Effect of Thermomechanical Processing on the Microstructure and Properties of a Low Carbon Copper Bearing Steel

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A boron treated copper bearing HSLA steel containing austenite formers like manganese and nickel, somewhat lower in amount than that in HSLA 100 variety of steel is chosen for the study. The role of thermomechanical processing on the microstructure and mechanical properties of the above steel has been investigated. Differential scanning calorimetric study is carried out for understanding the precipitation behaviour of copper in HSLA steel under the influence of boron. The microstructure of the experimental steel is found to consist of laths of martensites and bainite. MA constituents of ribbon like morphology are observed at the lath boundaries. Higher strength properties of the steel are attributed to the presence of finely distributed precipitates of copper and microalloy carbides.

KEY WORDS: HSLA steel; copper; boron; thermomechanical processing; microstructure; mechanical properties.

1. Introduction

In recent times, considerable efforts have been directed towards the production of high strength low alloy (HSLA) steels which can meet the requirements of a composite set of properties, namely: high strength, high resistance to brittle fracture, low temperature toughness as well as high degree of weldability. This has led to the development of a series of steels which contain low to very low percentage of carbon, sufficient alloying elements to obtain a desired level of $\gamma \rightarrow \alpha$ transformation temperature, microalloying and thermomechanical controlled processing (TMCP) for toughening through microstructural refinement. HSLA 80, HSLA 100 and ultra low carbon bainitic (ULCB) steels are the present day versions of the new family of steels.1–3

Recently, it has been demonstrated that TMCP, followed by direct water cooling envisages an improvement in properties of the copper bearing HSLA steels.4 The sub-zero impact properties of these steels are reported to be poor if too much of MA constituents are present in the microstructure in the form of ribbons or thin films.5 However the above property may be considerably improved if the TMCP steel is tempered above 600°C.6

Detailed microstructural analysis of HSLA 100 variety of steels containing a high percentage of austenite formers has been reported elsewhere.7 However, the role of thermomechanical treatment in the evolution of microstructure and properties in similar steels with low amount of austenite formers, viz. manganese and nickel, is not yet documented well. Further, when boron is added to similar steels, it leads to a synergistic effect with niobium in lowering the $\gamma \rightarrow \alpha$ transformation temperature. Boron itself is known to segregate at grain and subgrain boundaries.8 Copper and microalloy carbides are reported to form both homogeneously and also heterogeneously at dislocations in the low carbon TMCP steels.9 Maruyama et al.10 has elegantly demonstrated through DSC studies that the precipitation behaviour of copper in similar steels are strongly sensitive to matrix structure. It has been further proved that a b.c.c.$\rightarrow$9R transformation takes place during the coarsening of copper particles, which are initially formed as b.c.c copper clusters. Moreover, microalloy carbides are known to form at the intragranular deformation bands during the TMCP of HSLA steels.

It therefore appears that precipitation of copper may be considerably influenced when boron containing microalloyed steels are thermomechanically processed. The present paper describes the role of TMCP on the microstructure and hence the mechanical properties of the above steel has been investigated. Differential scanning calorimetric study is carried out for understanding the precipitation behaviour of copper in similar steels are strongly sensitive to matrix structure. It has been further proved that a b.c.c.$\rightarrow$9R transformation takes place during the coarsening of copper particles, which are initially formed as b.c.c copper clusters. Moreover, microalloy carbides are known to form at the intragranular deformation bands during the TMCP of HSLA steels.

2. Experimental

The composition of the steel, under investigation is presented in Table 1. The liquid metal from a vacuum induction melting unit was cast into cylindrical ingots of dimensions 60 mm diameter $\times$ 300 mm length. These ingots were homogenized at 1 250°C, forged and then hot rolled to 12.5 mm thick plates.

Controlled rolling was carried out on the hot rolled plates so that a finish rolling temperature of about 750°C was obtained after five passes. Degree of deformation was varied in different thermomechanical processing schedules, as
shown in Table 2. After controlled rolling 1 some samples were directly quenched in water from the finish rolling temperatures.

Mechanical properties of the TMCP plates were determined by tensile and impact tests. Optical, scanning and transmission electron microscopies (TEM) were carried out for microstructural studies and to understand the precipitation behaviour of copper, DSC studies were employed. Further, age hardening the test coupons from TMCP bars were subjected to the temperature range of 300 to 650°C for a period of one hour. Isothermal ageing was also conducted at 500°C to study the ageing behaviour of the TMCP steels.

3. Results and Discussions

3.1. Microstructures

A variety of microstructures (Figs. 1–6, 8) are seen to be produced in the thermomechanically processed steels. When the steel is tempered at 450°C for one hour after air cooling from the finish rolling temperature, 750°C in schedule 1, the major microstructural constituent appears to be acicular bainite/precipitation hardened martensite (Fig. 1). The bainite/martensite region is decorated by regularly aligned second phase constituents, commonly called MA constituent in this type of steel. However the same optical photomicrograph contains certain areas wherein some irregularly arranged granular second phase particles are observed. These phases are called granular ferrite/bainite and will be discussed later. When the steel is directly cooled in water after finish rolling under TMCP schedule 2 the microstructure is seen to consist of acicular bainite/martensite (Fig. 2). The prior austenite grain boundaries are clearly distinguished and are found to be elongated due to the high amount of deformation in the last pass of control rolling. On the contrary, a low deformation percent at the finish rolling pass in TMCP schedule 3 has resulted in a less acicular nature of the prior austenite grains (Fig. 3). In the scanning electron micrograph of the present alloy under TMCP schedule 1, a phase, containing relatively small amount of non aligned second phase particles, is seen to exist (Fig. 4). This is thought to be the proeutectoid ferrite and has probably formed due to a slower cooling of the deformed alloy from the low FRT. In chromium bearing HSLA steels such primary ferrite has been observed as grain boundary allotriomorph.11)

Transmission electron micrograph of the direct cooled
alloy under TMCP schedule 2 shows the laths of ferrite with high dislocation density (Fig. 5). It is in general, difficult to differentiate between martensite and bainite in this low carbon HSLA steels but previous workers have used the lath width as the yardstick of describing martensite or bainite. Following that, the laths in Fig. 5 are said to be of martensites. Along the lath boundaries, thin ribbons of MA constituents are seen to be present.

Figure 6 shows the evidence of copper and carbide precipitates in the microstructure of the steel thermomechanically processed under schedule 2 and then aged at 500°C for one hour. EDX analysis from the same sample confirms the presence of copper in the microstructure of the TMCP alloys (Fig. 7).

From such microstructural observation it is found that the experimental alloy produces lath martensite/bainite in its microstructure when directly cooled after finish rolling. However slower cooling rate during continuous cooling of the TMCP steel leads to the formation of what has been termed granular bainite by Krauss et al. The grain boundary phase in Fig. 4 is precluded from being considered acicular ferrite (due to Shibata et al.) or the bainitic ferrite on ground that while the former nucleates intragranularly, the latter, when formed at the grain boundaries is generously associated with MA constituents. Even rectangular bainite due to Tian et al. reportedly contains a high amount of non-aligned second phase particles. Non-aligned second phase particles may be present both in acicular ferrite/bainite and proeutectoid ferrite. However in proeutectoid ferrite the presence of carbide phase is rather scanty. In view of the presently available evidence and on the basis of earlier reports the above microstructural phase is considered herein to be the grain boundary allotriomorph of ferrite. Subgrains of ferrite with high dislocation density are revealed in Fig. 8. Though similar structures of straight and coherent boundary have been called recovered bainite by Tian et al, Shibata described them differently. Figure 8 however depicts a granular appearance of MA constituents with ferrite subgrains separated by low angle boundaries. The above photograph however resembles granular bainite due to Krauss et al. more than anything else. Hence they are accepted as granular ferrite (α°) in the present case.

3.2. DSC Study

The DSC heating curve for the present alloy reheated to 950°C after TMCP and followed by iced water quenching is shown in Fig. 9. A small exothermic peak at 200°C is seen to precede the broad exothermic peak in the temperature range of 300–380°C. This broad exothermic peak denotes
the formation of copper precipitates. The activation energies of the processes associated with the above peaks are found to 232.48 kJ/mol and 235.5 kJ/mol respectively. The observation is very similar to that of others and it is conjectured that the small peak at 200°C in the DSC heating curve of the present alloy is due to the formation of clusters of copper atoms. The formation of these b.c.c. copper atom clusters preceede the formation of e-copper as characterised by the broad exothermic hump in the DSC curve. The small exothermic hump at 200°C is akin to that for formation of G.P. zones in age hardenable alloys. High hardenability of the present alloy has been able to suppress the precipitation of copper, which was taken in solution in full at 950°C and then rapidly quenched in iced water. The solid solution decomposes to b.c.c. copper at the initial stage of ageing and finally e-copper is formed. From the present observation a clue to the precipitation behaviour of copper in TMCP steels may be obtained. The ageing curves of the TMCP and reheat-quenched alloy are shown in Fig. 10. From the ageing curves, it is quite clear that TMCP alloys are far less responsive to age hardening than the reheat quenched alloys. It seems that most of the copper is precipitated during TMCP. If the samples were not put to DSC heating just after quenching, the small exothermic peak would not have probably appeared as experienced by one of the authors elsewhere. Thus copper has the tendency of precipitating very fast in steels. Though the mechanism is unclear, the precipitation of copper in this steel is supposedly a spontaneous phenomenon.

The above conjecture is further corroborated by the TEM micrograph of the TMCP sample (schedule 1) which shows good amount of homogeneously distributed copper precipitates in the direct cooled samples (Fig. 11).

3.3. Mechanical Properties

Evaluation of mechanical properties of the alloy under investigation, as shown in Table 3, illustrates that microalloying and controlled TMCP of this low-carbon steel impart a considerably higher strength, compared to conventional hot rolling. The CVN values at −40°C of the TMCP specimens are, however, quite low. These properties can be explained on the basis of optical and TEM microstructures. Microstructures of specimens under various TMCP schedules have the common features of laths of martensite and/or bainitic ferrite with high density of dislocations. Precipitates, presumably of alloy carbides and copper are also visible in abundance. All these features are conducive to

<table>
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<th>Thermomechanical treatment</th>
<th>U T S (MPa)</th>
<th>Y S (MPa)</th>
<th>% R A</th>
<th>% Elongation</th>
<th>CVN value at −40°C (J)</th>
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<tr>
<td>Schedule 3</td>
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<td>1034</td>
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high strength. However, in almost all the microstructures, the MA constituents are found to exist mainly at the lath boundaries of bainitic ferrite (Fig. 11) and have assumed thin ribbon like morphology. MA constituents of this type, promote the nucleation of cracks and hence impair the impact properties. With a fast post-TMT cooling viz. iced water cooling, the amount of the hard and brittle MA constituent is considerably high. The presence of these MA constituents in the matrix of highly dislocated lath martensites in direct cooled steels is responsible for the poor sub-ambient impact properties as observed in the present investigation.

4. Conclusion

The microstructure of the TMCP alloy is comprised of laths of martensites/bainites with some evidence of granular ferrite. MA constituents appear ribbon-like along the lath boundaries. High strength is achieved by fine dispersion of microalloy carbides and copper in an otherwise strong matrix of lath martensites. The poor sub-ambient impact properties are due the objectionable morphology of MA constituents.

REFERENCES