Chapter 1: Introduction

1.1 Principles of microalloyed steel

Over the last three decades high strength low alloy steels (HSLA steels) containing microalloying elements, such as, Ti, Nb and V, have widely been used in pipeline, ship-building, construction, engineering and automotive applications. Microalloying elements are frequently added in steel in small amounts (less than 0.1 wt%) either independently or in combination. These elements form relatively small and stable carbo-nitride precipitates (nano-meter to micro-meter sized), which improve the mechanical properties by providing grain-refinement and precipitation strengthening [Gladman, 1997a; Tither, 1992]. Microalloying additions increase the yield strength two to three times over plain carbon-manganese steel [Gladman, 1997a; Tither, 1992] without raising the carbon equivalent, CE $\left(CE = wt\%C + \frac{wt\%Mn}{6} \right)$ [Lincoln, 1993], which is necessary to ensure good toughness, formability and weldability [Gladman, 1997a].

The proportions of HSLA steel used for different products and applications in the mid-1980s (compared to carbon or other alloy steels) are summarized in **Table 1.1.1** [Tither, 1992]. Microalloyed steels can be substituted for plain carbon steels because of their superior properties (strength, toughness and weldability), better weight reduction and lower cost [Bleck, 2005; Korchynsky, 2005]. Commercial thermo-mechanical controlled rolled (TMCR) and air-cooled HSLA steels generally have yield strengths in excess of 550 MPa with impact transition temperatures less than -30°C in plate thicknesses up to ~ 60 mm. Properties can be improved further by controlled or accelerated cooling after TMCR [Gladman, 1997a; Tither, 1992; Korchynsky, 2005].

The pressure to reduce the weight of automobiles [ULSAB, 1998] and the ever-existing threat from lightweight materials such as aluminium- or magnesium-based alloys has led to continuous improvement in high strength steel (HSS). Mechanical properties of various improved steel grades are shown in **Fig. 1.1.1**. Even in the advanced high strength steels (AHSS) (such as, dual phase, complex phase, TRIP and TWIP steels) microalloying elements not only provide strengthening effects but also control the evolution of microstructures, from their effect on phase transformations (**Table 1.1.2**) [Bleck, 2005]. Although, Al and some other elements (like B) are also added in steel at small quantities these are not generally termed as microalloying elements [Gladman, 1997a]. The combination of microalloying additions along with thermo-mechanical controlled rolling (TMCR) and controlled cooling is the most suitable commercial processing route for the mass production of high strength steels.

Table 1.1.1: Proportion (in percentage) of HSLA steel used for different end products and applications relative to carbon and alloy steel [Tither, 1992]

Application and End Use	Europe (%)	North America (%)	Japan (%)
Line Pipe	95	95	95
Ship-building	40	20	75
Offshore			
Plates	90	30	70
Sections	70	20	10
Pressure Vessels	30	25	85
Structural	30	20	10
Section, Automotives	70	70	30
Section, Ships	15-30	20	10
Rebar	100	5	10
Plates	25	20	10-30
Sheet and Coil (including galvanized sheet)			
Automotive	20	10	10-30
Building (not rebar)	95	80	70

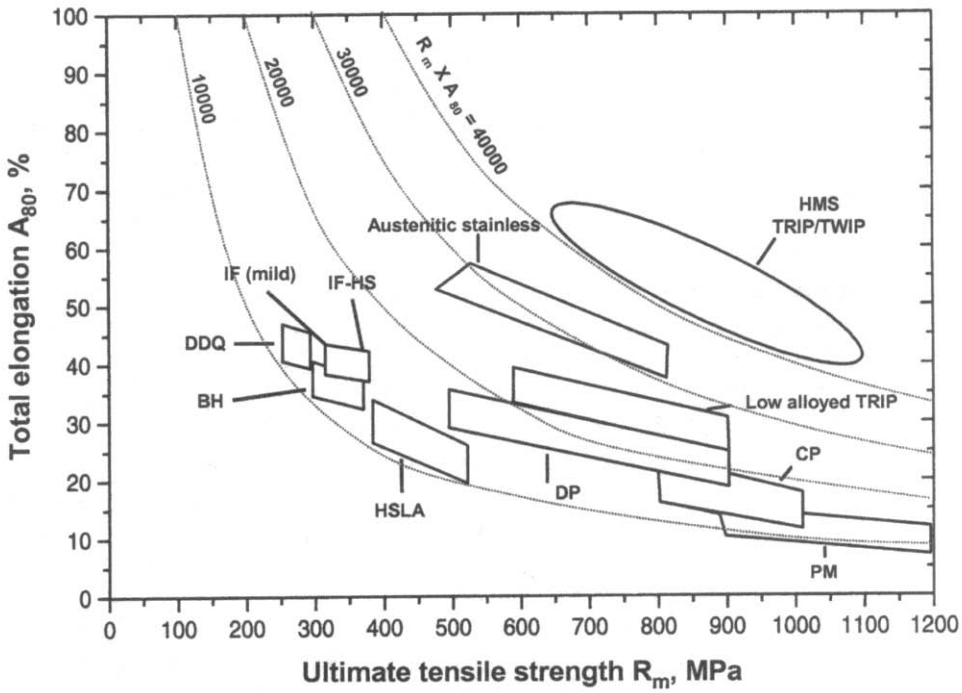

Fig. 1.1.1: Typical mechanical property ranges (ultimate tensile strength and elongation) of different grades of mild and high strength steels [Bleck, 2005].

[**Note: The abbreviations used in the figure are as follows:

IF (mild): Interstitial free mild steel, microalloyed, single ferrite phase microstructure and deep-drawing grade.
IF-HS: Interstitial free steel, strengthened by Mn and P addition.
DDQ: Deep drawing grade mild steel.
BH: Bake hardening grade steel, additional strengthening occurs during paint baking.
HSLA: High strength low alloy steel, containing microalloying elements.
DP: Duel phase steel, with ferrite + 5-30 volume percent martensite islands.
Austenitic stainless: Complete austenite microstructure contains high amount of nickel (Ni) and chromium (Cr).
TRIP: Transformation induced plasticity steel (low alloyed or high alloyed) with ferrite + bainite + retained austenite microstructure.
CP: Complex phase steel with strengthened ferrite + bainite + martensite.
PM: Partly or fully martensitic steel.
HMS-TRIP: High Mn steel with the concept of strain-induced retained-austenite to martensite transformation.
HMS-TWIP: High Mn steel with the concept of strain-induced mechanical twinning.]

Table 1.1.2: Effect of microalloying elements (including Al) on microscopic featureand macroscopic properties of steels [Bleck, 2005].

Element	Microscopic effect						Macroscopic effect					
	Coarse precipitates	Fine precipitates	Grain boundary segregation	Grain refinement	Cementite formation	C enrichment in γ_{Ret}	Kinetics of recrystallization	Kinetics of γ/α transformation	Kinetics of γ/α_B transformation	Ms-temperature	Matrix strengthening	
Nb		+		++		+	--	- / +	-	-	++	
Ti	+	+		+			-	+				
V		+		+			-	+			+	
Al		+		+	-	+		+		+		

[**Note: here γ_{Ret} is retained austenite; γ is austenite; α is ferrite; α_B is bainite; Ms is martensite start temperature. Meaning of the symbols used in the table are as follows: +: positive effect of the microalloying element, i.e. the microalloying element promotes the effect; (-): negative effect of the element, i.e. the element opposes the effect; ++: highly positive effect; --: highly negative effect; -/+: element can have either positive or negative effect depending on other factors]

1.1.1 Effects of microalloying elements:

The various effects of microalloying elements on microscopic features and macroscopic properties of steels are summarised in **Table 1.1.2** [Bleck, 2005]. The most important actions of each microalloying element in steel are listed below [Heisterkamp, 1971; Gladman, 1997a]:

V: The higher solubility of V compounds (carbide and nitride) ensures that there is complete dissolution of V during slab reheating to provide interphase precipitation during the austenite to ferrite transformation (~ 700-900 °C) or random precipitation in ferrite phase. Those precipitates are fine in size (< 5 nm) and provide precipitation strengthening in steel [Gladman, 1971].

Ti: Precipitation of large TiN particles (that can affect the toughness [Balart, 2000; Fairchild, 2000a] in liquid steel (due to the low solubility of TiN in austenite) can be avoided by a restricted Ti addition (< 0.02 wt% Ti) to give a fine (~ up to 400 nm) and extremely stable TiN distribution. Such precipitates limit grain growth during reheating and improve toughness, especially in the heat-affected zones of weldments [Gladman, 1997a; Tither, 1992].

Nb: The most significant effect of Nb in HSLA steel is its ability to form strain-induced, fine Nb(C, N) precipitates upon deformation below ~ 1000 °C. A marked drop in the solubility of Nb in austenite between high (~ 1300°C, i.e. 1573K) and low (~ 900 °C, i.e. 1173K) temperatures lead to such strain-induced precipitation. Strain-induced precipitates retard the recovery and recrystallization of the deformed austenite structure and that is used for grain refinement in thermomechanical controlled rolling [Gladman, 1997a; DeArdo, 2003].

Apart from microalloying elements the specific effects in microalloyed steels can be influenced by the additions of aluminium (Al) or any other more conventional alloying elements [Gladman, 1997a]. Aluminium is commonly used as a deoxidant, but an excess of around 0.02 wt% or more residual Al remains in solution in Al treated steel. Residual Al combines with free nitrogen in solution to form AlN particles. TiN is the only microalloy precipitate that is more stable in austenite than AlN. Any un-dissolved AlN particles prevent grain coarsening during reheating.

1.1.2 Processing of microalloyed steel

A common processing route for HSLA steel plate is shown in **Fig. 1.1.2** [Gray, 1983]. After steel making in basic oxygen furnace or electric arc furnace the molten metal is continuously cast. Compared to ingot casting, continuous casting not only improves the casting yield but also a smaller billet or bloom sections can be cast instead of large ingots. This reduces the amount of hot-working required to produce the semi-finished and finished products, which saves the energy, time and cost of production [Gladman, 1997a]. The continuous cast slabs are reheated prior to rolling. Reheating reduces the inhomogeneity of the cast structure, makes the steel soft for subsequent deformation and dissolves the majority of microalloy precipitates to achieve the maximum benefit of microalloying. A three stage controlled rolling schedule with double hold is quite a common practice to achieve the maximum grain refinement. Any stage of processing (casting, reheating or rolling) can be important for the formation of microstructure and precipitates in the final rolled plate and therefore, the microstructural changes taking place at every processing stage need to be studied.

Hot metal desulphurisation
Steel making vessel
Primary deoxidation, desulphurisation during tapping
Argon flushing, vacuum degassing, calcium injection etc.
Continuous casting
Air cooling / stack cooling / pit cooling / isothermal treatment
Machine scarfing + slab inspection + dressing
Reheating
Thermomechanical Controlled Rolling (TMCR)
Stage I – Hold - Stage II – Hold - Stage III
Stack cooling /air cooling
Surface inspection, ultrasonic inspection

Fig. 1.1.2: Flow chart showing the typical processing route for TMCR-microalloyed-pipeline steels. The dark shaded stages are important from the point of view of grain structure and therefore, are studied in the present investigation to follow the changes in grain size [Gray, 1983].

1.2 Objectives

Major objectives of the present study can be divided into the following three categories:

1.2.1 Characterization and prediction of microalloy segregation and inhomogeneous distribution of microalloy precipitates in as-cast slab.

Clustering of coarse microalloy precipitates (such as, dendritic (Nb,Ti)(C,N) and TiN) in the interdendritic region of as-cast slab can lead to slab-surface cracking during continuous casting. Hence, prediction and control over precipitate size and spatial distribution of the precipitates is crucial for maintaining the cast-slab quality. There is a lack of understanding on the effect of segregation on the stability of microalloy precipitates and on the precipitate size distributions at different regions (solute-rich and solute-depleted) of as-cast slab. Hence, the present study aims to propose a model, for predicting the spatial distribution in size and volume fraction of the microalloy precipitates. The modelling study to be based on the detailed characterization and analysis of microalloy segregation along with the quantitative assessment of the nature, shape, size and spatial distribution of the microalloy precipitates in as-cast slab.

1.2.2 Studying the effect of microalloy precipitates in as-cast slab on the austenite grain structure in the reheated steel.

In order to reduce the austenite-grain size variation and the associated grain size bimodality during reheating an increase in Ti level has been recommended by the earlier studies. Present study aims to verify the beneficial effect of Ti addition in reducing the austenite-grain size variation during the reheating treatment of microalloyed steels. Present study also aims to propose a model for the prediction of austenite-grain size variation by considering different metallurgical aspects responsible for such variation, such as, micro-segregation during casting, coarsening and dissolution of microalloy precipitates and austenite-grain growth during reheating. Such a model may help in selecting the appropriate reheating temperature for achieving uniform austenite-grain structure after the reheating treatment of a continuous cast slab, which can ultimately improve the quality of rolled plate.

1.2.3 Evaluating the effect of prior-processing history of the steel on the austenite grain structure during reheating treatment.

Microalloy precipitates play a significant role in controlling the austenite-grain size during any reheating treatment. Now the nature, size, and distribution of these precipitates are expected to depend on the starting processing condition, such as, as-cast condition and rolled condition. Therefore, the austenite-grain growth during the reheating treatment may depend on the prior-processing history of the steel. However, systematic studies are rare on this aspect. Present study aims to identify the effect of processing history and the retained strain present in the starting structure, on the austenite-grain growth, which may help in improving the accuracy of the existing grain-growth models. Objective of this study is to compare the austenite-grain structures develop after reheating a HSLA steel for three different starting conditions namely, as-cast, hot-rolled and thermo-mechanically controlled rolled conditions.