# CHAPTER 6

# SUMMARY AND CONCLUSIONS

## 6.1 SUMMARY

In mining and automotive sectors, failures of the mechanical components are due to the tribological reasons and as a rough estimation, one third of world's energy resources appear as friction in one hand and waste in other hand. This shows the importance of tribology, which would lead to considerable savings. Research efforts have been made with an aim to reduce the wear of mineral processing equipments (vibrating screens, cyclones, pumps, and heavy medium vessels) and also to reduce the wear of automotive components (crankshafts, connecting rods, axle, and gear). The frequent replacement of these components increases the equipment downtime and maintenance cost, thereby reducing the process efficiency. Hence, the present research work studies the effect of cryogenic treatment on properties in En 19 steel. Two kinds of cryogenic treatment, namely shallow (SCT, $-80$ ◦C×5 h) and deep cryogenic treatment (DCT, $-196$ ◦C×24 h) are carried out between quenching and tempering in conventional heat treatment process. The aim of present study is to provide a guide for the automotive and heat treating engineers so that they know the treatment conditions for the parts to be produced. Besides, this research work will also assist the engineers to save time, energy and cost.

## 6.2 CONCLUSIONS

Based on this research through various tests and characterization studies, the following conclusions are drawn

- Both shallow and deep cryogenic treatment promotes the transformation of retained austenite into martensite, causing an increase in hardness. The most positive effect after the transformation of retained austenite along with the carbide precipitation increases dimensional stability.

- Wear resistance has been increased by 118.38% for SCT samples and 214.94% for DCT samples when compared to CHT samples. In addition, the increase in wear resistance of DCT samples is 44.39% with respect to SCT samples. It is also found that wear linearly increases by increasing load at constant sliding velocity. The wear linearly increases with respect to sliding velocity at constant applied load. The lowest coefficient of friction is obtained in DCT samples treated at -196ºC for 24 hours.

- The improvements in wear resistance of both SCT and DCT samples with respect to CHT samples decreases with increasing load and also there is a reduction in coefficient of friction with the increasing load for each sample.

- The toughness of the En 19 steel is not significantly influenced by SCT and DCT samples. However, the expected drop in toughness for these samples due to the reduced amount of austenite, is not observed. This is interpreted as the possible evidence of a *low temperature* condi*tioning of* *martensite*, leading to a finer transition carbides precipitation during tempering

- A slight reduction in tensile strength can also be found out. This has to be expected and is not so interesting from the point of view of the application. However, in view of the enhancement attained in wear resistance, where developments of 143% for shallow cryogenic treatment and 250% for deep cryogenic treatment are reported, the insignificant decrease in tensile strength suggests that the reduced tensile strength is an acceptable deviation. The scanning electron microscope analyses of the fracture surfaces indicate the tensile samples subjected to the deep cryogenic treatment, which show lesser ductility reflected in slightly lower tensile strength.

- Both shallow and deep cryogenic treatment promotes the transformation of retained austenite into martensite causing an increase in hardness and wear resistance. It also proved that the entire elimination of retained austenite is not attained even after the samples are treated at deep cryogenic conditions. Hence, small amount of retained austenite are present in deep cryogenically treated samples and shallow cryogenically treated samples.

- Similar values of compressive macrostresses are measured after quenching and further SCT while higher stresses developed after DCT. The reduction in temperature reduces density of lattice defects and thermodynamic instability of martensite driving carbon and alloying elements to nearby defects. These clusters act as nuclei for the formation of fine carbides when stress is relieved or tempered subsequently. The precipitation of carbides in tempered SCT and DCT samples is responsible for the residual stress relaxation

- However, the decrease in the temperature of cryogenic treatment leads to more transformation of austenite into martensite and hence, greater compressive residual stress develops in the untempered DCT samples when compared with SCT and CHT respectively

- It is revealed that the residual state of surface stress is found to decrease by 164% for DCT (-69.1 MPa) when compared to CHT (+ 108.1 MPa), whereas for SCT (+19.6 MPa) the decrease is 82% when compared to CHT (+108.1 MPa)

- This residual stress analysis concludes that in En 19 steel maximum compressive stress is developed after DCT, before tempering. This is highlighted to positively influence the state of stress after stress relieving. Tensile stress is observed in tempered CHT and SCT samples while a residual compressive stress is found after DCT.

- It is concluded that the SCT and DCT help to reduce the tensile residual stress state on the surface of the En 19 steel. The compressive stress on the surface of the DCT samples leads to increase in hardness, wear resistance, and impact resistance of the steel components. It also gives resistance to the crack growth

- The corrosion behaviour of the cryogenically treated (SCT and DCT) and the conventionally heat treated (CHT) samples is studied in alkali environment. The deep cryogenic treatment seems to offer higher corrosion resistance than the other samples, which together with the high increase in wear resistance makes this treatment a potentially interesting one for improvement of overall performance of the En 19

- A slight reduction in inverse quality factor ($Q^{-1}$) and damping percentage are observed in the shallow cryogenic treatment and deep cryogenic treatment samples when compared to conventional heat treatment sample.

- From the optimization study, the percentage contribution of hardening temperature (A) is 17.34%. The optimum hardening temperature is 880°C. The next significant factor is tempering temperature (C), which contributes to 11.6% over wear loss. The optimum temperature is 200°C. The soaking period (B) and tempering period (D) have least influence on wear loss, which contributes 2.32% and 2.35%, respectively. The optimal value of soaking period (B) is 24 hours, and the tempering period (D) is one hour.

- It is identified that both the interaction of soaking period vs. tempering period (BxD) and the hardening temperature vs. tempering temperature (AxC) is more significant than the interacation of other factors. Following that the hardening temperature versus soaking period (AxB) have some influence and the interaction effect among the other remaining factors have the least influence.

From the present research work, it is concluded that the cryogenic treatment could enhance the hardness, wear resistance, compressive residual stress and corrosion resistance of En 19 steel pertaining to screen section used in mineral processing industries besides other components namely rifle barrels, joints, bushes, gears, axle shafts, crank shafts, connecting rods and steering components. The purpose of this present study is to provide a guide for the automotive and heat treating engineers so that they know the treatment conditions and benefits for the part to be produced.

## 6.3 SCOPE FOR FUTURE RESEARCH WORK

The purpose of this study is to show a proper engineering evaluation on the effect of cryogenic treatment on behaviour of a high-demand alloy, En 19 steel. The scope for further study is as follows:

- The mechanism of shallow and deep cryogenic treatment, the size, the pattern of distribution and precipitation of carbides may be analyzed by using TEM analysis
- Fatigue analysis to predict the fatigue life of the cryogenically treated En 19 steel can be carried out
- Thermo mechanical analysis can be carried out to find the dimensional stability of samples subjected to shallow and deep cryogenic treatment
- Fracture toughness tests can also be determined to find out the influence of cryogenic treatment on this property
- A study on stress corrosion cracking to detect differences in corrosion between various treatments is possible
- Optimization of some other deep cryogenic treatment parameters namely soaking temperature, cooling rate and

heating rate can be further studied to identify the best combination of some more treatment conditions

- Mathematical modelling of the optimization process can also be carried out using intelligent softwares namely Genetic algorithm and Artificial Neural Network