## ABSTRACT

Increased usage of ductile iron has been maintained in the last decade despite a fall in the overall iron production. It is for the reason that it has been regarded as a versatile engineering material. It provides best combination of overall properties with castability, hardenability and corrosion resistance comparable to those of gray irons and mechanical properties equivalent to those of steels. Austempered Ductile Iron is a further development of ductile iron achieved by austempering heat treatment of the latter. By varying the temperature and time of austempering, the strength of ADI may be varied from about 985 MPa at 10-15 % elongation to 1760 MPa at 1-3 % elongation. The high strength of ADI combined with its excellent fatigue and wear properties and ease of casting to near net shape often make it an ideal material for application in auto-engine components like crankshaft, camshaft and gears etc. In view of its relatively lower cost and an excellent combination of properties, new applications of this material are developing slowly but steadily in other fields also. Because of its potential as an emerging material, ADI has drawn attention of research workers worldwide.

ADI is developed by two-step process involving austenitization and austempering of ductile iron. During austenitization, the cast matrix is transformed to austenite, which transforms further during austempering process. In general, austempering progresses in two sequential stages. In stage I, the matrix austenite transforms isothermally to bainitic ferrite and high carbon austenite, relatively stable against transformation to martensite. In stage II, the high carbon austenite decomposes to ferrite and carbide. In an ideal austempering process stage I stage II are separated in time so that high carbon austenite forming in stage I reaches a plateau with negligible or no martensite. The mechanical properties of ADI reach their optimum values during this time interval. This time period of austempering treatment is known as the "processing window". The morphology and

the relative amounts of various constituent phases present in austempered structure are responsible for the wide range of mechanical properties in ADIs. However, suitable alloying of ADI components is required to achieve good austemperability and desired austempered structure. The choice of alloying elements for ADI is generally restricted to nickel, copper, manganese and molybdenum. However, their composition has to be selected judiciously. Manganese, though, is the most potent austemperability agent but its segregation at eutectic cell boundaries delays the bainitic transformation and on air-cooling after austempering, results in the formation of martensite. Also, processing window of ADIs produced from ductile irons having different contents of manganese narrows down with increase in manganese in ductile iron.

While higher manganese irons can be easily produced, the production of low manganese irons is extremely difficult from practical point of view. It was therefore, felt that there is a need to produce a commercially viable ductile iron with a minimum possible manganese content. Molybdenum, the next potent austemperability agent, also shows a similar effect as that of manganese though to a lesser extent. So its addition should also be limited. Copper and nickel on the other hand do not segregate at cell boundaries and improve austemperability. Their addition to ductile iron can be made to compensate for the reduction in austemperability due to lowering of manganese content. However, very limited work has been carried out so far for ductile irons alloyed with nickel and copper. Keeping the above considerations in mind, the present study has been undertaken with ductile irons of the following two compositions cast in the form of 1" Y-blocks in a commercial foundry:

- 3.48C, 2.028Si, 0.22Mn, 0.05Cr, 0.016Ni, <u>0.6Cu</u>, 0.04Ti, 0.03Mo, 0.0079Sn, 0.012V, 0.02Al, rest Fe.
- 3.48C, 1.83Si, 0.23Mn, 0.01Cr, <u>1.05Ni</u>, <u>0.6Cu</u>, 0.04Ti, 0.015Mo, 0.0046 Sn, 0.002V, 0.02Al, rest Fe.

It is possible to achieve in ADI, a wide range of mechanical properties by variation of heat treatment parameters, provided that these parameters are closely controlled. Their incorrect selection may result into inhomogeneous microstructure with undesirable constituents like martensite or carbides leading to a reduction of the mechanical properties. Therefore, it is desirable to model the austenitization process in ductile iron so that reasonably uniform carbon concentration in austenite could be ensured. Further, a study of heat treatment properties may provide broad guidance to the heat treaters, who would like to develop ADI with proper microstructure in the ductile irons under investigation.

A mathematical model has been developed in the present study to understand the progress of austenitization process. The austenitization time required to produce homogeneous austenite with equilibrium carbon content has been related to the structural parameters of cast ductile iron like radius of graphite nodule, radius of austenite cell, volume fraction of graphite, volume fraction of ferrite in cast matrix and diffusion constant. The minimum austenitization times required to achieve equilibrium carbon content in austenite have also been determined using this model and compared with those obtained experimentally for two austenitization temperatures of 850 and $900^0$C in both ductile irons. The evolution of austempered microstructure in Cu alloyed ADI has been studied by using optical metallography, Vickers hardness and micro hardness after austempering at the austempering temperature of $330^0$C for austempering times ranging from 0.5 to 150 minutes following austenitization at $900^0$C for 60 minutes. The variations in the austempered microstructure, the volume fraction of retained austenite, $X_\gamma$, the average carbon content of retained austenite, $C_\gamma$, their product $X_\gamma C_\gamma$ and the size of bainitic ferrite needles with austenitization time have been investigated on samples austempered at $330^{0}$C for 60 minutes after austenitization at austenitization temperatures of 850 and $900^{0}$C. The influence of austempering temperature in copper iron on the above mentioned structural parameters has also been investigated for three austempering temperatures of 270, 330 or $380^{0}$C for 60 minutes at each temperature after austenitization at $850^{0}$C for 120 minutes or at $900^{0}$C for 60 minutes. The influence of austempering time on the structure and hardness has been studied on samples austempered at $330^{0}$C. Similar studies have also been carried out on copper- nickel alloyed iron for austempering at the same temperature of $330^{0}$C following austenitization at $850^{0}$C. The kinetics parameters for transformation have been calculated using Avarmi equation for both the irons.

The influence of both austenitization and austempering temperatures and times on the mechanical properties like hardness, 0.2% Proof stress, UTS, % elongation, quality index, impact strength has been investigated for both the ductile irons. Strain hardening behaviour has been investigated for Cu alloyed ADI and strain hardening coefficients 'n' and work hardening rate R' have been calculated from the variation of true stress with true strain. The mechanical property paths for UTS vs. % elongation and UTS vs. impact strength have been established for both the Cu alloyed and Cu-Ni alloyed ADIs when austempered at $330^{0}$C and these are compared with those reported for higher manganese and lower manganese ADIs by earlier investigators. Fracture surfaces from failed impact and tensile specimens have been studied on Cu alloyed ADI developed by austempering for 60 min. at three austempering temperatures of 270, 330 and $380^{0}$C, after austenitization at $900^{0}$C for 60 min. The crack initiation and propagation has also been investigated for copper alloyed ADI from the transverse sections of the samples failed by tensile test.

The entire work presented in this dissertation has been divided into nine chapters. Chapter-I presents the background and importance of ADI. Chapter-II surveys the available literature on the development of ADI, alloying elements in ADI, changes in austempered structure and mechanical properties with heat treatment parameters for differently alloyed ADIs investigated by other workers. Finally, the problem of present investigation has been formulated in the existing gap in knowledge base evident from the literature survey. Chapter-III deals with the experimental procedure adopted for making ductile irons and their heat treatment to develop ADI. The methods of metallographic study, X-ray diffraction and mechanical testing employed respectively for the examination of microstructure, structural parameters and mechanical properties like hardness, micro hardness, 0.2% Proof stress, UTS, % Elongation, Quality index and Impact strength have also been outlined in chapter-III. Chapter-IV deals with theoretical analysis of austenitization of ductile iron. A mathematical model has been developed to study austenitization of ductile iron. The results regarding the changes in microstructure and structural parameters with heat treatment temperature and time, which also affects austempering kinetics, have been presented in chapter-V. Chapter-VI deals with the changes in the mechanical properties of Cu alloyed ADI with heat treatment parameters, its fractomicrographic study for different heat treatment parameters. These results have been compared with those obtained by other workers for differently alloyed ADIs produced by using different heat treatment parameters. Chapter-VII presents the changes in the mechanical properties of Cu-Ni alloyed ADI with heat treatment parameters and these have been compared with those obtained for Cu alloyed ADI under similar heat treatment conditions. Their mechanical property paths have also when compared. Important conclusions drawn from the present investigation and suggestions for further work have been listed respectively in chapters-VIII and IX.