MACHINABILITY ASSESSMENT IN ELECTROEROSION DISSOLUTION MACHINING

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ABSTRACT

This paper describes the metal removal process in the combined thermal-electrochemical machining, EEDM, of some materials and alloys. It introduces indices that evaluate their machinability in terms of the rate of material removal, energy utilization and, surface roughness. The interaction between the machinability indices and the working gap impedance, melting point and thermal conductivity is made clear.

Keywords: Machinability, Surface roughness, Power utilization factor, Gap impedance, Thermal conductivity, Melting point.

Nomenclature

Vcc	Open circuit voltage, volt.
Vg	Gap voltage, volt.
Ig	Machining current, A.
Rb	Generator resistance, Ω.
Zg	Gap impedance, Ω.
Pg	Gap power, Watt.
Ra	Surface roughness, μm.
Ei	Energy utilization index, mm^3/j.
RR	Removal rate, mm^3/min.
RPP	Removal/pulse, mm^3.
RRi	Removal rate index, %.
Rai	Roughness index, %.
f	Cutting rate, mm/min.

INTRODUCTION

The process of EEDM is a new development that combines the features of electrochemical machining ECM and electrodischarge machining EDM. Such a combination produces high cutting rates as much as 20 times of that obtainable in ECM and EDM [1]. The produced surface quality is much improved if compared to EDM and the surface layer that produced by the thermal effects is removed by the smoothening dissolution mechanism. In EDM, El-Hofy and Khairy [2] postulated that the heat affected layer reaches 5 μm. Therefore, trim cut or abrasive polishing is necessary for simultaneous improvement in precision and surface finish [3]. EEDM can be activated by applying a pulsed voltage between two electrodes separated by an inter electrode gap that is filled with electrolyte. In some cases, electrode vibration is introduced to assist flushing away the machining products that accumulate in the inter electrode gap due to the dissolution of the anodic workpiece and erosion of the tool and workpiece. The prospects of machinability of metals and alloys are well understood for the traditional machining processes. Attempts have been made for theoretical prediction of the machinability in wire EDM [4]. In a further work Levy and Maggi [5] evaluated the machinability of the different steel grades during wire EDM. Moreover, the work of Khairy [6] mainly dealt with introducing a machinability system for ECM while reference [7] derived machinability indices for some of the thermal, and electrochemical machining processes. No such analysis is made yet for the combined thermal-electrochemical machining process This paper describes the machinability of some metals and alloys under the action of the combined thermal-electrochemical mechanisms. New indices suitable for this particular process have been expressed for a wide range of industrial materials. Graphite that is extensively used for EDM electrode manufacture, heat resisting alloys, light weight aluminum alloys and some steels have been selected. The choice of these materials has been made in order to compare the traditional EDM-materials such as steels and aluminum with the non-metallic EDM-material such as graphite. Experiments have been designed to quantify the reaction of the different materials when they are machined by the combined EEDM process. The mechanism of metal removal has been also explained using statistical analysis of variance and linear regression models.

EXPERIMENTAL PROCEDURE

Linear cuts were achieved in 6 mm thick plates at different speeds of 0.9, 1.5, 2.1 and 2.7 mm/min. $NaNO_3$ electrolyte of 200 g/l and 0.25 mm wire were used. Metal removal rate, energy consumed and surface roughness were evaluated in order to determine the machinability of the tested materials and alloys.

RESULTS AND DISCUSSIONS

Figure (1) shows a schematic diagram for the electrical elements of the machining process in terms of the gap impedance Zg and the binary resistance of the generator circuit, Rb. Given the open circuit voltage, Vcc, both the machining current, Ig, and voltage, Vg, can be calculated using the following equations:-

$$Ig = \frac{Vcc}{Rb + Zg} \tag{1}$$

$$Vg = \frac{Zg\,Vcc}{Rb + Zg} \tag{2}$$

Hence the gap power Pg,

$$Pg = \frac{Zg\,Vcc^2}{(Rb + Zg)^2} \tag{3}$$

For the given values of Vcc and Rb the machining current depends on the magnitude of the gap impedance. The gap impedance reflects the instantaneous condition of the inter electrode gap such as gap width, electrode vibration, electrolyte contamination level, flow rate, and other dynamic properties. The presence of machining products such as debris and solidified metal particles play a major role in determining the gap impedance. Figure (2) shows the increase of machining current as the gap impedance decreases. The same figure also displays the relationship between the gap impedance and gap voltage. It should be mentioned here that the gap impedance reflects the type, duration and intensity of the machining phases occurring in the inter electrode gap. Low impedance enhances the erosion process and consequently produces high removal rate RR through the intensified arcs that are normally associated with high instantaneous current as well as reduced gap voltage. Regarding the relationship between gap impedance and the size of the machining gap in EEDM, it is clear that the gap impedance decreases at small gap sizes. Such an observation has been reflected on the machining current and hence the current density. The effects of both the cutting rate and work material, on the current density, Tables (1-2), are highly significant. Due to the increase of current and the decrease of voltage, Figure (2), the machining power has a maximum value at certain gap impedance.

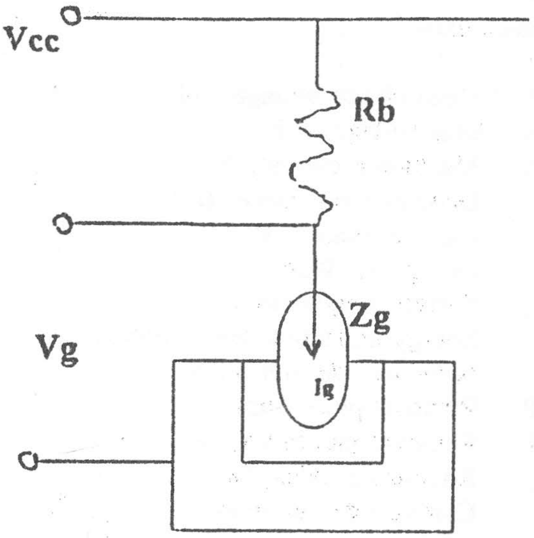

Figure 1. Equivalent generator and gap circuit during on-time.

For the tests conducted at different rates and, the family of materials under consideration, analysis of variance have shown that the gap impedance is more significantly affected by the cutting rate than the work material, Table (1). This observation has been confirmed using the results of Table (2) which indicates that the change in gap impedance when testing both inco 901 and stainless steel 316 was insignificant.

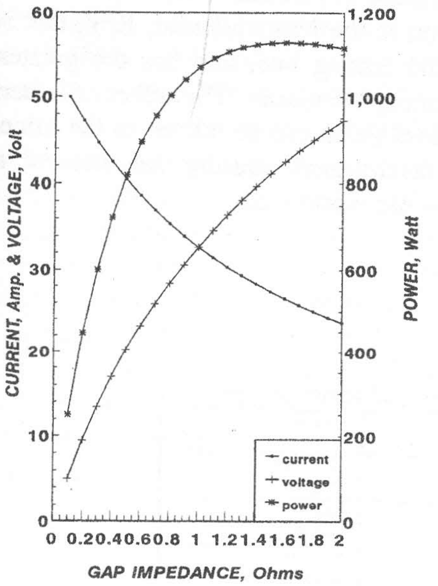

Figure 2. Effect of gap impedance on machining voltage, current and power.

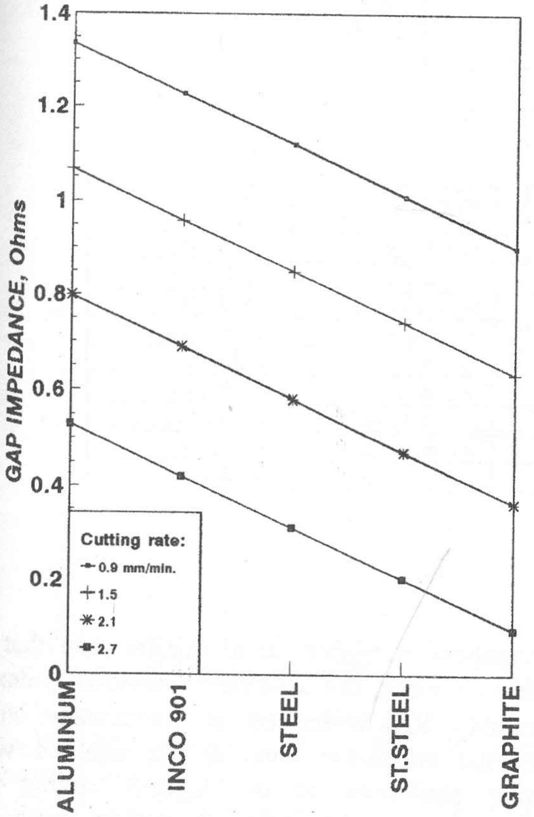

Figure 3. Effect of work material and cutting rate on gap impedance.

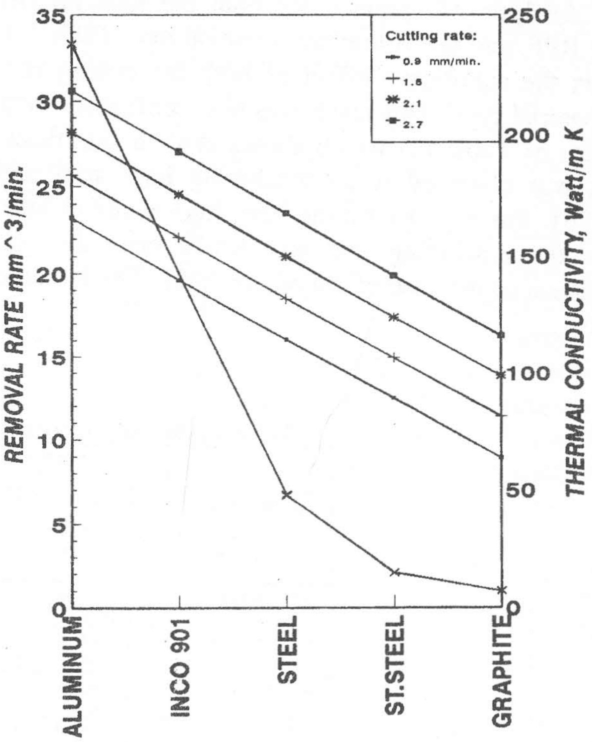

Figure 4. Effect of work material and cutting rate on the volumetric removal rate.

The gap impedance has also been found to decrease, significantly, the percentage of arcs, the current density whilst increases the percentage of open circuit pulses, sparks and the break down voltage. It should be noted from Table (2) that for the group of steels experimented, there was no significant effect on both the intensity of arcing and sparking occurring in the inter electrode gap. However a significant effect was clear among the other materials such as aluminum and graphite. Figure (3) shows the decrease of the gap impedance, Zg, with the machining rate, f, due to the reduced size of the inter electrode gap. Additionally, for a given cutting rate the gap impedance has the highest level when machining aluminum and a minimum level when cutting graphite.

MACHINABILITY INDICES

Material Removal Index:

Regarding the rate of material removal, RR, tests show the decrease of removal rate from aluminum towards graphite while it increases at greater cutting rates. Analysis of variance for both the removal per pulse, RPP, and the volumetric removal rate, Table (1), reflects the significant effect of both the cutting rate and material type. This result was also confirmed using the data of Table (2) which shows that no significant effect was observed when machining both steel and inco 901. For a given cutting rate, high removal rates widen the machining gap and hence raise the gap impedance as the case of aluminum 2017. The increase of the removal rate, Figure (4) can be explained using the results of Figure (5) because the removal rate has a direct relation to the removal/pulse, RPP, that becomes high with the cutting rate, and has the greatest value when machining aluminum. The effect of material type on the removal/pulse can be related to the principles of the major mechanisms causing the material removal from the anodic workpiece.

Table 1 Analysis of variance for the feed rate and material type

	Degrees of freedom	Mean square	F value
Current density	material 4 feed 3	146.14 88.77	14.11 ** 11.43 **
Gap impedance	material 4 feed 3	0.34 0.72	3.82 ** 8.15 **
Removal rate	material 4 feed 3	104.52 37.82	95.25 ** 34.47 **
Removal/pulse	material 4 feed 3	0.09 0.04	50.57 ** 24.18 **
ECD ratio	material 4 feed 3	2395.31 423.72	23.0 ** 4.07 *
EDE ratio	material 4 feed 3	2388.4 417.97	23.37 ** 4.09 *
Energy factor	material 4 feed 3	0.020 0.016	12.10 ** 9.63 **

Table 2 Effect of material type on the process characteristics

	ALUMINUM	INCO	STEEL	ST. STEEL	GRAPHITE
Current density	16.51 ±01.29 a	18.875 ±.03 ac	12.54 ± 1.24 b	19.41 ±2.28 dc	21.02 ± 0.75dc
Gap impedance	00.94 ±00.15 a	0.55 ± 0.08 ac	1.11 ± 0.33 ad	0.61 ± 0.17 ac	0.23 ± 0.02 bc
Removal rate	27.41 ±01.85 a	21.35 ± 0.98 b	21.57 ± 1.44b	16.43 ± 1.65 c	11.20 ± 2.71 d
Removal/pulse	00.82 ±00.03 a	0.67 ± 0.04 b	0.66 ±0.05 b	0.52 ± 0.07 c	0.34 ± 0.08 d
ECD ratio	55.00 ±03.00 a	61.00 ±3.00 ae	34 .0 ± 10.0 b	76 .0 ± 8.0 ce	0.0 ± 0.0 d
EDE ratio	45.00 ±03.00 a	39.0 ± 3.00 a	66.0 ± 10.0 b	24.0 ± 8.0 c	100 ± 0.0 d
Arc ratio	85.00 ±13.60 a	68.0 ± 13.0 ab	64 .0 ± 22.5 ab	67.0 ± 18.0 ab	100.0 ± 1.0 ac
Spark ratio	12.50 ±11.00 a	26 .0 ± 15.0 ab	24.0 ± 14..0 ab	26.6 ± 18.0 ab	0.0 ± 1.0 ac
Energy factor	0 0.31 ±00.01 a	0.27 ±0.03 ad	0.35 ± 0.05 ac	0.21 ± 0.04 bd	0.12 ± 0.05 c

N.B :Different letters indicate a significant effect.

Using the EDM basses the thermal conductivity of aluminum is greater than that for steel and its specific heat is smaller. The high thermal conductivity enables the transport of high heat flux even over a small temperature gradient. The low specific heat supports the recession of the melting isotherm when the heat flux of the source decreases [4]. Furthermore, from the ECM principles the specific removal rate in cubic mm per minute ampere is higher for aluminum than that for steel. In this work, the volumetric removal index of machinability, RRi, is derived, as a percentage, on the basis of the maximum removal rate attained when machining aluminum at the highest cutting rate experimented. For the different cutting rates and materials, this index is plotted in Figure (6). Accordingly, for the different materials under consideration, higher cutting rates raise the process machinability index. The same figure displays that the machinability index, RRi, decreases from aluminum to inco, steel, stainless steel and finally comes graphite. Spur [4] concluded, in EDM, that materials with small thermal conductivity are intensively heated but due to the high spatial temperature gradient this is restricted to a small volume. The difference in the molten volume do not strongly depend on the melting temperature. On the other hand a moderate heating of a rather large volume with a lower spatial temperature gradient takes place in materials with a high thermal conductivity. Here the molten volume is significantly affected by the melting temperature. In this regard Figure (5) shows that the melting point of aluminum is much smaller than that for steels.

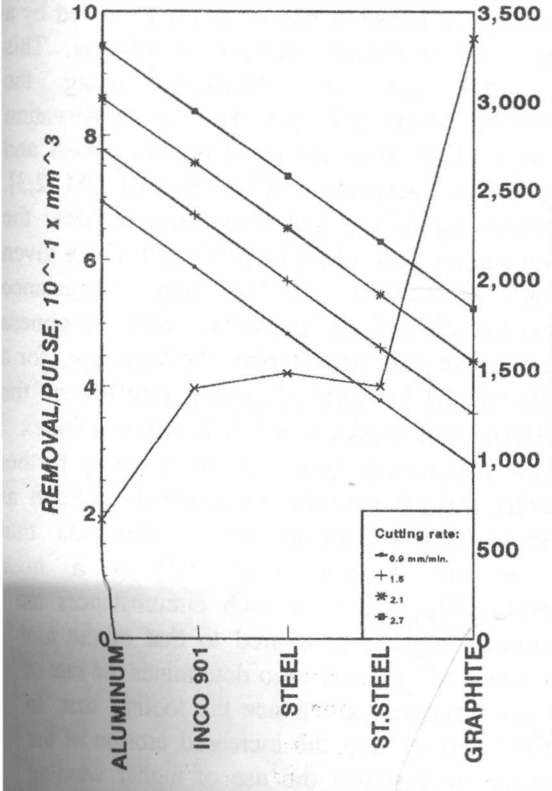

Figure 5. Effect of work material and cutting rate on the removal/pulse.

It should be mentioned however that for a given cutting rate the increase of gap impedance indicates a rise in the machinability index RRi. Under such conditions, for machining accurate components, the gap width which determines the size of the side clearance, should be kept as minimum as possible which contradicts with the requirements of high machinability, process stability and the maximum productivity. In such a case cutting at enhanced machinability is recommended with special care to the size of the side gap through the proper selection of the electrode size. The poor machinability of graphite is reflected on the minimum level of gap impedance attained. Control of gap impedance and hence the machinability is possible during EEDM through the proper change of pulse electrical characteristics such as current, duration. However care should be considered with respect to electrode erosion.

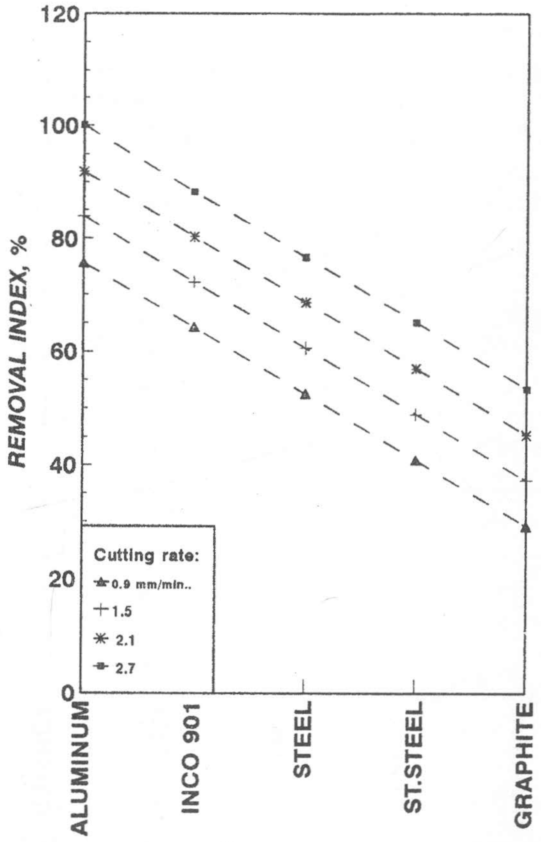

Figure 6. Effect of work material and cutting rate on the removal index.

Energy Utilization Index:

This index determines how efficiently the electrical energy is consumed in the material removal process. Higher values indicate better machinability. As shown in Figure (7), for a given material, this index becomes higher with the cutting rate due to the increased volume/pulse and consequently the removal rate. Furthermore, when machining at a given rate the material of higher index is easier to machine or cut at a lower cost than another. In this regard, among the tested materials, graphite is the most difficult to machine while aluminum has the greatest machinability index. Tables 1,2 reveal that both the cutting rate and work material significantly affect the energy utilization index. Moreover, the increase of the volumetric removal/pulse RPP and hence the rate of metal removal significantly affects the energy utilization index Ei.

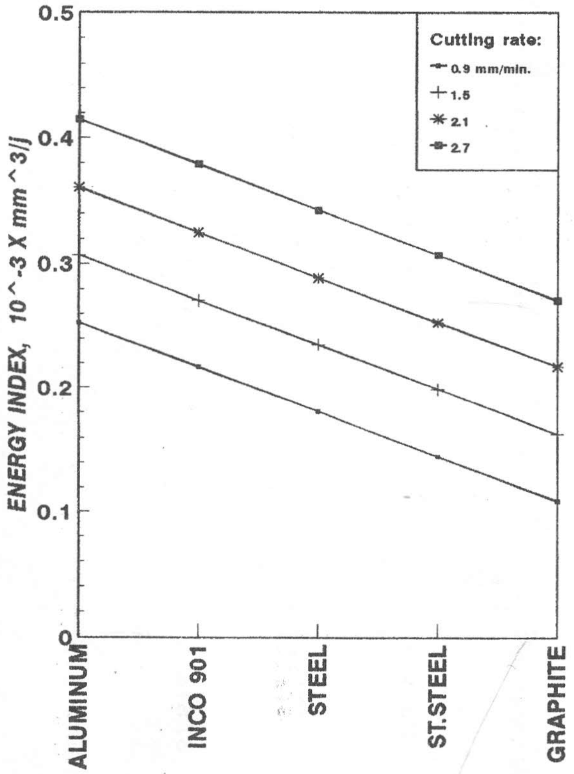

Figure 7. Effect of work material and cutting rate on the energy index.

Surface Roughness Index

In EEDM, the surface generated depends on the volume removed by each successive pulse which, in some cases, determines the crater size. For the group of materials under consideration, the increase of the machining rate raises the volume removed per pulse RPP, Figure (5), and hence the surface roughness Ra, Figure (8). Such an increase is mainly related to the discharging action that is normally associated with narrow gaps, and low gap impedance. Under such circumstances, higher energies are made available in the plasma channel. At a given machining rate, a material of high machinability with respect to the removal rate, where RRi and Ei are high, produces rough surfaces and hence low surface roughness index Rai. Therefore, machining for the highest rate and minimum energy consumption contradicts with high machinability with respect to surface roughness because the best roughness index is attained at the lowest machining rate. Under such circumstances, the intensity of the dissolution process is highest. The production engineer must, therefore, make a compromise between the process productivity and surface roughness or achieves rough cuts at the highest possible rate which is followed by a finish cut with minimum surface roughness. This finishing pass can be performed using the electrochemical phase only [6]. Such an observation explains why ECM produces good surface finish and low removal rate compared to EDM and EEDM [2,3]. Direct monitoring of the gap impedance reflects the state of the surface that might be produced. For a given cutting rate, a material of low gap impedance produces a smooth surface, and hence, high roughness index, Rai, as the case of graphite. Additionally, for a given material, the increase of cutting rate lowers the gap impedance and results in a low roughness index.

In EEDM applications such as die sinking further machinability indices can also be determined such as the linear/volumetric erosion index. Materials that machine at low erosion ratio reflects a high machinability, RRi, since, in such circumstances the removal rate is highest compared to that of the tool electrode. Electrode erosion ratio determines the rate of electrode consumption and hence the tooling cost. In case of EED-wire cutting the increased erosion of the tool electrode necessitates the use of higher winding speed in order to avoid wire breakage. Such an increase, in wire speed, raises the electrode consumption factor especially at increased cutting rates, high input power, low electrolyte feeding rates, and other conditions that raise the intensity of arcing and sparking in the inter electrode gap. The electrode consumption factor is high in EDM and has a zero value during ECM due to the absence of tool-electrode erosion.

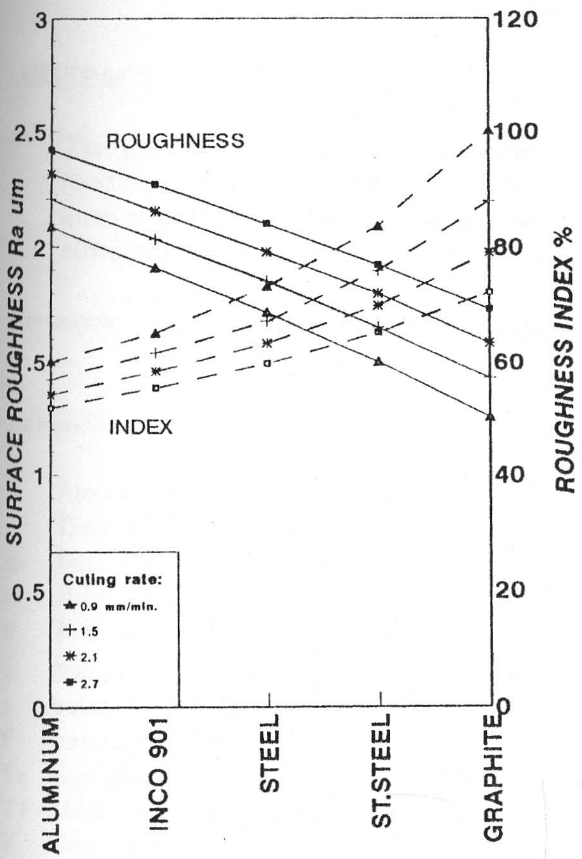

Figure 8. Effect of work material and cutting rate on the surface roughness and roughness index.

Among the other EEDM process parameters that may affect the indices of machinability are the machining medium and its dynamic characteristics. The contamination level of the machining medium can be controlled through proper electrolyte flushing and suitable filtration. Consequently, the gap impedance and hence removal efficiency can be improved. The pressure of pumping the electrolyte in the inter electrode gap affects also the size of the gas bubbles and hence the intensity and concentration of the erosion process which has a direct impact on the on the machinability indices during EEDM.

CONCLUSIONS

1- EEDM machinability can be evaluated through direct monitoring of the gap impedance.
2- High machinability with respect to the removal process and the energy utilization factor are associated with larger gap impedance.
3- Better surface quality and higher roughness indices, are achievable at low gap impedance.
4- The gap impedance is inversely proportional to the machining rate and the material melting point.
5- Considering the physical properties of the selected materials, the melting point and the thermal conductivity have a major influence on the machinability.

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