CHAPTER-6

CONCLUSIONS, LIMITATIONS
AND
SCOPE FOR FUTURE WORK
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6.1 CONCLUSIONS

In the present work, a generic hybrid model for optimal selection of electrical discharge machining process parameters for mould and die steel materials has been developed. An integrated RSM-NSGA-ANFIS approach was used to develop generic hybrid model for relating the process parameters i.e. discharge current (I), pulse-on time (Ton) and pulse-off time (Toff) to machining characteristics SR and MRR. The developed generic hybrid model was validated with the new work materials (AISI A2 and AISI D3) for predicting its behavior. The following conclusions have been drawn within the experimental region of the selected input process parameters:

- Based on review of literature, most influencing process parameters were identified as discharge current, pulse on-time and pulse off-time on machining characteristics such as SR and MRR.

- It was found that same range of process parameters are not applicable for graphite and copper tool while performing pilot experiments using one factor at a time (OFAT) approach. Graphite tool at high discharge current (21.87 A) or low discharge current (3.12 A), high pulse-on time (1000 µs) and too short pulse-off time (10 µs) shows the tendency of short circuiting and arcing resulting in erratic behaviour of the machine.

- Experiments were performed according to design matrix based on face centered CCD for AISI 1040, AISI 52100, AISI D2, AISI M2 and AISI P20 steel using copper electrodes, it was seen that in all the five work materials least surface roughness was achieved by process parameter combinations of I= 3.12 A, Ton= 1000 µs and Toff= 1000 µs whereas, highest surface roughness was obtained with I= 21.87 A, Ton= 1000 µs and Toff= 1000 µs. It was also noticed that process parameter combination I= 21.87 A, Ton= 10 µs and Toff= 10 µs gives highest MRR for all the work materials except AISI P20. In AISI P20 work material, highest MRR was achieved with I= 21.87 A, Ton= 1000 µs and Toff= 10 µs.
While conducting the experiments according to rotatable CCD for AISI 1040, AISI 52100, AISI D2, AISI M2 and AISI P20 steel using graphite electrodes, it was observed that in all the five work materials, least surface roughness was achieved by process parameter combinations of \( I = 3.12 \, \text{A} \), \( T_{\text{on}} = 500 \, \mu\text{s} \) and \( T_{\text{off}} = 500 \, \mu\text{s} \) whereas, highest surface roughness was obtained with \( I = 21.87 \, \text{A} \), \( T_{\text{on}} = 500 \, \mu\text{s} \) and \( T_{\text{off}} = 500 \, \mu\text{s} \). It was also noticed that process parameter combination \( I = 21.87 \, \text{A} \), \( T_{\text{on}} = 500 \, \mu\text{s} \) and \( T_{\text{off}} = 500 \, \mu\text{s} \) gives highest MRR for all the work materials except AISI 52100 and AISI P20. In AISI 52100 and AISI P20 work material highest MRR was achieved with \( I = 18.75 \, \text{A} \), \( T_{\text{on}} = 750 \, \mu\text{s} \) and \( T_{\text{off}} = 200 \, \mu\text{s} \).

Mathematical equations developed for different work-tool pair by using experimental data for surface roughness and material removal rate are as follows:

(a) For AISI 1040-Cu work-tool pair
\[
\begin{align*}
X_1[1/\sqrt{\text{SR}}] &= + 0.65031 - 0.039173 I - 0.0000265621 T_{\text{on}} + 0.0000314429 \nonumber \\
&+ 0.00124128T_{\text{on}}^2 + 0.000000334934 T_{\text{on}}^2 - 0.0000000593614 T_{\text{off}}^2 \\
Y_1[\ln(\text{MRR})] &= - 2.07887 + 0.58162 I + 0.00151642 T_{\text{on}} - 0.00282154 T_{\text{off}} 
onumber \\
&+ 0.0000511452 T_{\text{on}} + 0.0000172318 T_{\text{on}} T_{\text{off}} 
onumber \\
&- 0.014413 I^2 - 0.00000262199 T_{\text{on}}^2 + 0.000000948330 T_{\text{off}}^2
\end{align*}
\]

(b) For AISI 52100-Cu work-tool pair
\[
\begin{align*}
X_1[1/\sqrt{\text{SR}}] &= + 0.66415 - 0.042799 I - 0.000193320 T_{\text{on}} + 0.0000257673 T_{\text{off}} 
onumber \\
&- 0.0000102548T_{\text{on}} + 0.000000291140T_{\text{on}} T_{\text{off}} + 0.00131551 I^2 
onumber \\
&+ 0.000000262530 T_{\text{on}}^2 - 0.0000000469555 T_{\text{off}}^2 \\
Y_1[\ln(\text{MRR})] &= - 2.13047 + 0.59344 I + 0.00150091 T_{\text{on}} - 0.00263440 T_{\text{off}} 
onumber \\
&+ 0.0000473512 T_{\text{on}} + 0.00000175610 T_{\text{on}} T_{\text{off}} - 0.014652 I^2 
onumber \\
&- 0.00000260560 T_{\text{on}}^2 + 0.000000746874 T_{\text{off}}^2
\end{align*}
\]
(c) For AISI D2-Cu work-tool pair

\[ X_d[1/\sqrt{\text{SR}}] = 0.58290 - 0.030197 I - 0.000214371 T_{on} + 0.0000232759 T_{off} - 0.00000871767 I T_{on} - 0.00000187274 I T_{off} + 0.000870292 I^2 + 0.00000291316 T_{on}^2 \]

\[ Y_d[\ln(\text{MRR})] = -1.93675 + 0.52435 I + 0.00200974 T_{on} - 0.00181962 T_{off} + 0.000406561 I T_{on} + 0.00000139113 T_{on}^2 - 0.012233 I^2 - 0.00000027606 T_{on}^2 \]

(d) For AISI M2-Cu work-tool pair

\[ X_d[\ln(\text{SR})] = 0.68708 + 0.14709 I + 0.00151827 T_{on} + 0.000232410 T_{off} + 0.000619986 I T_{on} - 0.00000319034 T_{on} T_{off} - 0.00400670 I^2 - 0.00000186497 T_{on}^2 \]

\[ Y_d[\ln(\text{MRR})] = -2.09069 + 0.52435 I + 0.00220652 T_{on} - 0.00168493 T_{off} + 0.000437633 I T_{on} + 0.00000122996 T_{on} T_{off} - 0.012214 I^2 - 0.000000294203 T_{on}^2 \]

(e) For AISI P20-Cu work-tool pair

\[ X_d[\sqrt{\text{SR}}] = 1.57629 + 0.10490 I + 0.00266948 T_{on} - 0.0000022993 T_{off} + 0.000104880 I T_{on} + 0.0000185878 I T_{off} - 0.00244349 I^2 - 0.00000355629 T_{on}^2 \]

\[ Y_d[\ln(\text{MRR})] = -1.33324 + 0.45860 I + 0.00403869 T_{on} - 0.00457533 T_{off} + 0.000964887 I T_{on} + 0.00000203958 T_{on} T_{off} - 0.010651 I^2 - 0.000000539206 T_{on}^2 + 0.00000203997 T_{off}^2 \]

(f) For AISI 1040-Gr work-tool pair

\[ X_d[\text{SR}] = 0.69024 + 0.60137 I + 0.010189 T_{on} + 0.010472 T_{off} + 0.0000619 I T_{on} - 0.00000197514 T_{on}^2 - 0.00000102816 T_{off}^2 \]

\[ Y_d[\text{MRR}] = -5.12818 + 0.621 I + 0.018 T_{on} + 0.00766127 T_{off} + 0.000744197 I T_{on} - 0.00129796 I T_{off} + 0.056042 I^2 - 0.00000276978 T_{on}^2 \]
Chapter 6  Conclusions, limitations and scope for future work

(g) For AISI 52100-Gr work-tool pair

\[
X_i[(SR)] = +1.42878 + 0.64223 I + 0.00687937 T_{on} + 0.01198 T_{off}
\]
\[
+ 0.0005585901 T_{on}^2 - 0.0000166295 T_{on}^2 - 0.0000112922 T_{off}^2
\]

\[
Y_i[(MRR)] = -1.27558 + 0.57126 I + 0.010155 T_{on} - 0.00338963 T_{off}
\]
\[
+ 0.001708081 T_{on} - 0.001832241 T_{off} + 0.067949 I^2
\]
\[
- 0.0000279356 T_{on}^2
\]

(h) For AISI D2-Gr work-tool pair

\[
X_i[(SR)] = +4.12428 + 0.49744 I + 0.00778607 T_{on} - 0.00282456 T_{off}
\]
\[
+ 0.0006176201 T_{on} + 0.0003405641 T_{off} - 0.0000168974 T_{on}^2
\]

\[
Y_i[(MRR)] = +1.24404 - 0.45259 I + 0.012327 T_{on} + 0.00359002 T_{off}
\]
\[
+ 0.0009335341 T_{on} - 0.002472381 T_{off} + 0.13565 I^2 -
\]
\[
0.0000217339 T_{on}^2 + 0.0000133578 T_{off}^2
\]

(i) For AISI M2-Gr work-tool pair

\[
X_i[(SR)] = +4.31374 + 0.33742 I + 0.00437055 T_{on} - 0.00577366 T_{off}
\]
\[
+ 0.0001825861 T_{on} - 0.00000446378 T_{on} T_{off} + 0.021062 I^2
\]
\[
- 0.0000102705 T_{on}^2 + 0.0000105955 T_{off}^2
\]

\[
Y_i[(MRR)] = -0.079865 + 0.76636 I + 0.013613 T_{on} - 0.014094 T_{off} +
\]
\[
0.001329411 T_{off} + 0.00000199788 T_{on} T_{off} + 0.064371 I^2 -
\]
\[
0.0000244771 T_{on}^2 + 0.0000113780 T_{off}^2
\]

(j) For AISI P20-Gr work-tool pair

\[
X_i[(SR)] = -3.48632 + 1.36967 I + 0.013097 T_{on} + 0.010629 T_{off} +
\]
\[
0.0002391151 T_{off} - 0.0225999 I^2 - 0.0000214243 T_{on}^2 -
\]
\[
0.0000126260 T_{off}^2
\]

\[
Y_i[(MRR)] = -6.16362 + 0.76093 I + 0.020618 T_{on} + 0.00871754 T_{off}
\]
\[
+ 0.001365801 T_{on} - 0.001685091 T_{off} + 0.069340 I^2
\]
\[
- 0.0000360144 T_{on}^2
\]

- P-values for all the developed mathematical models of SR and MRR are less than 0.05, which indicates that models are significant at 95% confidence level.
- Largest F-value of the discharge current in all the models indicates that that it is the most influencing factor followed by pulse-on and pulse-off time.
• Internally studentized residuals for developed mathematical models of all five work materials lies between ± 3 Sigma limit without any outliers, further confirmed the prediction accuracy of the developed models.

• It was also observed from response surfaces that discharge current is the most influencing process parameters followed by pulse-on and pulse-off time.

• Two-dimensional contour plots were used for predicting the process parameters for the desired surface roughness or material removal rate. However, due to non-availability of exact process parameter settings on the machine the nearest available parameter settings resulted in minimum error of 1.23% and maximum error of 2.98% for SR. Similarly for MRR, the minimum and maximum error was observed to be 1.5% and 3.5% respectively due to limitations of the EDM machine.

• The average prediction error of the developed RSM-based mathematical models for SR were found to be 6.14%, 7.14%, 6.39% 6.56%, and 6.19% whereas, the prediction error on MRR models were observed as 7.64%, 7.86%, 8.24%, 7.56%, and 8.51% for AISI 1040-Cu, AISI 52100-Cu, AISI D2-Cu, AISI M2-Cu and AISI P20-Cu work-tool material respectively. This clearly indicates the limitations of prediction accuracy of the developed RSM-based mathematical models.

• In graphite tool, the average prediction error of the developed RSM-based mathematical models for SR were found to be 5.07%, 4.35%, 5.35%, 6.76 and 4.97% whereas, the prediction error on MRR models were observed as 7.28%, 5.47%, 6.45%, 5.80%, and 6.12% for AISI 1040-Gr, AISI 52100-Gr, AISI D2-Gr, AISI M2-Gr and AISI P20-Gr work-tool material respectively.

• It was found by using RSM-NSGA approach that for all the work materials, minimum Ra was obtained with low values of discharge current (3.12 Amp) and high values of pulse-on time (1000 μs) in case of machining with copper tool whereas; with graphite tool better surface roughness was obtained with low value of discharge current (3.12 Amp) and high value of T_{on} (600 to 725 μs). Among all the five work materials, it was noticed that AISI P20 material gives better surface finish of 1.82 Ra with copper electrode and 2.44 Ra with graphite electrode. In maximization of MRR, the optimal values of process parameters were found to be within the higher range of discharge current.
(21.03A to 21.87A), mid range of \( T_{on} \) (483 \( \mu \)s to 572 \( \mu \)s) and lower range of \( T_{off} \) (10 \( \mu \)s to 15 \( \mu \)s) during machining of copper tool. In case of graphite tool, maximum MRR was obtained at maximum value of discharge current (21.87 A) and minimum value of pulse off-time (200 \( \mu \)s) while the pulse-on time vary from 507 \( \mu \)s to 720 \( \mu \)s.

- Pareto-optimal values of each work-tool material combinations were compared with experimental values and found that SR and MRR values of Pareto-optimal sets and experimental are in close agreement with each other for more or less the same parameter settings of \( I \), \( T_{on} \) and \( T_{off} \).

- Due to variation in process parameter settings between Pareto-optimal sets and experimental one, variation on SR was observed between 0.28% to 5.95% with copper electrode in finish machining region. Whereas for MRR, this variation was on higher side, between 5.50% to 7.8% due to improper flushing of the debris during machining. In case of graphite tool, variation for SR was seen between 0.48% to 6.11% and variation for MRR was found between 2.22% to 7.51%.

- During rough machining with copper electrode, variation for SR was observed between 0.98% to 9.27% whereas; variation for MRR was seen from 0.60% to 7.64%. With graphite tool, variation for SR was noticed between 0.33% to 5.58% while; variation for MRR was seen from 0.18% to 5.34%.

- Four different ANFIS models were developed for prediction of SR and MRR independently using the database of copper and graphite tools. ANFIS-1 and ANFIS-2 models were trained with 498 data sets of copper tools whereas ANFIS-3 and ANFIS-4 were trained with 359 data sets of graphite tool. Total 729 rules were generated, 1503 nodes were required for 729 linear and 54 non-linear parameters. Different membership function were compared and finally triangular membership functions were used in training ANFIS models since it has a lowest RMSE 0.1881, 1.4532, 0.1562 and 0.2212 in ANFIS-1, ANFIS-2, ANFIS-3 and ANFIS-4 model respectively.

- A generic hybrid model was developed from integrated approach (RSM-NSGA II- ANFIS) for prediction of SR and MRR.

- The SR and MRR values of the model for AISI A2-Cu work-tool pair predictions were compared with experimental values. It was observed that at
all values of discharge current when pulse on-time is too high (1000 μs) and pulse off-time is too short (10 μs), model error of 14.14% and 11.75% was observed for SR and MRR respectively. Additionally, it was noted that in case of MRR, at lower values of discharge current (3.12A), high values of pulse-on time (1000 μs) and low pulse-off time (10 μs) the prediction error is higher (11.96% to 15.61%). This is mainly due to insufficient time available for removal of debris from the spark zone causing arcing.

- In AISI D3-Cu work-tool pair, it was seen that at higher values of discharge current (12.5 A to 21.87 A) MRR shows better prediction accuracy whereas; for lower value of discharge current (3.12 A to 6.25 A), the prediction error increases between 12% to 15%. Thus, the prediction error for MRR at lower value of discharge current seems to be on higher side because the values of MRR are very small at low values of discharge current. This is usually attributed due to arcing and improper flushing conditions.

- Wide differences between pulse-on time and pulse-off time (10μs to 500 μs), results in too high or too low duty cycle which is not desirable in EDM process. In AISI A2-Gr model this has resulted in an error of 15.71% and 11.79% for SR and MRR respectively for discharge current value of 12.5A. Too high or too low duty cycle causes arcing and disturbs the stability of spark generated by EDM.

- Thus the developed generic hybrid model was validated with new combinations of work-tool materials i.e. AISI A2-Cu, AISI D3-Cu, AISI A2-Gr, and AISI D3-Gr. Experimental results of new work-tool material pairs were compared with model predictions and average prediction error of the hybrid model for AISI A2 work material with copper and graphite tool was found to be 7.49% for SR and 6.60% for MRR. Similarly, the average prediction error of the model for AISI D3 work material was 6.20% and 6.73% for SR and MRR respectively.

- Thus, the overall mean prediction error of model validation was found to be 6.85% on SR and 6.66% on MRR giving good prediction accuracy.

Thus, the suggested hybrid (RSM-GA-ANFIS) methodology is found useful in selection of optimal process parameters for desired machining characteristics in die sinking electrical discharge machining operations. It also provides flexibility
to the user to predict the desired machining characteristics for a new mould and die steel material within the range of selected process parameters and material properties. In general the developed generic hybrid model was proven to perform well for die sinking EDM, giving reliable predictions and providing thus a possible way to avoid time and money consuming experiments for a new mould and die steel materials belonging to same group having the material properties lying within the limits of input values by which the models were trained.

6.2 LIMITATIONS OF THE PRESENT WORK

The developed generic hybrid model for selection of optimal process parameters for mould and die steel material has following limitations:

- The model is capable of predicting the machining characteristics within the interpolative region of the input parameters of I, T_{on}, T_{off}, \rho, k and C_p. Any extrapolation on input parameters may lead to unpredictable results.
- The developed generic hybrid model for SR and MRR gives the reliable predictions on the selected die sinking EDM.
- The model is valid for prediction of SR and MRR for copper and graphite tool only.
- In the present work, type of dielectric fluid, flushing conditions and polarity was kept constant. Any variations in these parameters may lead to an error in model prediction.
- Major limitations of the die sinking EDM selected for experimentation is that current selector toggle switches, pulse on rotary switch and pulse off rotary switch provides discrete process parameters variation. The current can be set in a step of 3.12 A, the pulse-on time and pulse-off time can be selected from 2 to 2000 \mu s in different steps (2, 5, 10, 15, 20, 30, 50, 75, 100, 150, 200, 300, 500, 750, 1000, 1500, 2000 \mu s). These constraints on selection of process parameters may further add error on model prediction. However, the limitations can be overcome by converting these current selector switches and rotary pulse selection switches in to digital one.
6.3 SCOPE FOR FUTURE WORK

Although the EDM machining has been thoroughly investigated for a group of die steel materials viz. AISI 1040, AISI 52100, AISI D2, AISI M2 and AISI P20 Steel work material, still there is a lot of scope for further investigations. The following suggestions may prove useful for future work:

- In the present work, entire range of machining parameters have been considered for developing the models for SR and MRR. The model prediction errors may be reduced by limiting the range of process parameters, thereby developing separate models for finish region, semi finish region and rough machining region.

- Due to limitations on the input parameters in ANFIS model, only three thermo-physical properties of the work material were considered during model development. Boiling point and vapor point of work material is the most important factor in MRR. However, due to non-availability of these values for the alloying element these properties were not considered, otherwise if available this may help in developing a more precise prediction model.

- The thermo-physical properties of the tool material may be considered in model development to improve the prediction accuracy.

- In the present work polarity of the tool was kept constant. The effect of polarity on hybrid model development needs to be studied.

- The effect of debris concentration in dielectric was not considered in the present work, which needs further investigations on the prediction accuracy of the developed hybrid models.

- Data base for a group of mould and die steel materials may be developed from the given model and can be interfaced to the EDM machine so that even un-skilled operator can select optimal parameters from the given data base.