Formation of spikes prevents achievement of the better material removal rate (MRR) and surface finish while using plain NaNO$_3$ aqueous electrolyte in electrochemical machining (ECM) of die tool steel. Hence this research work attempts to minimize the formation of spikes in the selected workpiece of high carbon high chromium die tool steel using copper nanoparticles suspended in NaNO$_3$ aqueous electrolyte, that is, nanofluid. The selected influencing parameters are applied voltage and electrolyte discharge rate with three levels and tool feed rate with four levels. Thirty-six experiments were designed using Design Expert 7.0 software and optimization was done using multiobjective genetic algorithm (MOGA). This tool identified the best possible combination for achieving the better MRR and surface roughness. The results reveal that voltage of 18 V, tool feed rate of 0.54 mm/min, and nanofluid discharge rate of 12 l/min would be the optimum values in ECM of HCHCr die tool steel. For checking the optimality obtained from the MOGA in MATLAB software, the maximum MRR of 375.78277 mm$^3$/min and respective surface roughness $R_a$ of 2.339779 $\mu$m were predicted at applied voltage of 17.688986 V, tool feed rate of 0.5399705 mm/min, and nanofluid discharge rate of 11.998816 l/min. Confirmatory tests showed that the actual performance at the optimum conditions was 361.214 mm$^3$/min and 2.41 $\mu$m; the deviation from the predicted performance is less than 4% which proves the composite desirability of the developed models.
composition of HCHCr die steel is presented in Table 1. The plain aqueous solution of 15% NaNO₃ and 40 g of Cu nanoparticles suspended in plain aqueous solution of 15% NaNO₃ were selected as electrolytes in these experiments [11]. The electrolyte solution was completely analyzed using deluxe water and soil analysis kit, Model-191E. A digital flow meter with two-digit accuracy was employed to adjust the flow rate of electrolyte to the IEG. Copper was chosen for fabrication of tool due to high electrical conductivity. In the present work, the IEG is set to be 0.5 mm initially throughout the experimentation [12]. Material removal (MR) is the difference in the weight of the workpiece before and after machining. The accuracy of measurement is ensured using Sartorius electronic weighing machine with three-digit accuracy. Mitutoyo surface tester with a range of 0–150 μm is used to measure surface roughness (Ra) and the average of values observed in three different surfaces on the workpiece is computed in each experiment. The process parameters used in the complete experiment are presented in Table 2.

3. Mathematical Modeling of Machining Parameters

Design Expert 7.0 software is used to determine the relationship among the selected influencing parameters. Three levels have been selected for influencing parameters of the applied voltage, electrolyte discharge rate, and four levels selected for tool feed rate. It is possible to assess the main and interaction effects of different machining parameters in L₃₆ array with most reasonable accuracy. A first-order experiment was performed to determine the magnitudes of the relative changes to the process parameters that would result in optimum MRR and surface roughness. It is obtained from the first-order experiments; copper nanoparticles suspended in aqueous NaNO₃ electrolyte significantly improve the MRR and surface roughness compared to plain aqueous NaNO₃ electrolyte. Subsequently, a second-order central composite design was selected to identify the optimum conditions which turn into the higher MRR and finest surface roughness. The general form of second-order polynomial mathematical model applied to investigate the parametric effects of ECM is

$$ Y_u = b_0 + \sum_{i=1}^{n} b_ix_{iu} + \sum_{i=1}^{n} \sum_{j\neq i} b_{ij}x_{iu}x_{ju} + \sum_{i<j} b_{ij}x_{iu}x_{ju}, $$

where $Y_u$ is the response and terms $b_0$, $b_i$, and so forth are the second-order regression coefficients. Various sets of parametric combinations results are obtained by conducting a series of experiments. The respective mathematical models representing MRR in view of plain aqueous NaNO₃ and Cu nanoparticles suspended in plain aqueous NaNO₃ electrolyte are computed as

$$ Y_{u1} (MRR) = -603.747 + 117.441X_1 - 170.503X_2 - 48.750X_3 + 12.903X_1X_2 - 0.215X_1X_3 + 11.491X_2X_3 - 3.442X_1^2 $$

$$ + 98.005X_2^2 + 3.305X_3^2, $$

$$ Y_{u2} (MRR) = -17.794 - 22.942X_1 - 340.754X_2 $$

$$ + 54.275X_3 + 6.834X_1X_2 - 2.018X_1X_3 $$

$$ + 4.178X_2X_3 + 1.642X_1^2 $$

$$ + 280.163X_2^2 - 0.682X_3^2, $$

where $Y_u$(MRR), $Y_{u1}$(MRR), $X_1$, $X_2$, and $X_3$ represent MRR of plain aqueous NaNO₃, Cu nanoparticles suspended in plain aqueous NaNO₃, applied voltage, tool feed rate, and electrolyte discharge rate, respectively. The developed mathematical model will enable improvement of the performance of ECM while machining HCHCr die steel. The degree of fitness of the developed mathematical model is confirmed through ANOVA test. The coefficient of determination $R^2$ for MRR in terms of aqueous NaNO₃ and Cu nanoparticles suspended in aqueous NaNO₃ solutions were 90.97% and
93.45%, respectively, which confirms the accuracy of fitness of the mathematical model.

The respective mathematical models representing surface roughness in view of plain aqueous NaNO₃ and Cu nanoparticles suspended in plain aqueous NaNO₃ electrolytes are computed as

\[ Y_u (SR) = -24.807 + 1.252X_1 + 6.630X_2 + 3.024X_3 - 0.239X_1X_2 - 0.070X_1X_3 - 0.478X_2X_3 \]  \quad (4)

\[ Y_{u_1} (SR) = -27.358 + 3.022X_1 + 9.793X_2 + 1.488X_3 - 6.251X_1X_2 - 0.072X_1X_3 - 0.487X_2X_3 \]  \quad (5)

where \( Y_u (SR), Y_{u_1} (SR), X_1, X_2, \) and \( X_3 \) represent surface roughness of aqueous NaNO₃, Cu nanoparticles suspended in aqueous NaNO₃ electrolyte, applied voltage, tool feed rate, and electrolyte discharge rate, respectively. The coefficient of determination \( R^2 \) obtained from ANNOVA for surface roughness in terms of aqueous NaNO₃ and Cu nanoparticles suspended in aqueous NaNO₃ electrolytes were 92.55% and 96.98%, respectively, which confirms the fitness of the mathematical model.

4. Optimization Using Multiobjective Genetic Algorithm in MATLAB

Evolutionary algorithms seem mainly suitable to solve multiobjective optimization problems, because they deal simultaneously with a set of possible solutions (population). The traditional mathematical programming techniques need a series of separate runs to find the optimum solution for multiobjective problems. Contrarily, this method allows finding several members of the optimal set in a single run of the algorithm. In this research work multiobjective genetic algorithm toolbox from the MATLAB software is chosen for optimizing the selected objectives, maximizing the MRR and minimizing the surface roughness. The ability of GA to simultaneously search different regions of a solution space makes it possible to find a diverse set of solutions for difficult problems with nonconvex, discontinuous, and multimodal solutions spaces [13–15].

5. Analysis of the Influence of Parametric on the MRR and Surface Roughness for Aqueous NaNO₃ Electrolyte

The mathematical models developed using RSM and presented in (2) and (4) were used in GA toolbox as fitness functions. The limitation for the optimization is given as follows:

\[ 6 \leq x_1 \leq 12, \quad 3 \leq x_2 \leq 9, \quad 3 \leq x_3 \leq 9. \]  \quad (6)

The GA generally includes three fundamental genetic operations of selection, namely, population, crossover, and mutation. These operations are used to modify the chosen solutions and select the most appropriate offspring to pass on to succeeding generations. The following parameters were considered during optimization using GA multiobjective tool. Population size = 225, crossover fraction = 0.8, mutation function = constraint dependent, crossover function = scattered, and number of iterations = 188.

Upon applying objective functions in GA tool, the results were obtained as tabulated in Table 3 and Figure 2.

The response plot shows the effects of applied voltage, tool feed rate, and electrolyte discharge rate on MRR and surface roughness of HCHCr die tool steel. MRR increases at higher voltage with the increase of tool feed rate and higher flow of electrolyte discharge rate at a mean time surface roughness slightly increased. A maximum MRR 306.69449 mm³/min was achieved under tool feed rate of 0.5399502 mm/min, 11.97976 lit/min of electrolyte discharge rate, and applied voltage of 17.995820 V. A minimum SR value of 1.513575 μm was observed at 12 V, 0.1100281 mm/min of tool feed rate, and 8.134412 lit/min of electrolyte discharge rate.

6. Analysis of the Influence of Parametric on the MRR and Surface Roughness for Cu Nanoparticles Suspended in Aqueous NaNO₃ Electrolyte

Table 4 and Figure 3 present the results from GA for Cu nanoparticles suspended in aqueous NaNO₃ electrolyte. MRR increases at higher values of electrolyte discharge rate and tool feed rate. The surface roughness decreases when the electrolyte discharge rate and tool feed rate are decreased. A maximum value of MRR 375.78277 mm³/min was obtained under 17.688986 V, 0.5399705 mm/min tool feed rate, and 11.998816 lit/min electrolyte discharge rate conditions. The minimum surface finish of 1.4973965 μm was observed at 17.999473 V, 0.2344207 mm/min tool feed rate, and 11.997052 lit/min electrolyte discharge rate condition.

It is obvious that the optimum search can be obtained based on the developed second-order response, surface equations for correlating the various process variable effects with
Table 3: Process decision variables along with optimized response from GA for aqueous NaNO₃.

| Sl. number | Voltage (V) | Feed rate (mm/min) | Discharge rate (lit/min) | MRR (mm³/min) | Surface roughness (micron) |
|------------|-------------|---------------------|-------------------------|---------------|---------------------------|
| 1          | 12          | 0.1100281           | 8.134412                | 132.46309     | 1.513575                  |
| 2          | 12.03021    | 0.1104329           | 9.087866                | 169.34532     | 2.152654                  |
| 3          | 12.014045   | 0.1039534           | 10.04123                | 206.68191     | 2.254694                  |
| 4          | 17.995146   | 0.5265484           | 11.98002                | 302.51291     | 2.656720                  |
| 5          | 12.000245   | 0.1005786           | 9.147932                | 153.98288     | 1.791250                  |
| 6          | 17.991590   | 0.3675932           | 10.04123                | 259.68191     | 2.164326                  |
| 7          | 12.006746   | 0.2003393           | 8.234414                | 137.00311     | 1.560310                  |
| 8          | 12.007321   | 0.1019808           | 10.06793                | 169.87964     | 2.159093                  |
| 9          | 17.989152   | 0.3175749           | 11.99351                | 250.47074     | 2.189059                  |
| 10         | 12.000245   | 0.1004096           | 9.719882                | 164.05383     | 2.038806                  |
| 11         | 17.986068   | 0.3813624           | 11.99307                | 263.68107     | 1.875754                  |
| 12         | 17.994398   | 0.5169848           | 11.97913                | 299.58104     | 2.623729                  |
| 13         | 17.985153   | 0.2530979           | 11.99503                | 233.31519     | 2.164326                  |
| 14         | 17.988464   | 0.3482414           | 11.99409                | 256.55458     | 2.219778                  |
| 15         | 12.012065   | 0.1043002           | 8.710513                | 145.82497     | 1.564311                  |
| 16         | 17.990082   | 0.4115904           | 11.98257                | 270.80421     | 2.330752                  |
| 17         | 17.986068   | 0.3813624           | 11.99307                | 263.68107     | 1.875754                  |
| 18         | 12.004311   | 0.104213            | 8.848672                | 148.38304     | 1.639634                  |
| 19         | 12.000057   | 0.2000266           | 8.109496                | 134.59464     | 1.771653                  |
| 20         | 12.015943   | 0.1038107           | 8.938570                | 150.04776     | 1.691262                  |
| 21         | 17.988003   | 0.4437773           | 11.99324                | 278.90557     | 2.397192                  |
| 22         | 12.001201   | 0.1004778           | 8.995683                | 151.23304     | 1.714381                  |
| 23         | 12          | 0.1038107           | 8.848672                | 148.38304     | 1.639634                  |

Table 4: Process decision variables along with optimized response from GA for Cu nanoparticles suspended in aqueous NaNO₃ electrolyte.

| Sl. number | Voltage (V) | Feed rate (mm/min) | Discharge rate (lit/min) | MRR (mm³/min) | Surface roughness (micron) |
|------------|-------------|---------------------|-------------------------|---------------|---------------------------|
| 1          | 17.688986   | 0.5399705           | 11.99816                | 375.78277     | 2.339779                  |
| 2          | 17.999473   | 0.2344207           | 11.997052               | 291.21779     | 1.4973965                 |
| 3          | 17.982536   | 0.3619794           | 11.990806               | 324.01735     | 1.6773238                 |
| 4          | 17.92326    | 0.5399910           | 11.998295               | 354.97140     | 2.350116                  |
| 5          | 17.974140   | 0.4719105           | 11.991869               | 354.97140     | 2.0744706                 |
| 6          | 17.986820   | 0.3385383           | 11.997197               | 317.93316     | 1.6169858                 |
| 7          | 17.995289   | 0.2727332           | 11.99707                | 300.7935     | 1.5171501                 |
| 8          | 17.981729   | 0.4545162           | 11.997314               | 350.076999    | 1.9885303                 |
| 9          | 17.970973   | 0.5010869           | 11.997924               | 366.45561     | 2.2630915                 |
| 10         | 17.991024   | 0.3212817           | 11.997223               | 313.33731     | 1.5817197                 |
| 11         | 17.957900   | 0.5030484           | 11.997998               | 364.38746     | 2.2357070                 |
| 12         | 17.955889   | 0.4263774           | 11.997138               | 342.18877     | 1.8924504                 |
| 13         | 17.896183   | 0.5389892           | 11.997894               | 375.34015     | 2.3713213                 |
| 14         | 17.917751   | 0.5150918           | 11.998277               | 368.07683     | 2.3296118                 |
| 15         | 17.960839   | 0.4768214           | 11.996795               | 356.60081     | 2.1042235                 |
| 16         | 17.913224   | 0.5219700           | 11.998223               | 370.14799     | 2.3709887                 |
| 17         | 17.963386   | 0.4965703           | 11.997834               | 362.44458     | 2.1984027                 |
| 18         | 17.997099   | 0.2431022           | 11.997066               | 293.37153     | 1.5003086                 |
| 19         | 17.991022   | 0.3212817           | 11.997223               | 313.3371      | 1.5817197                 |
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| Sl. number | Electrolyte | Obtained from GA | Confirmation test | Error |
|------------|-------------|------------------|-------------------|-------|
|            |             | MRR mm³/min      | SR µm            |       |
| 1          | Aqueous NaNO₃ | 306.69449        | 2.706127         | 4.13  |
|            | Cu nanoparticles suspended in aqueous NaNO₃ | 294.012 | 2.82 | 4.25 |
| 2          |             | 375.78277        | 2.339779         |       |
|            |             | 361.214          | 2.41             | 3.87  |

7. Confirmation Test

The confirmatory experiments were further conducted for the optimal parameters obtained from the MATLAB multiobjective GA tool. The error between optimum values from GA and the confirmation test was derived by considering the serial number 24 and serial number 1 from Tables 3 and 4, respectively, at the condition of maximum MRR and is shown in Table 5.

8. Conclusions

This work employs a multiobjective genetic algorithm (GA) tool to optimize influencing parameters of ECM to maximize the MRR and minimize surface roughness of HCHCr die steel. Based on the experimental results, the following conclusions are drawn.

(1) Material removal rate increases linearly with applied voltage and nonlinearly increases with tool feed rate. Surface roughness decreases with increase in the applied voltage and all tool feed rates. Mathematical models for MRR and surface roughness have been developed by Design Expert 7.0 software. It is useful for analyzing the influence of the various process parameters for achieving better MRR and surface roughness of HCHCr die tool steel.

(2) Genetic algorithm (GA) tool optimizes the range of influencing parameters in order to obtain a maximum MRR and minimum surface roughness. The experimental results reveal that applied voltage of 18 V, tool feed rate of 0.54 mm/min, and electrolyte discharge rate of 12 lit/min would be the optimum values in ECM of HCHCr die tool steel under copper nanoparticles suspended in aqueous NaNO₃ electrolyte solution machining condition.

(3) For checking the optimality obtained from the multiobjective GA in MATLAB, MRR of 375.78277 mm³/ min and surface roughness Ra of 2.339779 µm were predicted at applied voltage of 18 V, tool feed rate of 0.54 mm/min, and electrolyte discharge rate of 11.99 lit/min.

(4) Confirmatory tests showed that the actual performance at the optimum conditions was 361.214 mm³/ min and 2.41 µm; a deviation from the predicted performance is less than 4% at maximum material removal rate condition which has proven the composite desirability of the developed models for MRR and surface roughness under copper nanoparticles suspended in aqueous NaNO₃ electrolyte solution machining condition. Aqueous NaNO₃ electrolyte solutions performance is poor comparing to copper nanoparticles suspended in aqueous NaNO₃ electrolyte solution.

(5) Comparing the predicted performance of aqueous NaNO₃ and copper nanoparticles suspended in aqueous NaNO₃ electrolyte solutions on experimentally and mathematically, copper nanoparticles suspended in aqueous NaNO₃ electrolyte solution performs better for MRR and surface roughness on HCHCr die tool steel.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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