CHAPTER 5
CONCLUSIONS

Based on the results of the experiments and analyses carried out the following general conclusions are drawn:

- Application of solid-liquid mixture lubricants with a brush at the metal cutting zone is a better technique for reducing the cutting tool temperature as compared to cooling with flooded water and soluble oil mixture fluids while turning EN-31 steel.
- The reduction of tool temperature due to solid-liquid lubricants is due to reduction in heat produced at the chip-tool interface because of lubricating action by the solid-liquid lubricants seeping in the chip-tool interface, when applied at the shearing zone, as the coefficient of friction is much lower in this case as compared to flooded coolant applications.
- The reduction in tool temperature with flooded coolant application is due to the cooling action of the fluid applied. In this case the coefficient of friction is even higher than in dry machining.
- 10% boric acid + SAE-40 oil is the best solid-liquid lubricant out of the various combinations of solid-liquid lubricants applied with a brush is the best technique that improves all the machinability parameters. As a negligible quantity of lubricant seeps to the chip-tool interface, it may be regarded as a true minimum quantity lubrication technique (MQL) or near dry lubrication (NDL) technique.
- The tool-work thermocouple technique is a good method for measuring the average chip-tool interface temperature during metal cutting. The benefits of using the tool-work thermocouple are its ease of implementation and its low cost as compared to other techniques.
- The calibration technique used in this work is more simple and reliable technique as compared to other technique.
- The net percentage decrease in the chip-tool interface temperature value is dependent upon the type of minimum quantity lubrication. So there is decrease of chip-tool interface temperature values approximately from 18% to 20.48% due to flood, 23% due to 10% graphite + SAE-40 oil,
28% due to 10% MoS₂ + SAE-40 oil and 31% due to 10% boric acid + SAE-40 base oil as compared to dry machining. This shows the superiority of 10% boric acid + SAE-40 mixtures when used as lubricant in reducing the chip-tool interface temperature.

- Minimum quantity lubricant (10% boric acid + SAE-40 oil) reduces the cutting forces by about 6% to 9% due to flood, 12% due to 10% graphite + SAE-40 oil, 23% due to 10% MoS₂ + SAE-40 oil and 48.23% due to 10% boric acid + SAE-40 base oil. Similarly, the feed force reduces by 4% to 6% due to flood cooling, 16.92% due to 10% graphite + SAE-40 oil, 33.07% due to 10% MoS₂ + SAE-40 oil and 49.89% due to 10% boric acid + SAE-40 base oil.

- The surface quality is better controlled by the minimum quantity lubricants (10% boric acid + SAE-40 base oil, 10% MoS₂ + SAE-40 base oil and 10% graphite + SAE-40 base oil). There is a decrease in surface roughness values approximately from 4 to 8% due to flood machining, 10 to 12% 10% graphite + SAE-40 base oil, 14 to 17% due to 10% MoS₂ + SAE-40 base oil and 26% due to 10% boric acid mixed with SAE-40 base oil.

- Minimum quantity lubricant reduces the tool wear rate by about 9% to 13.84% due to flood machining, 12 to 28.41% due to 10% graphite + SAE-40 base oil, 35% due to 10% MoS₂ + SAE-40 base oil and 46.35% due to 10% boric acid mixed with SAE-40 base oil as compared to dry machining.

- The reduction in chip thickness was observed to be maximum (7% to 26%) with minimum quantity of lubrication technique as compared to dry and flood cutting. The minimum quantity lubricant (10% boric acid + SAE-40 base oil) reduces the chip thickness.

- Machining with 10% boric acid + SAE-40 base oil consumes the lowest power i.e. 41% less as compared to 10% graphite + SAE-40 base oil, 10% MoS₂ + SAE-40 base oil followed by dry and flood machining.

- The size and shape of chips produced with MQL are the most favorable ones for machining. Therefore, the chips obtained in MQL cutting conditions are easy to handle and economical to dispose off. Due to minimum quantity lubricant application, color of the steel chips shows more effective cooling and improvement in the nature of interaction at the chip-tool interface. 10% boric acid mixed with SAE-40 base oil (MQL) is more favorable for breaking the
produced chips into the desired shape and size as compared to 10% graphite + SAE-40 oil, 10% MoS₂ + SAE-40 oil, dry and flooded lubricant machining during steel turning operation.

- The shear angle increases to a maximum of 12% in MQL (solid-liquid) machining as compared to dry and flood machining. Higher shear plane angle means smaller shear plane which means lower shear force, cutting force, power, and cutting temperature and chip thickness. Higher shear plane angle produces better surface finish as well as it assists the chip to flow away from the work-piece.

- The feed rate has a higher effect on the chip-tool contact length than the cutting speed during turning of EN-31 steel. Hence, at higher feed rates, the chip-tool contact length increases. The solid-liquid (MQL) assisted turning produces lower values of chip-tool contact length as compared to the dry and flood-cooled turning, that results in lower cutting zone temperatures and lower tool wear rate. It has been confirmed by the experiments. The reduced chip-tool contact length produces lower compression ratio, which improves surface finish during steel turning. Among the three (solid-liquid) MQL lubricant assisted turning, 10% boric acid + SAE-40 oil assisted turning is more effective as compared to 10% MoS₂ + SAE-40 oil, 10% graphite + SAE-40 oil assisted turning.

- The MQL(solid-liquid) assisted turning produced low values of specific cutting force compared to dry and flood turning and it produces lower cutting zone temperatures and tool wear rate, which improves the surface finish during steel turning. Among the three (solid-liquid) MQL lubricant assisted turning, 10% boric acid + SAE-40 oil assisted turning shows better results as compared to 10% MoS₂ + SAE-40 oil, 10% graphite + SAE-40 oil assisted turning.

- Among the three (solid-liquid) MQL lubricant assisted turning, 10% boric acid + SAE-40 oil assisted turning shows maximum machining ratio as compared to 10% MoS₂ + SAE-40 oil, 10% graphite + SAE-40 oil assisted turning. Dry and flood condition assisted turning observed low values of maximum machining ratio as compared to solid-liquid lubricant turning. So, it can
beconcluded that early failure of the cutting tool occurs in dry machining followed by flood coolant and then (solid-liquid) MQL machining.

- The microhardness of chip is the lowest when machining is performed with 10% boric acid mixed with SAE-40 base oil (MQL) compared to other solid-liquid lubricants, dry and flooded coolant machining.
- Global Lubricant index determined by AHP-TOPSIS method has also proved that 10% boric acid + SAE-40 oil MQL is the best technique.
- Mathematical models developed using RSM coupled with factorial design to predict the various machinability parameters such as chip-tool interface temperatures, cutting forces, surface roughness, tool wear rate, chip thickness, chip micro-hardness and power consumption for turning EN31 steel with tungsten carbide tool under dry, flooded coolant machining and solid-liquid MQL lubricants are statistically valid and sound. These are validated by the confirmation run experiments therefore proven that they could be used for prediction within the range of cutting speed, feed rate, depth of cut, tool nose radius and concentration of solid lubricants specified. These models can be utilized to select the levels of turning parameters. Using these models, a noticeable savings in time and cost may be expected. (empirical models are given in Annexure II)
- ROVOP technique is a useful technique that scans the entire area determining optimal values of cutting velocity and percentage concentration of lubricants. The maximum cooling efficiency is obtained at optimum combination of higher cutting velocity (189m/min) and lower combination of solid-liquid lubricants (10% solid lubricants + SAE-40 oil).
  The maximum cooling efficiency is obtained when applying 10% boric acid with SAE-40 base oil during steel turning operations as compared to 10% graphite and 10% MoS2 powder mixed with SAE-40 base oil.
- The application of response surface approach with grey relational grade analysis to determine the best combination values of cutting parameters, such as cutting speed, feed rate, depth of cut and tool nose radius for simultaneously improving different machinability characteristics during turning of En31 steel with tungsten carbide tool under dry, flooded and MQL (solid-liquid) machining is an efficient multi-objective optimization technique.
A multi-objective performance characteristic is calculated, called as grey relational grade by using grey relational analysis. The response surface models developed for the grey relational grade are reliable models. Then, multi-objective optimization is done using these response surface models. The model predictions agree well with the experimental results. The best combination of cutting parameters that improve the machinability indices (such as chip-tool interface temperature, surface roughness, cutting forces, and tool wear and chip thickness) simultaneously are determined by the method (The models are given in Annexure III).

The principal component analysis, used to determine the corresponding weighting values of each performance characteristics whilst applying grey relational analysis to a problem with multiple-performance characteristics, is proven to be capable of objectively reflecting the relative importance of each performance characteristic.

These developed grey relational models can be effectively used to predict the correlation between machining parameters and multi-performance grey relational grade under dry, flooded and solid-liquid (MQL) lubricant/cooling machining. These developed models will help in selecting the best combinations of machining parameters for achieving optimum multi-performance (machinability) characteristics during steel turning process under given machining conditions. This eventually reduces the machining time, operation efforts, cost and save the cutting tools. A good combination among the machining parameters can provide better multi-performance characteristics (highest grey relational grade).

The proposed algorithm greatly simplifies the optimization design of lathe turning parameters with multiple-performance characteristics. Thus, the solutions from this method can be used by engineers who are willing to search for an optimal solution of metal cutting operation. In future, this study can be extended to different metal cutting operation with different work materials and machine tools and hybrid optimization technique.

- Optimum combination of machining parameters for the best machinability of En-31 steel material are cutting velocity 189m/min, feed rate 0.06mm/rev, depth of cut 0.2mm, tool nose radius 1.2mm and MQL (10% boric acid + SAE-40 oil).
• Various machinability indices at this optimum combination of cutting parameters are chip-tool interface temperature 291.83°C, cutting force 84.22 N, feed force 54.70 N, surface roughness 8.19 µm, tool wear rate 0.240 mg/min and chip thickness 0.30mm.

The conclusions drawn from the study of the effect of temperature of MQL on machinability, using Taguchi design and Utility concept, are given below.

• The effect of feed rate is much more pronounced than the effects of depth of cut and MQL lubricant temperature (10% boric acid + SAE-40 oil), on the surface roughness.

• For minimum surface roughness, use of lower feed rate (0.05mm/rev), medium depth of cut (0.4mm) and low lubricant temperature (10°C) are recommended to obtain better surface finish for the specific test range. Thus the surface finish is better if cooled lubricant is applied.

• For minimum power consumption low feed rate (0.05mm/rev), high depth of cut (0.4mm) and high lubricant temperature (50°C) are optimum parameters.

• Deviations between actual and predicted S/N ratio of surface roughness and power consumption are small.

• To control turning process for minimizing the power consumption with MQL (10% boric acid+SAE-40 oil), the lubricant temperature plays an important role. On increasing the lubricant temperature the cutting forces decrease means minimum power consumption. Power consumption decrease by 21%.

• Surface finish deteriorates as the lubricant temperature increases within the used range of parameters.

• The analysis of means (ANOM) technique has proved that the combinations required for simultaneously minimizing the surface roughness and power consumption in turning EN-31 steel with tungsten carbide insert under MQL are: feed rate at low level, depth of cut at middle level and lubricant temperature at higher levels.

• The utility based Taguchi method applied to this problem is a fruitful technique for evaluating the optimum parameter setting. This approach is efficient enough to solve multi-response optimization problem. Confirmatory test has validated the parameter setting determined by utility based Taguchi method at 95% confidence level.