Chapter 5

Conclusions

The aim of the present investigation was electric discharge drilling of small diameter deep hole in nickel-base superalloy, Inconel 718 using different tool electrode materials such as copper, copper-tungsten and graphite. The key operating parameters and their ranges were identified. The machining performance was done with respect to the following: (i) Material Removal Rate (MRR), (ii) Tool Wear Rate (TWR), (iii) Electrode Wear Ratio (EWR) and (iv) Depth Averaged Surface Roughness (DASR), and effect of operating parameters were studied on responses namely MRR, TWR, EWR and DASR. Then, the performances of copper, copper-tungsten and graphite tube electrodes were compared. Copper electrode was selected for drilling high aspect ratio deep hole (62 mm depth) in Inconel 718. The geometrical quality of the high aspect ratio deep holes were studied with respect to the following: (i) Hole Profile, (ii) Depth Averaged Radial Overcut (DAROC) and (iv) Hole Quality Factor (HQB). Based on the experimental observations empirical models were developed as a function of operating parameters to predict MRR, TWR, EWR, DASR and DAROC. The following observations are drawn from the present investigation:

5.1 ELECTRIC DISCHARGE DRILLING OF INCONEL 718 USING COPPER ELECTRODE

(i) The factors such as average current, duty factor, electrode rotation and higher order effects of them, the interaction effects between average current and duty factor, and average current and electrode rotation have significant contributions in MRR model.

(ii) The MRR increases with the increase in average current, duty factor and electrode speed whilst pulse on-time has moderate effect on MRR.

(iii) Copper electrode tool wear significantly varies with average current, pulse on-time and electrode speed. The tool wear increases with average current and electrode speed and decreases with pulse on-time.

(iv) The factors such as average current, pulse on-time and higher order effect of average current, pulse on-time and electrode rotation, and interaction effect
between average current and pulse on-time, average current and electrode rotation have significant contribution on DASR model. The DASR increases with the increase in average current and pulse on-time.

(v) Increase in electrode speed leads to increase in MRR whereas DASR decreases to minimum value (in the range 200 - 300 rpm) and then increases.

(vi) For Inconel 718 and copper electrode, pulse on-time is less significant on MRR but highly significant on DASR. Hence low value of pulse on-time (20 µs) is recommended for low DASR value with high MRR.

(vii) The process parameters are optimized for the maximum MRR with the specified surface roughness values 3 and 3.5 µm using desirability function approach. The optimized parameters are in good agreement with the experimental values.

5.2 ELECTRIC DISCHARGE DRILLING OF INCONEL 718 USING COPPER-TUNGSTEN ELECTRODE

(i) Effect of average current and electrode speed on MRR is significant. The MRR increases with the increase in pulse on time up to 60 µs and then decreases. The maximum MRR is obtained at high average current and electrode speed.

(ii) In the case of TWR and EWR, it is observed that most influencing parameters are average current and electrode speed, higher order effect of average current, and the interaction between average current and electrode speed. The parameter pulse on-time has got less effect on EWR.

(iii) The average current, pulse on-time and higher order effect of pulse on-time are significant on DASR model. The effect of duty factor and electrode speed on surface roughness is insignificant. In order to obtain good surface finish, low values of average current and pulse on-time should be selected.

(iv) As rotational speed of the electrode increases, the DASR value decreases to a certain minimum value (upto 225 rpm) and then increases, whilst the increased electrode speed has produced high MRR and EWR.

(v) The confirmation experiments show that predicted responses are fairly in good agreement with the experimental values.
5.3 ELECTRIC DISCHARGE DRILLING OF INCONEL 718 USING GRAPHITE ELECTRODE

(i) The MRR is strongly influenced by average current, pulse on-time, electrode speed and interaction between average current and pulse on-time. The duty factor is statistically insignificant on the MRR for the significance level considered.

(ii) The MRR increases with the increase in current and electrode speed whilst it decreases with the increase in pulse on-time within the range of investigation.

(iii) The factors average current and pulse on-time are significant on TWR and EWR. The TWR and EWR for the graphite electrode are very low i.e. in no wear range (EWR < 1%). The maximum value of TWR and EWR observed within the range of study are 0.236 mg/min and 0.69 %, respectively.

(iv) The linear and quadratic effect of average current and pulse on-time, and interaction factors such as average current and pulse on-time, average current and duty factor, electrode speed and duty factor are statistically significant on DASR.

(v) As the pulse on-time increases, DASR increases up to a certain value and then decreases. Hence low value of pulse on-time (~ 20 µs) is recommended for good surface finish and high MRR.

(vi) The confirmation experiments show that predicted responses are fairly in good agreement with the experimental values.

5.4 SUMMARY

The summary of the observations are given below:

- Copper electrode has produced high MRR and low DASR with moderate electrode wear.
- The graphite electrode has produced moderate MRR and high DASR with EWR < 1% (no wear range). Whereas, the copper-tungsten electrode has produced low MRR with moderate DASR and EWR.
- High aspect ratio deep hole drilling of Inconel 718 using copper electrode shows three distinct segments in the hole profile: wide mouth at the top, barrel shape at the midway and narrow end at the bottom.
The DAROC is strongly influenced by pulse on-time. It increases with the increase in pulse on-time. The minimum and maximum DAROC obtained are 1.5 and 5% of the tool diameter.

The best HQF (1119 mm²) is obtained at I = 4 A, t_{on} = 40 μs, N = 300 rpm and η = 60%. The parameters corresponding to the best HQF condition are considered as reference parameters for obtaining good quality hole profile.

To obtain good geometrical quality hole with good surface finish and better material removal rate, moderate amperage of 4 to 8 A, low pulse on-time of 20 μs, and electrode speed between 200 and 300 rpm could be selected for Inconel 718 work material and copper electrode.

The DAROC and standard deviation of hole radius along the depth of hole are much less compared to STEM processes.

The present study provides a valuable source of reference for the selection of parameters like average current, pulse on-time, duty factor and electrode rotational speed to make good quality holes with high aspect ratio in nickel-base (Inconel 718) superalloy. The results obtained from the current research would be a good technical database for aerospace/automotive manufacturing on small diameter deep hole drilling of Inconel 718 superalloy.

5.5 SCOPE FOR FUTURE WORK

Present investigations have established sufficiently close relationship between the effect of operating parameters (average current, pulse on-time, duty factor and electrode speed) on MRR, TWR, EWR and DASR in deep hole drilling of Inconel 718. These studies are based on purely empirical methods. To know the effect of EDM deep hole drilling process in depth, fundamental parameters such as, gap current, voltage, pulse time, physical and thermal properties of electrode materials needs still accurate methods. This can be achieved by numerical analysis and simulation of deep hole drilling process. Further, the recast layer thickness can be investigated along the deep holes and modeled in order to optimize the process parameters to minimize the recast layer thickness. Attempts can be made to improve the surface roughness of EDM drilled holes by developing a hybrid process i.e. EDM combined with abrasive process, abrasive electric discharge drilling.