given boundary conditions. In the case of Magnesium about 52 J are necessary to cut 1 mm^2 using the Sodick W-EDM machine tool. In contrast to this 382 J are necessary to cut the same amount of HS6-5-3, which is about 7 times higher. This fact is an explanation for the significant difference in maximum cutting rate which could be achieved by the performed technology development shown in Figure 14. Despite the lower discharge frequency resulting in almost half the discharge energy the cutting rate is almost 4 times higher for the machining of the magnesium alloy.

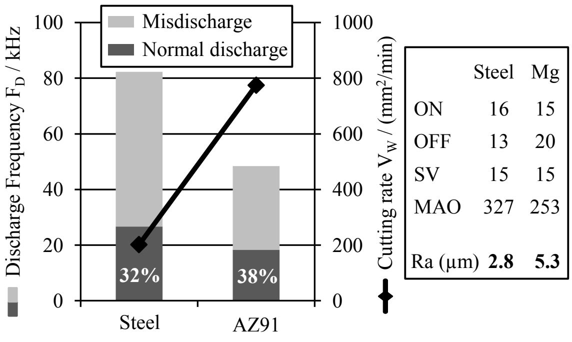

Figure 14: Optimized technologies for steel and magnesium

Very interesting is the fact that the energy input of 40 kJ/min in this case is much higher compared to 8 kJ/min which can already lead to a wire breakage as seen in Figure 13. Therefore not only the mean energy brought into the process but especially a local concentration of discharges needs to be prevented. The goal for the technology development should therefore be to maximize volume as well as the distribution of the discharge energy over time.

4. Summary and Outlook

It could be shown that it is not possible to explain the actual process conditions in W-EDM by looking at the input parameters alone. Every parameter variation leads to opposing trends between the discharge energy of the single discharge and the actual discharge frequency resulting in an unpredictable equilibrium according to the SV-parameter. The finding of a global maximum is difficult due to infinite local maxima and unfavorable parameter combinations leading to wire breakage below the achievable cutting rate.

Using the presented process analysis tool every process condition can be explained, rated and linked to the input parameters including the workpiece material. The presented work can therefore provide the basis for an intelligent model based technology development.

In the future the algorithm will be implemented using a FPGA module to enable a real time process monitoring tool to analyze any process including unstable conditions.

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