CHAPTER VIII

CONCLUSIONS

The present investigations on heat treatment of copper alloyed and copper-nickel alloyed ADI has led to the following conclusions:

1. The average carbon content of austenite appears to saturate after 120 min. of austenitization at 850^0C and after 60 min. of austenitization at 900^0C. The theoretical time of austenitization, for saturation of carbon content of austenite, calculated from the mathematical model is in good agreement with these experimental results.

2. The mathematical model suggests that the time required for complete austenitization increases exponentially with reciprocal austenitization temperature.

3. When copper alloyed iron is autenitized at 900^0C for 60 minutes and subsequently austempered at 330^0C, the bainitic ferrite needles appear after an incubation period of 2 min. preferentially at the graphite/austenite interface as indicated by metallography and measurements of microhardness.

4. Further progress of austempering process takes place by the bainitic transformation in the intercellular regions and there is increase in the number and size of bainitic ferrite needles which reject carbon in the surrounding austenite enriching it with carbon to make it stable. On quenching after austempering, the microstructures obtained, show that the amount of retained austenite increases and the amount of martensite decreases with progress of austempering and in later stage martensite disappears completely.

5. When the time of austenitization is increased to achieve more uniform carbon distribution, the bainitic ferrite and retained austenite get distributed more uniformly as evident from the austempered microstructures of copper alloyed ADI.

6. When the austenitization time is increased beyond 60 min. at 900^0C, the austempered microstructure becomes relatively coarser, possibly due to grain growth in austenite and the distribution of bainitic ferrite and retained austenite becomes non-uniform.

7. When the austenitization temperature is increased from 850 to 900^0C, the carbon content of austenite increases and the austempered microstructure of copper alloyed ADI coarsens. The volume fraction of retained austenite increases resulting in blocky retained austenite.

8. The volume fraction of retained austenite and its carbon content increase with increasing austenitization time because of more carbon dissolution from the nodule but the increase in the size of bainitic ferrite needle is marginal showing significant grain growth of austenite till equilibrium is attained.

9. The average volume fraction of retained austenite, its average carbon content, the product $X_\gamma C_\gamma$ and the size of bainitic ferrite needles in austempered copper alloyed iron increase on increasing austenitization temperature from 850 to 900^0C.

10. When austempering is carried out at 270^0C, the austempered microstructure of copper alloyed ADI consists of lower bainite in the form of fine needles with the retained austenite in between these ferrite needles.

11. The morphology of bainitic ferrite changes from lower to upper bainite when the austempering temperature is increased. The size and the amount of retained austenite also increase.

12. When austempering is carried out at relatively higher temperature of 380^0C, the microstructure of copper alloyed ADI consists of coarse upper bainite with no lower bainite and relatively more retained austenite present in large blocky form.

13. At short austempering time at a given temperature the austempered microstructure at ambient temperature consists of bainitic ferrite, retained austenite and a substantial amount of martensite. As the austempering time is increased the amount of bainitic ferrite and retained austenite increase while the amount of martensite decreases. Martensite phase eventually disappears beyond a certain austempering time.

14. When the austempering temperature is increased from 270 to 380^{0}C, the volume fraction of retained austenite, the product $X_\gamma C_\gamma$ and the size of bainitic ferrite needle increase for both the austenitization temperatures. The average carbon content in retained austenite increases with austempering temperature for austenitization at 850^{0}C while for austenitization at 900^{0}C it increases up to 330^{0}C and then decreases.

15. The volume fraction of retained austenite, its carbon content and $X_\gamma C_\gamma$ in copper alloyed ADI increase with increasing austempering time at 330^{0}C, reach a plateau and then decrease for both the austenitization temperatures.

16. The austempered microstructures of Cu-Ni alloyed ADI consists primarily of lower bainite and retained austenite when austempered at 270^{0}C; however, it consists primarily of upper bainite and retained austenite for austempering at 330^{0}C.

17. Significantly more amount of upper bainite has been observed in the austempered microstructure of Cu-Ni alloyed ADI than that observed in copper alloyed ADI austempered at 330^{0}C.

18. The austempered microstructure of Cu-Ni alloyed ADI changes in respect of its constituents with austempering time similarly as observed for copper alloyed ADI given in conclusion 13.

19. The variations of volume fraction of retained austenite, its carbon content and the product, $X_{\gamma}C_{\gamma}$ with austempering time in Cu-Ni alloyed ADI are similar to those observed in copper alloyed ADI as outlined in conclusion 15.

20. Increasing austenitization temperature and the addition of nickel in the base iron results in decreasing the rate of stage I of austempering reaction. However, the increasing austenitization temperature has relatively stronger effect on the austempering kinetics compared to that of addition of nickel in base ductile iron. Carbon is a potent element causing delay in stage I of austempering process and it may be controlled by austenitization temperature.

21. The mechanical properties measured are highly consistent in different samples for copper alloyed ADI austenitized at 850^{0}C for 120 min. and at 900^{0}C for 60 min. when austempered at 330^{0}C. This has been attributed to homogeneity of microstructure.

22. When the austenitization temperature is increased from 850 to 900^{0}C, the hardness decreases due to coarsening of microstructure in the ADI austempered at a temperature in the range between 270 to 330^{0}C. However, for austempering at 380^{0}C, there is a marginal increase in hardness with austenitization temperature possibly due to formation of martensite in the middle of blocky austenite.

23. In copper alloyed ADI it has been observed that hardness of copper alloyed ADI is relatively high at short austempering time due to the presence of martensite and it decreases with the progress of austempering process as the amount of martensite decreases. However, there is a slight increase in hardness at longer austempering times possibly due to stage II reaction in the sample.

24. The proof stress of ADI decreases with increasing austenitization temperature because of coarsening of bainitic ferrite. A Hall-Petch like relation may be applied for proof stress and the size of bainitic ferrite needle.

25. In copper alloyed ADI, there is decrease in proof stress with increasing austempering temperature for both the austenitization temperatures of 850 and 900^{0}C due to the change of morphology and the size of bainitic ferrite.

26. In copper alloyed ADI, the proof stress is relatively low at short austempering time due to the presence of martensite and it increases with the progress of austempering process as the amount of martensite decreases and the amount of bainitic ferrite increases. The decrease in proof stress at longer austempering time may probably be attributed to the onset of second stage of austempering.

27. When austempering temperature increases from 270 to 380^{0}C, the UTS of Copper alloyed ADI decreases because of change of morphology of bainitic ferrite.

28. When the austenitization temperature is increased from 850 to 900^{0}C, the UTS increases due to increased carbon content of retained austenite in the austempered microstructure in the copper alloyed ADI austempered at temperatures of 270 to 330^{0}C. However, for austempering at 380^{0}C, the UTS values are higher for samples austenitized at relatively lower temperature of 850^{0}C than those austenitized at 900^{0}C, which may be due to formation of martensite in the middle of blocky austenite.

29. In copper alloyed ADI, the UTS is small at short austempering times because of significant amount of martensite in the microstructure. As the austempering time increases the UTS increases due to increasing amounts of bainite and retained austenite after which it becomes more or less constant due to stability in the amount of bainite and retained austenite and disappearance of martensite.

30. In copper alloyed ADI, the percent elongation increases monotonically with increasing austempering temperature from 270 to 380^{0}C for austenitization at relatively lower temperature of 850^{0}C. This increase in percent elongation is due to a change in the morphology of bainitic ferrite, increasing amount of retained austenite, its carbon content and the product $X_\gamma C_\gamma$. However, at a relatively higher austenitization temperature of 900^{0}C, percent elongation increases with austempering temperature up to 330^{0}C, beyond which it decreases possibly due to formation of martensite in the middle of blocky austenite.

31. In copper alloyed ADI, the percent elongation is low at short austempering time due to the presence of martensite in the austempered microstructure and increases monotonically with austempering time accompanied by increasing amount of austenite and its carbon content in the austempered microstructure. For austenitization at relatively higher temperature of 900^{0}C the decrease in percent elongation at longer austempering time may be due to the onset of second stage of austempering.

32. In copper alloyed ADI, the quality index, QI, increases monotonically with increasing austempering temperature from 270 to 380^{0}C when austenitization is carried out at the temperature of 850^{0}C because of increasing ductility and decreasing UTS values. However, for austenitization at a relatively higher temperature of 900^{0}C, QI increases with increasing austempering temperature up to 330^{0}C, thereafter, it decreases when the austempering temperature is increased to 380^{0}C. The decrease in the latter case may be attributed to the presence of martensite at the middle of blocky austenite.

33. The quality index is low at short austempering time because of lower UTS and percent elongation. It increases on increasing austempering time as both UTS and % elongation increase. For the samples austenitized at relatively higher temperature of 900^{0}C, the quality index decreases at longer austempering times.

34. The copper alloyed ADIs exhibit higher instantaneous strain hardening coefficient, n, and a higher work hardening rate at small strain and both these variables decrease with increasing strain. Retained austenite formed in these ADIs, therefore, does not show any significant TRIP phenomenon.

35. SEM observations of fractured specimens of copper alloyed ADI for low austempering temperature of 270^0C indicate that the deformation is restricted primarily to the regions near the nodule. There is very little deformation in the intercellular regions. Many dimples of small size are present around the graphite nodule. This may be attributed to presence of lower bainite and lower volume fraction of retained austenite in austempered microstructure. As the austempering temperature is increased to 330^0C, the dimpled region spreads and the size of dimples increases. At an austempering temperature of 380^0C, the fractured surface shows a large number of dimples spread uniformly over the entire surface, which may be attributed to change in morphology of bainitic and increase in the volume fraction of retained austenite. However, in some regions microcleavage may also be observed.

36. The microstructures of transverse section of samples fractured under tension indicate that microvoids appear to form at the graphite-matrix interfaces, which then develop into cracks in the matrix adjacent to the graphite nodules.

37. The crack that has initiated at the graphite nodule and has propagated through the bainitic-ferrite/austenite interface when bainitic ferrite makes an angle greater than 45^0 with the applied load and cuts through it when the angle is less than 45^0 with the applied load.

38. When the austempering was carried out at 380^0C for 60 min., it has been observed that a number of cracks have initiated at the graphite nodule. However, these cracks have propagated through a very small distance into the matrix and then terminated. Some cracks have propagated along ferrite/austenite interface. Cracks are observed in the intercellular

region, which cuts through the bainitic ferrite laths. Inclusion particles present near the graphite nodule may also provide easy path for the propagation of crack.

39. Impact strength decreases with increasing austenitization temperature because of coarsening of microstructure. The difference is relatively less at lower austempering temperatures of 270 and 330^{0}C but it is more pronounced at higher austempering temperature of 380^{0}C.

40. When the austempering temperature is increased the impact strength increases because of increased amount of retained austenite and a change in the morphology of bainitic ferrite from lower to upper bainite.

41. The impact strength is very poor at short austempering time, which may be attributed to the presence of martensite. When the austempering time is increased the impact strength increases because the amount of martensite in the microstructure decreases and the amount of retained austenite increases. The impact strength decreases at longer austempering times, which may be due to the onset of the second stage of austempering.

42. Austempering at 270^{0}C for 60 min. after austenitization either at 850^{0}C or 900^{0}C of copper alloyed ADI results in mechanical properties close to those specified for ASTM grade 1200/4 having high strength and low ductility while austempering at 330^{0}C for 60 min. results in ADI close to ASTM grade 1050/7 having medium strength and good ductility. Austempering at 380^{0}C for 60min. produces an ADI close to ASTM grade 850/10 having low strength and high ductility.

43. The combination of mechanical properties like UTS, percent elongation and impact strength of copper alloyed ADI austempered at 330^{0}C fall below those specified in ASTM standard for short austempering time below of 30 min. The mechanical properties of ADI are better than those specified for standard ASTM grades for austempering times between 60 to 150 minutes in the present study.

44. The trend in the variation of all the mechanical properties like hardness, UTS, % elongation, quality index and impact strength with austempering time is similar for Cu-Ni alloyed ADI to those observed for the copper alloyed ductile iron heat treated similarly.

45. The level of hardness observed in austempered copper alloyed iron is higher than that of austempered Cu-Ni alloyed iron for all austempering times between 30 to 150 minutes.

46. The highest proof stress achieved in Cu-Ni alloyed ADI is lower than highest proof stress observed in copper alloyed ADI when austempered at the same austempering temperature of 330^{0}C after austenitization at 850^{0}C for 120 minutes.

47. The UTS of Cu-Ni alloyed ADI is higher than that of the copper alloyed ADI for a short austempering time of 30 min. However, beyond 30 min. of austempering, the UTS of Cu-Ni alloyed ADI is lower than that of copper alloyed ADI, which may be attributed to an increased amount of upper bainite in Cu-Ni alloyed iron for the same austempering temperature.

48. The highest percent elongation in austempered Cu-Ni alloyed iron is higher than that observed in copper alloyed ADI, which may be attributed to presence of significantly more amount of upper bainite in austempered microstructure of Cu-Ni alloyed ADI.

49. The highest quality index achieved in Cu-Ni alloyed ADI is significantly higher than that observed in copper alloyed ADI due to more percent elongation.

50. The impact strength of Cu-Ni alloyed ADI is relatively poorer than that of copper alloyed ADI for all the austempering times between 30 to 150 minutes, used in the present investigation.