CHAPTER 5

SUMMARY AND CONCLUSION

In the earlier chapters, the effects of process variables on response characteristics (Material removal rate and surface roughness) of the micro-end milling process and micro wire electro discharge grinding process have been discussed. An optimal set of process variables that yields the optimum quality features to machined parts produced by micro machining processes has also been obtained. The important conclusions from the present research work are summarized in this chapter.

CONCLUSION

In this research work, the statistical techniques such as Taguchi method, Pareto ANOVA method, Taguchi quality loss function (TQLF), Principal component analysis (PCA) and Response surface methodology (RSM) are proposed for the optimization of quality characteristics in micro-end milling and micro WEDG processes.

MICRO-END MILLING PROCESS

Micro-end milling is emerging as an important milling process and it is widely used in most of the manufacturing industries due to its capability of producing complex geometric surfaces with reasonable accuracy and surface finish. In micro end milling material removal rate and surface
roughness are important aspects which require attention from industry personnel as well as Research and development. The responses of MRR and $R_a$ depend on the micro-machining parameters like spindle speed, feed rate and depth of cut. Based on the experimental work and analysis for the micro-end milling process using Taguchi technique and Pareto ANOVA, the following results are obtained.

Taguchi’s robust design of experiment technique is suitable to analyze the micro-end milling problems. This experimental results and analysis show that the optimal parameters for single response (MRR and $R_a$) in micro-end milling process using Taguchi approach and Pareto ANOVA for data analysis draw same conclusion. It is concluded that use of high cutting speed, low depth of cut and low feed rate are recommended to obtain the good surface finish in micro-end milling process. The optimum micro-end milling process parameters for good surface finish is determined as spindle speed = 80000 rpm, feed rate = 0.2 $\mu$m/sec and depth of cut = 10 $\mu$m. The optimized machining parameters are used for the confirmation of experiments for validation; the measured value for the surface roughness is 0.01 $\mu$m.

Also on the basis of the experimental result and analysis, it is concluded that use of medium value of spindle speed, higher value of depth of cut and higher value of feed rate are recommended to obtain the maximum MRR in micro-end milling process. The optimum micro-end milling process parameters for maximum MRR is determined as spindle speed = 70000 rpm, feed rate = 0.8 $\mu$m/sec and depth of cut = 40 $\mu$m. The optimized machining parameters are used for the confirmation of experiments for validation; the measured value for the MRR is $1.33\text{mm}^3/\text{min}$. 
When the single response problem is considered, one factor can be considered as very important to one quality characteristic while the other may not be so for the other quality characteristics in the micro-machining processes. However, most of the cases in industrial products present Multiple response problems. This problem can easily be augmented with the use of TQLF and a powerful multivariate statistical method called PCA.

In these experimental works, the significant factors and its interaction effects on maximum MRR and minimum $R_a$ are identified using Taguchi quality loss function. The optimum machining parameters are determined using TQLF technique for the multiple-response to achieve maximum MRR and minimum $R_a$. The optimum machining conditions for the spindle speed (A), feed rate (B) and depths of cut (C) are determined as 70000 rpm, 0.2µm/sec and 40µm respectively. The optimum response values of MRR and $R_a$ are 0.40mm$^3$/min. and 0.010µm respectively. As per the experimental result it is being concluded that, the TQLF technique is suitable for the optimization of Multiple-response problem. Taguchi’s parameter design methodology has been proved as an effective approach for producing high quality products at relatively low cost.

Engineering judgment for multiple response problems usually bring uncertainty to the decision-making process. In this work, Principal component analysis methodology is used for the Multiple-response optimization problem. The significant factors and its interaction effects are identified using PCA method for the multiple response optimization of micro-end milling process. The optimum machining conditions for the spindle speed (A), feed rate (B) and depth of cut (C) are determined as 70000 rpm, 0.8µm/sec and 40µm respectively in micro-end milling process using PCA technique. The optimum
response values of MRR and $R_a$ are 1.33mm$^3$/min and 0.073µm respectively. Based on the experimental result it is concluded that the PCA is suitable for the above-said problem. The predicted value of multiple response performance index (Z) is 0.6412 which is calculated by using additive model. The measured value of multiple response performance index (Z) is 0.707 which shows the good prediction accuracy.

As per the experimental results it is concluded that, the TQLF and PCA methods are suitable for the optimization of Multiple-response problem in micro-machining processes. However the TQLF and PCA techniques will give optimized parameter values in discrete form. Now-a-days MEMS technology is employed in micro-machining processes. So it is also possible to control the value of micromachining parameters in terms of non-discrete values. Hence in this research work, RSM is used to predict the optimized parameters of micro-machining processes. Statistical models have been developed for the MRR and $R_a$ using central composite design with three level factors. The optimum machining parameters are determined using these models for the multiple-response to achieve maximum MRR and minimum $R_a$. It is derived that at moderate speeds and depth of cut greater than 20 µm, the MRR is improved. Also it is observed that the surface finish is better when the feed rate is low and there is no significant influence of cutting speed on $R_a$. Further the developed models from multiple response optimizations, the optimum machining conditions for the spindle speed, feed rate and depth of cut are determined as 79438 rpm, 0.29µm/sec and 10µm respectively. The optimized machining parameters are used for the confirmation of experiments for validation and it is observed that the percentages of error for MRR and $R_a$ are 0.29% and 0% respectively, showing good agreement with the predicted responses.
MICRO-WEDG PROCESS

Micro-wire electro discharge grinding is a widely employed material removal process used to manufacture micro-components requiring intricate shapes and profiles with high level of surface finish. On the basis of experimental work and analysis for the micro-WEDG process using Taguchi technique and Pareto ANOVA, the following results are obtained.

Taguchi’s robust design of experiment technique is suitable to analyze the micro-WEDG problems. These experimental results and analysis show that the optimal parameters for single response (MRR and $R_a$) in micro-WEDG process using Taguchi approach and Pareto ANOVA for data analysis draw same conclusion. As per the statistical analysis, it is determined that capacitance is the most significant factor for surface roughness. These experimental results and analysis show that use of low feed rate, capacitance and voltage are recommended to obtain the good surface finish in micro-WEDG process. The optimum micro-WEDG process parameters for good surface finish are determined as feed rate = $2\mu$m/sec, capacitance = 0.2nF and Voltage = 80V within the tested range of experiment. The optimized machining parameters are used for the confirmation of experiments for validation; the measured value for the surface roughness is 0.03 µm.

From the statistical analysis, it is concluded that feed rate, capacitance and voltage is the most significant factor for MRR. At the same time the result shows that the individual effect of feed rate, capacitance and voltage are contributing more on MRR comparing to the interaction effect. Also through this experiment it is decided that the use of medium feed rate, higher value of capacitance and voltage are recommended to obtain the maximum MRR in micro-WEDG process. The optimum micro-WEDG
process parameters for the maximum MRR are determined as feed rate = 4µm/sec, capacitance = 10.0nF and Voltage = 120 V within the tested range of experiment. The optimized machining parameters are used for the confirmation of experiments for validation; the measured value for the MRR is 0.39 µm.

In this experimental works, the significant factors and its interaction effects on maximum MRR and minimum $R_a$ are identified using Taguchi quality loss function. The optimum machining parameters are determined using TQLF technique for the multiple-response to achieve maximum MRR and minimum $R_a$. The optimum machining conditions for the Feed rate (B), Capacitance (D) and Voltage (F) are determined as 4µm/sec, 0.1nF and 120V respectively in micro-WEDG process. The optimum response values of MRR and $R_a$ are 0.12mg/min. and 0.07µm respectively. Based on the experimental result it is derived that the TQLF technique is suitable for the optimization of multiple response problem.

Also in this work, Principal component analysis methodology is used for the Multiple-response optimization problem. The significant factors and its interaction effects are identified using PCA method for the multiple response optimization of micro-WEDG process. The optimum machining parameters are determined using multiple response performance index value for the multiple-response to achieve maximum MRR and minimum $R_a$. The optimum machining conditions for the Feed rate (B), Capacitance (D) and Voltage (F) are determined as 4µm/sec, 10.0nF and 120V respectively in micro-WEDG process. The optimum response values of MRR and $R_a$ are 0.39mg/min. and 0.59µm respectively. The predicted value of multiple response performance index (Z) is 0.6927 which is calculated by using
additive model. The measured value of multiple response performance index (Z) is 0.7711 which shows the good prediction accuracy.

Statistical models have been developed for the MRR and $R_a$ using central composite design with three level factors. The optimum machining parameters are determined using these models for the multiple-response to achieve maximum MRR and minimum $R_a$. The developed model for MRR is tested for its significance using ANOVA analysis. As the feed rate increases the spark energy is more involved in material removal which increases MRR till it reaches to the optimum. For further increase of feed rate from the optimum, there will be a reduction in contact time between tool and work piece to get the enough spark energy which reduces the MRR and also affects the surface finishing. Also with increase of capacitance, high energy dissipated which erodes more work material with stronger spark. A part of energy is used to spark the unflashed material. Because of this a lower amount of MRR it is concluded that the surface finish is better when the capacitance and voltage seem to be low and further found that there is no significant influence of feed rate on $R_a$. From the desirability surface for Feed rate (B), Capacitance (D) and Voltage (F), the optimum machining conditions for the Feed rate (B), Capacitance (D) and Voltage (F) are determined as 0.02µm/sec, 0.1nF and 89.56V respectively. The optimum response values of MRR and $R_a$ are 0.027mg/min. and 0.04µm respectively. Optimized machining parameters obtained from Multiple response optimization are used in verification experiments. From the verification experimental results, the values of MRR and $R_a$ are observed as 0.03mg/min and 0.04µm respectively. The percentage of error for MRR and $R_a$ shows good prediction accuracy.
Among the various methods for optimization of micro-machining processes used in this research work, the Response surface methodology is proved to be more reliable than the other statistical techniques.

**SCOPE FOR THE FUTURE WORK**

- In this work, Multiple-response optimization methods have been applied for micro-WEDG process and micro-end milling processes. These experimental works can be extended to other micro machining processes like micro-EDM drilling process, micro-wire EDM process, micro-ECM process micro-turning process etc.,

- The number of input machining parameters can be extended (like wire speed, wire tension, length of work-piece etc. in micro-wire EDG process) and hence the data-base can be improved by experimentation.

- The experiment can be replicated with other tool and work-piece material.

- The parameters used in the micro-end milling process can be extended to the direction considering the other parameters of cutting tools such as length, radius and flute can be considered for more accuracy point of view.

- In this work, Taguchi technique, Principal component analysis technique and Response surface methodology are used. This experimental data can be analyzed using other intelligent
techniques like Artificial Neural Network (A.N.N), Neuro-fuzzy, Particle Swarm Optimization, Genetic Algorithm, Hidden Markov model (H.M.M) etc.

- The weightages to be assigned to various characteristics in Multiple response optimization models should be based upon requirements of industries.