5.1 SUMMARY

The present study is mainly concerned with assessment of the performance of different electrodes in micro electrical discharge machining of EN24 die steel. All the trials have been conducted with parameters being selected based on $L_{16}$ orthogonal array and ensuring generation of reliable data. The major conclusions drawn from the observations are presented in this chapter.

It is found that among the electrode materials, Cu facilitates highest MRR while with W electrode only least MRR is realized. Next to copper, AgW has shown better MRR than other two electrodes and also MRR registered a rise up to the range of gap voltage 100-120V, above which it drops down. While considering four levels of discharge energy, it is seen that with higher discharge energy MRR drops down. Experimental results indicate that gap voltage up to medium range, lower capacitance, higher feed rate and medium threshold facilitate better MRR.

Copper exhibits higher TWR followed by copper tungsten and tungsten shows the lowest. In the lower discharge energy, minor variations in TWR are observed. In the medium and high discharge energy copper shows high electrode wear than that of other electrodes as it exhibits identical machining conditions due to its highest thermal conductivity. Similarly, wear
of copper is greater owing to its lower density and hardness than the other electrodes used. With lower feed rate when discharge energy increases, rise in TWR is observed with almost all electrodes. Due to the increase in feed rate, an increase in TWR is observed to a certain level and in the higher feed rate TWR drops down.

As per the experimental investigations, Cu and CuW show the maximum overcut than the other electrodes used for machining process. With medium discharge energy range, relatively constrained overcut occurs and uniformly good quality erosion can thereby be obtained. With lower and higher discharge energy, high percentage of overcut is observed. Overcut tends to increase with higher voltage combination and increasing discharge energy.

It is seen that Cu electrode exhibits reducing (drops) circularity error up to 100V combination, above which a rise in circularity error occurs. It is also found that with the increase of discharge energy, the circularity of the micro-holes increases. Cu experiences least circularity error with 100V conditions. Among the tungsten based electrodes, AgW exhibits increasing circularity error up to 100V, followed by a drop. CuW and W exhibit a reducing order of circularity error up to 120V, followed by a rise. It is seen that mostly Cu and CuW exhibit wider variation in circularity error, attributed to higher order tool wear and MRR.

With the increase of gap voltage SR gradually increases. AgW electrode provides lower SR when compared to other electrodes, whereas copper exhibits higher SR. It is found that low discharge energy is optimal for achieving minimum SR. The presence of HAZ and micro-cracks are found almost in all the electrodes used. It is observed that Cu and CuW electrode shows deeper HAZ than W and AgW. While using W and AgW only lesser micro-cracks are observed. From the EDAX analysis, it is identified that the
significant amount of carbon migrated to the workpiece due to decomposition of dielectric determines the hardness of the machined surface. W and AgW exhibit highest micro-hardness and better surface finish whereas CuW and Cu show lesser hardness. For Cu and CuW more debris is spattered on the machined surface. W and AgW specimens exhibit minimum debris and a few pin holes (micro pore) and cracks are identified.

Based on the effect of input parameters, the overall performance analysis shows that gap voltage and capacitance exert more influence than feed rate and threshold. Tungsten-based electrodes prove to be better as they exhibit good surface finish with lower TWR but copper exhibits the highest MRR.

As in the conventional EDM, discharge energy plays a vital role on the performance of the electrodes with micro-EDM. Optimizing the machining conditions based on MRR, TWR and SR, the electrodes specific conditions have been arrived at.

According to the integration of GRA and S/N ratio, it is concluded that gap voltage and capacitance are the main influencing parameters rather than feed rate and threshold. Moreover, the significant machining parameter for whole machining performance is gap voltage 80-100V, capacitance 0.1nF and threshold 20- 60%. However, fine feed rate is required for all the electrodes whereas higher feed rate is expected for tungsten electrode. Considering the significance of surface roughness in micro-EDM, both W and AgW facilitate better surface finish while Cu results in higher order surface roughness. The performance characteristics such as MRR, TWR and SR are improved together by the method proposed in this study.

For the better productivity and accuracy of EN24 die steel, SPSS software was employed for modeling of MRR, TWR and SR. These responses
were validated experimentally. To obtain higher MRR, it is identified that the Cu electrode requires higher gap voltage whereas W and AgW are more sensitive to gap voltage. All the electrodes require least order threshold and least order capacitance. Cu electrode shows higher MRR with lower feed rate while other electrodes require the higher feed rate. Modeling of TWR and surface roughness indicates that all the electrodes exhibit direct proportionality to gap voltage, capacitance and feed rate, while it is inversely proportional to threshold. The result shows that out of all the input parameters, gap voltage proves to be the most influencing factor.

Among the electrodes, Cu exhibits higher order MRR, tool wear, overcut and circularity error, while tungsten shows better performance. It is also identified that Cu can be used for rough cutting, while tungsten and tungsten-based electrodes are for fine finishing. As proved by the experiments, the die-sinking micro-EDM can achieve high quality micro-holes with suitable electrodes.

5.2 CONTRIBUTION TO RESEARCH

This research work offers new insights into the performance of die-sinking micro-EDM of EN24 die steel using different electrodes. Based on the effect of input parameters and analysis of various output performance, the material specific electrode was identified to produce quality micro-holes. In order to identify the most significant parameters value for machining performance the Taguchi-based grey relational analysis was used and this optimization technique is recommended to be a useful tool for predicting MRR, TWR and SR. Further a mathematical modeling was employed to analyze the influencing factors and also identified the related constraints. These findings are useful to the micro-EDM researchers and manufacturing engineers in selecting the appropriate parametric combinations for machining EN24 die steel. It is expected that the models and experimental data in this
work would help the micro-EDM researchers not only to extend the understanding of the process but also to improve the process and product design.

5.3 SCOPE FOR FURTHER RESEARCH

In die-sinking micro-EDM process, further research can be done using different materials such as doped semi/non-conductive materials, composite and ceramic materials. Further, ultrasonic vibrated workpiece and tank can be adopted to enhance the performance of the process. An in-depth study can be done to understand the influence of properties of electrodes as they affect the output performance. Geometry prediction and simulation of die-sinking micro-EDM process can be done for the better understanding of the influence of machining parameters on the responses. Future study can concentrate on producing new composite electrodes with specific properties suitable to produce micro-holes.