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ARTICLE

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Experimental studies on improving the performance of electrochemical machining of high carbon, high chromium die steel using jet patterns

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Electrochemical machining (ECM) is a non-traditional process used mainly to cut hard or difficult-to-cut metals, where the application of a more traditional process is not convenient. Stiff market competition and ever-growing demand for better, durable and reliable products has brought about a material revolution, which has greatly expanded the families of difficult-to-machine materials namely high-carbon, high-chromium die steel; stainless steel and superalloys. This investigation attempts to analyze the effect of electrolyte distribution on material removal rate (MRR) and surface roughness (SR) on electrochemical machining of high-carbon, high-chromium die steel using NaCl aqueous solution. Three electrolyte jet patterns namely *straight jet in circular*, *inclined jet in circular* and *straight jet* in spiral were used for this experimentation. The results reveal that electrolyte distribution significantly improves the performance of ECM and the straight jet in spiral pattern performs satisfactorily in obtaining better MRR and surface roughness.

Keywords : Electrochemical machining, Surface roughness, Electrolyte jet pattern

1. Introduction : Electrochemical machining (ECM) is one of the most important non-traditional machining processes to efficiently machine materials especially with high hardness. By use of the ECM process an anodic dissolution of the material being machined occurs very rapidly [1, 2]. This technological advantage of the ECM process can be used to produce complex geometrical forms with high precision in electrically conductive work pieces [3, 4, 5]. During the ECM-machining there is an extremely low generation of thermal energy between the tool-electrode and workpiece being machined, without provoking modifications of material microstructure, as for example, in the case of using electrical discharge machining (EDM) or laser to machine cavities in metallic materials. Because of this fact, the ECM technology is an important technical alternative within the field of manufacturing process to machine steels without the direct generation of thermal stresses in their microstructures, also with total absence of a tool wear during the machining process. The above mentioned advantages of the ECM-machining is a very interesting premise to apply this technology to machine hard materials, such as : high-carbon, high-chromium (HCHCr) die steel, stainless steel and superalloys [6, 7]. Hence, the experimental investigations of this research paper made an attempt to improve the machining characteristics of HCHCr die steel material using the electrolyte jet patterns like *straight jet in circular*, *inclined jet in circular* and *straight jet in spiral*, so that the electrolyte solution of the ECM-process can be introduced into the interelectrode gap (IEG) related to the workpiece being machined with a special form and volume of hydraulic flow. The results of these experiments are presented in the following in terms of material removal rate (MRR) and surface roughness of the electrochemically machined work pieces using NaCl aqueous solution as working medium.

2. Experimentation : The electronics and mechanical characteristics of the tool-machine presented in Figure (1), enable performing the ECM-machining of a metallic workpiece by the principle of ECM sinking. The workpiece and tool-electrode are the anode and cathode respectively, both separated by an electrolyte solution with a controlled electrical conductivity [8]. With a predetermined electric voltage applied between these electrodes a high intensity of current passes through the electrolyte solution contained within the working gap, as a result of which the anodic dissolution of the workpiece material takes place locally. The geometrical form being generated in this workpiece corresponds approximately to the geometry of the tool electrode with sinking movement. The chemical concentration of the electrolyte used in the experiments was adjusted as 15 %, corresponds to a value of electrical conductivity of this working medium in ms/cm. A digital flow meter (model Endress+Hauser) with high accuracy was employed to precisely adjust the volumetric flow of electrolyte to the ECM-machining process.

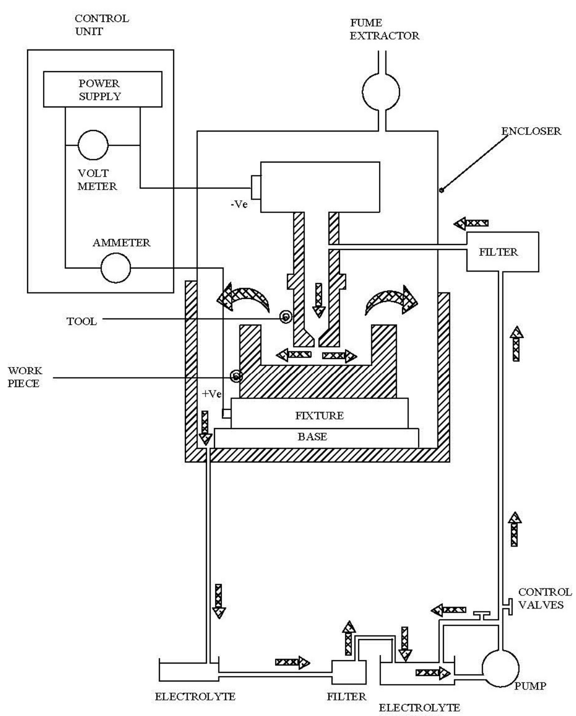

Figure (1) : Schematic of ECM setup.

This flow being supplied from the electrolyte reservoir of the tool-machine passes through the tool-electrode which is of tubular form and laterally insulated to avoid any stray current effect. An IEG, which is usually smaller than 0.1 mm, is formed because of machining taking place between the tool-electrode and workpiece. In the present work, the value of IEG is 0.1 mm and maintained as a constant. The dimension of gap is responsible for a high precision of the electrochemical machining process. In some situations, applied electric voltage between the tool and workpiece with an extremely small IEG, if exists, electric discharge can occur through the electrolyte solution [8], will cause damage in the surface of the tool-electrode and also affect the surface roughness of the machined workpiece. In the present research work, the material of tool-electrode is constituted of copper. Copper is the material of tool commonly used in various applications of ECM process because of its high electrical conductivity [10, 11, 12]. The geometrical characteristics of the tool electrode make it possible to apply the electrolyte solution into the IEG with particular forms of jet patterns as shown in Figure (2), to perform the ECM machining on HCHCr die steel work pieces.

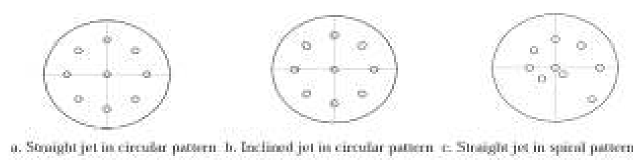

Figure (2) : Different electrolyte jet patterns

The chemical composition of selected material is given in Table (1).

Table (1) : Chemical compositions of high-carbon, high-chromium die steel.

Element	Wt. %	Element	Wt. %
C	1.8	V	0.042
Cr	12.23	Mg	0.01
Ni	0.416	Mo	0.01
Si	0.492	S	0.047
Mn	0.205	P	0.038
Co	0.192	Fe	84.52

Different angles of hole in the jet patterns of tool-electrode consequently produce specific effects of the electrolyte solution in the mechanism of electrochemical anodic dissolution of the workpiece material, which directly influences on the material removal rate and surface roughness of the machined workpiece. Simulation studies using computational fluid dynamics can also be used to optimize the angles of hole of the jet patterns in order to achieve desired results in the ECM process. A combination of a distinctive form of jet pattern with other parameters of the ECM process such as tool feed rate, voltage applied between the electrodes and electrolyte flow rate enhances MRR and surface roughness of the machined work piece **[13, 14, 15]**. The combination of these process parameters and their influences on MRR and surface roughness of the machined workpiece is the central focus of this research work. The range of these parameters is given in Table (2).

Table (2) : Working condition of experiments.

Voltage (V)	12, 15 and 18
Current (A)	0 - 280
Inter electrode gap (mm)	0.1
Feed rate (mm/min)	0.1, 0.21, 0.32 and 0.54
Electrolyte discharge rate (l/min)	8, 10 and 12
Selected electrolyte	15 % NaCl aqua solution
Tool material	Copper
No. of jets in the tool - electrode	9
Dimension of tool	Outer diameter : 25.4 mm Diameter of hole : 1 mm Laterally insulated (to avoid the stray effect)
Inclination angle of jet and nature	34^o and inward
Tool - electrode condition	Non – rotating
Selected ECM – process parameters to be varied during experiments	Applied voltage, Tool feed rate, Electrolyte discharge rate
Electrolyte temperature range (^{o}C)	30 - 40
Work material with hardness	High carbon high chromium die steel- 63 HRC
Machining time (min)	3

For each combination of these parameters, the workpiece was machined for 3 minutes in the experimental setup which is shown in Figure (3) (Model Meta Tech).

Figure (3) : ECM set up for non - rotating tool experiment.

2.1 MRR – Measurement : MRR is measured as the result of the electrochemical machining process based on the process parameters which are varied in these experiments like tool feed rate, voltage applied between electrodes, electrolyte flow rate and types of jet pattern on the HCHCr die steel. The mathematical difference between the weight of the workpiece before and after the electro chemical machining processes, divided by the total machining time, is calculated as MRR. MRR is determined by using a weighing machine with high measurement accuracy (model Sartorius electronic weighing machine with 0.001 mg accuracy).

2.2 Surface Roughness Measurement : The equipment used to measure the surface roughness is Mitutoyo roughness tester for performing superficial evaluations of the HCHCr die steel through different jet patterns. In the present investigation, the value of surface roughness Ra in *micron* has been defined as a variable to be measured, being obtained through the study of three measures of surface roughness in different points over the machined surface and the average value of these measures is Ra. The complete plan for full factorial design with mixing level is presented in Table (3) **[16]**.

Table (3) : Plan for full factorial design (Mixing level)

Experiment number	Voltage (V)	Feed rate (mm/min)	Discharge rate (lit/min)
1	12	0.1	8
2	12	0.21	8
3	12	0.32	8
4	12	0.54	8
5	12	0.1	10
6	12	0.21	10
7	12	0.32	10
8	12	0.54	10
9	12	0.1	12
10	12	0.21	12
11	12	0.32	12
12	12	0.54	12
13	15	0.1	8
14	15	0.21	8
15	15	0.32	8
16	15	0.54	8
17	15	0.1	10
18	15	0.21	10
19	15	0.32	10
20	15	0.54	10
21	15	0.1	12
22	15	0.21	12
23	15	0.32	12
24	15	0.54	12
25	18	0.1	8
26	18	0.21	8
27	18	0.32	8
28	18	0.54	8
29	18	0.1	10
30	18	0.21	10
31	18	0.32	10
32	18	0.54	10
33	18	0.1	12
34	18	0.21	12
35	18	0.32	12
36	18	0.54	12

3. Results and Discussion :

3.1 At 12 V Voltage : Figure (4) shows the effects of electrolyte jet patterns on MRR and surface roughness for the HCHCr die steel with different electrolyte flow rates. The electrolyte jet patterns significantly have an effect on the MRR and surface roughness under different electrolyte flow rates, voltage and tool feed rates. Among the selected jet patterns, straight jet in spiral pattern performs better in achieving improved MRR and surface under 12 V condition. The straight jet in spiral pattern facilitates to prevent the generation of short circuits during the machining process because of pattern of electrolyte distribution in the IEG and also aids for better use of the electrical current in the electrochemical machining process. A maximum MRR of 432.607 mm^3/min is achieved by using the straight jet in spiral pattern under tool feed rate of 0.54 mm/min and electrolyte flow rate of 12 lit/min conditions. This result is 14.8 % higher when compared to the result of MRR using straight jet in circular pattern. Higher volume of electrolyte flow and pattern of distribution of flow in the IEG tend to remove the quantity of debris like precipitated metal hydroxides from the working gap which arises due to anodic dissolution of the workpiece material. Hence, a lower surface roughness of 1.94 micron is noticed in the results of straight jet in spiral pattern on HCHCr die steel in contradicting it is achieved at 10 lit/min as electrolyte flow rate and tool feed rate of 0.54 mm/min. The combined objectives being interdependent, it is very difficult to achieve the maximum MRR with minimum surface roughness together. The achieved surface roughness at 12 lit/min with a maximum MRR of 432.607 mm^3/min is 2.23 micron, which is 14.94 % higher than that of 1.94 micron achieved at 10 lit/min with a MRR of 396.709 mm^3/min. This 14.94 % increase in surface roughness is achieved with the gain of 9 % MRR.

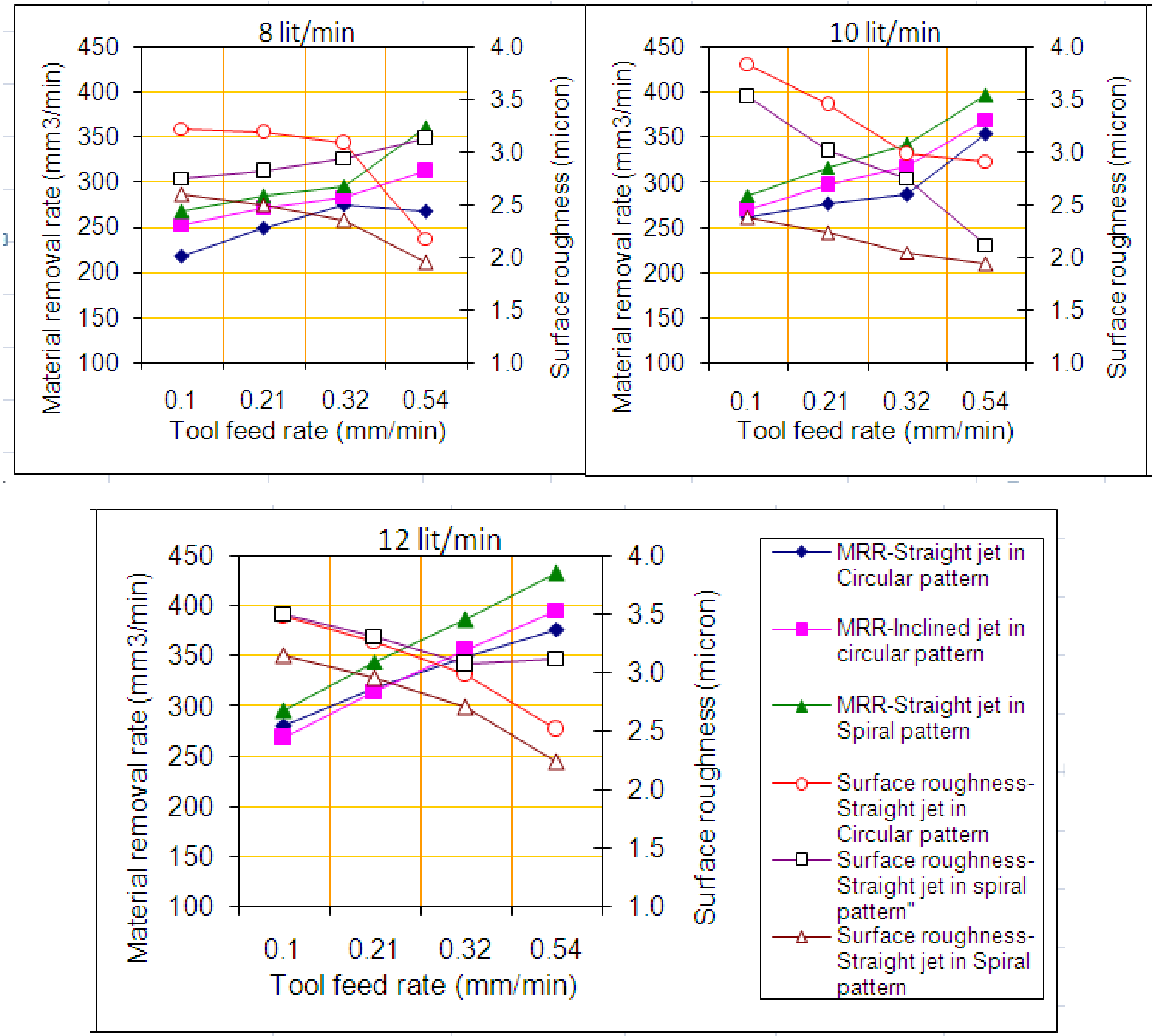

Figure (4) : Effects of electrolyte jet patterns in MRR and surface roughness of HCHCr die steel at 12 V.

3.2 At 15 V Voltage : The effects of selected jet patterns on the MRR and surface roughness of HCHCr die steel at 15 V with different electrolyte flow rates are shown in the Figure 5. The result of experiments at 15 V also strongly reveals that the electrolyte jet patterns have significantly influenced in improving the performance of ECM. It is observed through experimental results that a straight jet in spiral pattern has consistently given better MRR at electrolyte flow rates of 10 lit/min and 12 lit/min for different tool feed rates. For straight jet in circular pattern at 10 lit/min electrolyte flow rate, the resultant MRR pattern shows as abrupt increase in MRR. The cause of this abrupt increase in MRR pattern due to the effective removal residues in the IEG with an electrolyte flow rate of 10 lit/min at tool feed rate which ranges between 0.32 mm/min and 0.54 mm/min, resulting in improved MRR. At 12 lit/min, a minimum surface roughness of 1.22 micron is obtained (at 0.54 mm/min) by straight jet in spiral pattern tool because of effective action of the pattern of jets in flushing out the debris at higher flow rates from the gap. This is proven by the achieved result, which is 65.94 % lower (1.22 micron at 12 lit/min) when compared to the result of surface roughness of 1.85 micron using the same jet pattern at 8 lit/min.

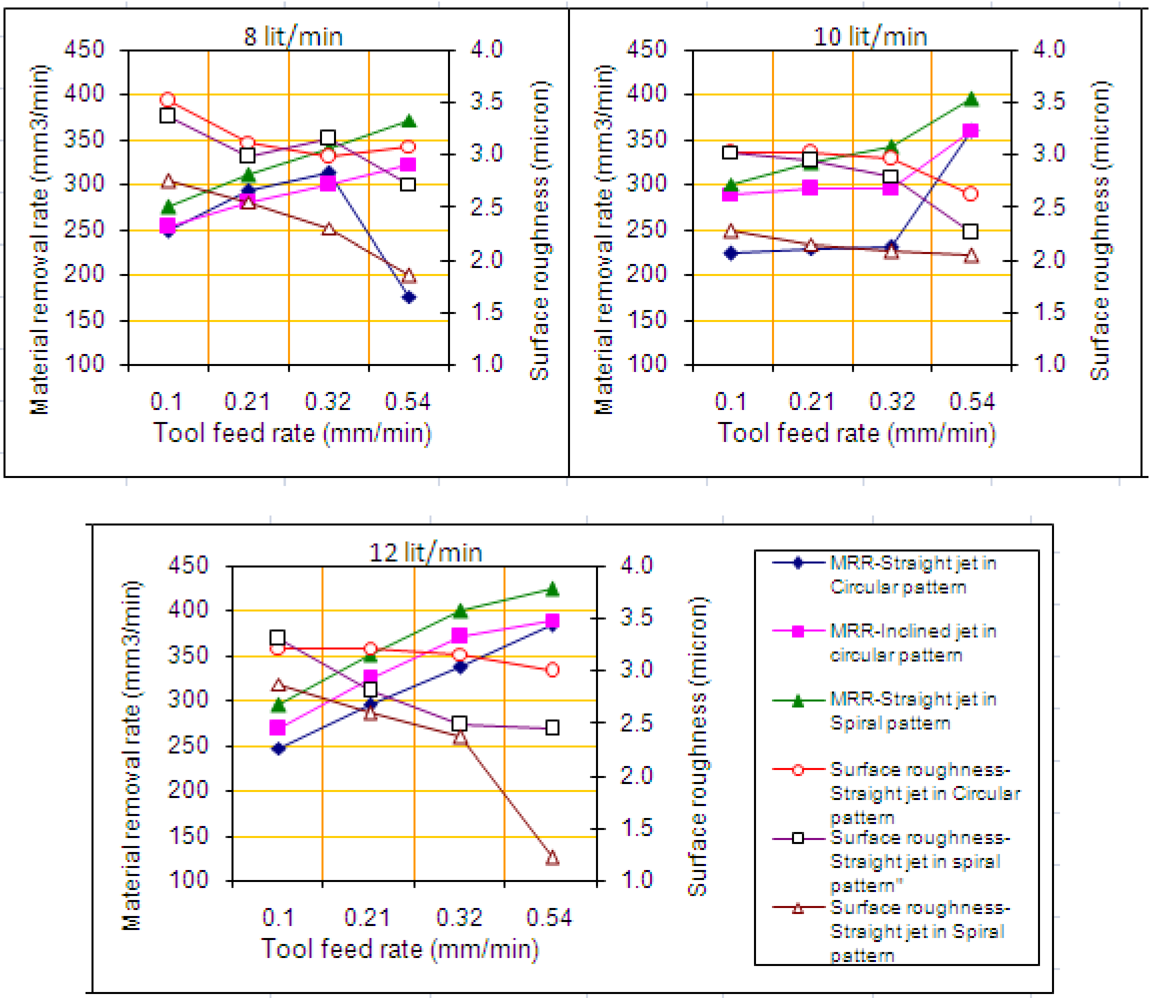

Figure (5) : Effects of electrolyte jet patterns in MRR and surface roughness of HCHCr die steel at 15 V.

3.3 At 18 Voltage : Possibilities of generation of electric discharges are higher in the working gap when the tool feed rate and applied voltage between the electrodes is higher. Hence, it is recommended to use higher intensities of electrolyte flow between tool electrode and workpiece to avoid electrical isolation of the working gap due to the gases emanating from electrochemical reactions. This in turn prevents the generation of short circuits during the machining process and also aids in better usage of the electrical current in the electrochemical machining process. A maximum MRR of 462.863 mm^3/min is achieved by using a straight jet in spiral pattern with 18 V, 0.54 mm/min and 12 lit/min conditions as shown in figure 6. This is 20.53 % and 22.42 % higher when compared with straight jet in circular pattern and inclined jet in circular pattern respectively under the same working conditions. It is evident that straight jet in spiral pattern tends to generate a lower value of surface roughness within the selected range of variation of tool feed rate. The reason for this pattern of behavior is that the flow of electrolyte admitted into the IEG provokes a minimum fluid turbulence at the Work piece surface when compared with the other forms of electrolyte jet patterns and consequently leads to a more homogeneous condition of ECM-material dissolution during the machining process. A minimum surface roughness of 2.21 micron is obtained using a straight jet in spiral pattern under 18 V, 0.54 mm/min and 12 lit/min conditions. The percentage of improvement analysis with reference to the straight jet in circular pattern is presented in table 4.

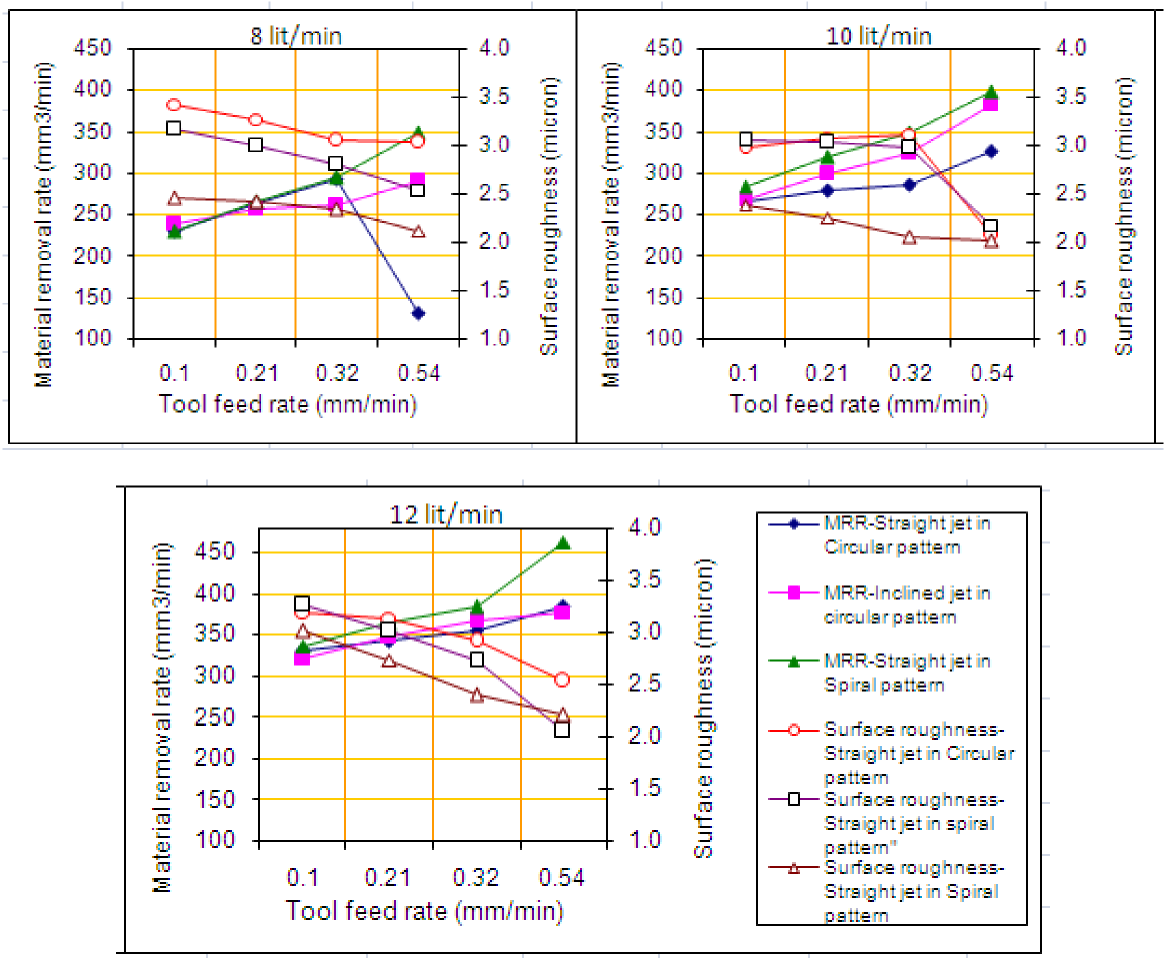

Figure (6) : Effects of electrolyte jet patterns in MRR & surface roughness of HCHCr die steel at 18 V.

Table (4) : Improvement analysis with reference to a straight jet in circular pattern tool.

Sr. No	Description	Types of jet pattern		
		Straight jet in Circular pattern	**Inclined jet in Circular pattern**	**Straight jet in spiral pattern**
1	Maximum achieved MRR (mm^3/min)	384.017	378.077	462.863
2	Corresponding surface roughness achieved (micron)	2.99	2.06	2.21
3	Working conditions	15 V, 0.54 mm/min, 12 lit/min	18 V, 0.54 mm/min, 10 lit/min	18 V, 0.54 mm/min, 12 lit/min
4	Percentage of improvement on the selected objectives	Reference jet pattern	-1.57 % in MRR and 45.14% in surface roughness	20.53 % in MRR and 35.29 % in surface roughness
5	Minimum achieved surface roughness (micron)	2.07	2.06	1.22
6	Corresponding MRR achieved (mm^3/min)	325.855	378.077	425.085

4. Error Analysis : Error analysis is the study and evaluation of uncertainty in measurements. The ability to evaluate these uncertainties and keep them to a minimum is significantly important. The present study has used the coefficient of variation for the set of samples (36) as the major component for error analysis. Coefficient of variation is a normalized measure of dispersion of a probability distribution. The coefficient of variation is defined as the ratio of the standard deviation to the mean which is the inverse of the signal-to-noise ratio [17]. It is an extent of variability in relation to mean of the population. Also coefficient of variation is useful, because the standard deviation of data must always be understood in the context of the mean of the data. The calculated values of coefficient of variation for different jet patterns are tabulated in Table (5).

Table (5) : Analysis of coefficient of variation.

Sr. No	Description	Straight jet in Circular pattern		Inclined jet in Circular pattern		Straight jet in spiral pattern	
		MRR	SR	MRR	SR	MRR	SR
1	Mean (μ)	294.065	2.98	293.067	2.94	344.229	2.14
2	Coefficient of variance (%)	20.81	13.33	18.52	14.62	16.45	12.32

The coefficient of variance values for straight jet in spiral pattern in MRR and surface roughness are lower than that of remaining jet patterns. The results of coefficient of variation significantly prove that performance of straight jet in spiral pattern is better in terms of consistently achieving improved MRR and surface roughness values for all consideration.

5. Conclusions : Experiments are conducted for improving the performance of ECM using different jet patterns namely *straight jet in circular*, *inclined jet in circular* and *straight jet* in spiral jet without rotational movement condition with 15 % NaCl electrolyte solution. The effects of jet patterns on the selected objectives of ECM on MRR and surface roughness of high-carbon, high-chromium die steel are studied along with other influencing parameters. The experimental results strongly prove that there is an impact of jet patterns on the MRR and surface roughness values in ECM process.

We conclude that :

1. Among the selected jet patterns, straight jet in spiral pattern performed significantly in improving the performance of ECM.

2. The maximum MRR of 462.863 mm^3/min is achieved by using straight jet in spiral pattern under the conditions of 18 V, 0.54 mm/min and 12 lit/min which is 21.49 % and 24.41 % higher when compared with straight jet in circular pattern and inclined jet in circular pattern respectively under the same working conditions.

3. The minimum surface roughness of 1.22 micron is obtained by a straight jet in spiral pattern tool under 15 V, 0.54 mm/min and 12 lit/min condition and this achieved surface roughness is the lowest surface roughness of HCHCr die steel.

4. The result of error analysis shows the consistency of straight jet in spiral pattern in improving the performance of ECM in terms of higher MRR with lower surface roughness.

5. The result of experiments also paves the way to further conclude that it needs a systematic investigation of ECM process using different electrolyte solution with different combinations for different materials to achieve a better MRR and improved surface roughness.

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