ABSTRACT

For the last two decades, a considerable research work has been carried out on the development of high strength low alloy steels for melting the stringent requirements in specific applications. In particular, these high strength low alloy steels find applications in structural and automotive industry because of the outstanding mechanical properties combined with good formability. Based on the modifications in the chemistry (both substitution elements and micro-alloying elements), microstructure, grain refinement, thermo-mechanical treatments and by many strengthening mechanisms, a number of high strength low alloy steels have developed with a wide range of mechanical properties. Micro alloyed steel is a class of advanced high strength steel containing micro-alloying elements such as Vanadium (V), Titanium (Ti), Niobium (Nb), Aluminium (Al) and Boron (B). The total amount of these elements in these steels is maintained upto 0.20 wt %. These steels are not only used for structural applications, but also used in automotive industry because of better mechanical properties, very good fabricability and good resistance to atmospheric corrosion compared to the conventional carbon steels.

The selection of micro-alloyed steels largely depends on the end user requirements such as (i) reduction in thickness, (ii) weldability, (iii) formability and (iv) environmental degradation. However, for many applications, the selection of micro-alloyed steels is in favor of high strength to weight ratio, i.e. high specific strength as compared to the conventional structural steels. The strength to weight ratio of the micro-alloyed steels can be accomplished by one or more of many strengthening mechanisms along the micro-alloying elements. The primary strengthening mechanisms that

operative in these steel are as follows: (i) solid solution, (ii) grain boundary, (iii) precipitation and (iv) phase transformation. Off these strengthening mechanisms, grain refinement strengthening mechanism is a very powerful in the micro-alloyed steels because it increases not only strength but also toughness without sacrificing weldability and ductility.

With Hall-Petch equation, the quantitative relationship between yield strength of the micro-alloyed steels and grain size can be evaluated. The grain refinement in the micro-alloyed steels can be accomplished by three factors, which are as follows: (i) pin down the austenite grains during reheating by undissolved precipitates of carbides or carbo-nitrides and nitrides, (ii) prevent recrystallization and grain growth by reprecipitation of precipitates of carbides and carbo-nitrides in austenite during hot rolling and (iii) refine the ferrite grains during transformation of austenite to ferrite by presence of carbides and carbo-nitrides (V(C, N), Nb(C, N), Ti(C, N), AlN, Zr(C,N) and B(C,N). Addition of Al as micro alloying element leads to the formation of aluminium nitride which has a strong capability to enhance the mechanical properties of the developed steel. In addition, Boron has also similar effect on refinement of grain size and improvising strength of the steel.

Development of micro-alloyed steels with V, Nb and Ti for increased strength and toughness has well documented by many researchers. The effect of V, Nb and Ti on the phase transformation, precipitation formation, recrystallization temperature, grain growth and deformation mechanism of the micro-alloyed steels is corroborated. However, the role of Zr addition on grain refinement and mechanical properties is not extensively studied. The studies on development of micro-alloyed steels with elements in combinations of Zr with Nb, Ti, V, B and Al for improved mechanical properties are very limited. To bridge the gap in the literature, the present research work aims at the development, microstructural and mechanical evaluations of Zr-bearing

micro-alloyed cast steels with further addition of micro-alloying elements such as Nb, Ti, V, B and Al.

In the first phase of experimental work, the production of thirteen cast steels with non micro-alloyed cast steel and micro-alloyed cast steels containing zirconium, niobium, titanium, vanadium, boron and aluminium elements were cast in CO_2 moulds. Subsequently, microstructural analysis and mechanical properties evaluations were carried for the thirteen cast steels in the as-cast conditions.

The as-cast steels show a mixed microstructures consisting of pearlite and ferrite with relatively a large grain size and irregular shape of ferritic grains. These microstructures are refined for fine ferrite grains by normalizing heat treatment it is carried out at 1000^{o}C for 1 hour per inch followed by cooling in the atmospheric air.

Phase II: Investigation on micro structural examination using Scanning Electron Microscope (SEM) with Energy Dispersive Spectroscopy (EDS) and Transmission Electron Microscope (TEM) with Energy Dispersive Spectroscopy (EDS) and mechanical properties such as hardness, ultimate tensile strength, yield strength, percentage elongation, impact energy and fractography analysis of non micro-alloyed and micro-alloyed cast steels in the normalized condition are discussed.

It is observed that the Zr-bearing microalloyed steels with Nb, Ti, B shows the presence of higher volume acicular ferrite with a very fine grain size of around 5-10 microns as compared to the non micro-alloyed cast steel. In addition, the inter-lamellar spacing of pearlite as well as presence of carbides precipitates compounds were seen clearly in the heat treated samples by TEM. It is also observed that the presence of precipitates accounts for the

improvement of strength and toughness of steels containing micro alloying elements after normalizing heat treatment. The micro-alloyed cast steel showed tensile strength nearly two times higher than the non micro-alloyed cast steel. However the percentage elongation of non micro-alloyed and micro-alloyed cast steels is almost equal. This can be attributed due to the presence of very fine ferritic grains resulted by formation of carbides or carbo-nitrides in the micro-alloyed steels. Among the twelve micro-alloyed cast steels, it is observed that zirconium and boron addition in the steel shows a very good submicron grains with balanced strength and toughness as compared to the rest of investigated micro-alloyed steels.