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Ageing behavior of a Cu-bearing ultrahigh strength steel

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Abstract

On ageing at different temperatures a various combination of properties has been obtained for this Cu-bearing ultrahigh strength steel. A substantial increase in strength has been obtained at 450 °C, accompanied by a drop in percentage elongation, percentage reduction in area and toughness. At 550 °C temperature extensive ε-Cu precipitates have been observed. The increased strength value retained in the temperature range of 450–600 °C and a secondary hardening peak obtained at 600 °C is probably due to the formation of fine Mo carbide precipitates. The decrease in strength at 650 °C along with an increase in percentage elongation, percentage reduction in area and toughness is due to the coarsening of Cu particles and a partial recovery of matrix. At 700 °C most of the Cu precipitates become rod shaped and formation of fresh martensite with a dark contrast is observed at the lath boundaries.

Keywords: Ageing; Ultrahigh strength steel; Copper precipitates; Lath martensite; Mechanical properties

1. Introduction

The latest development of high strength low alloy (HSLA) grade steels are HSLA-80 and HSLA-100, which were designed by US Navy in the early 1980s of the last century. The excellent combination of properties of these steels replaced high yield (HY) steels, i.e. HY-80 and HY-100 grade steels effectively [1]. In late 1990s a series of experiments were carried out to enhance the strength and toughness of HSLA-80 and HSLA-100 grade steels by proper combination of microstructure, alloying elements and suitable processing parameters. Efforts were given for a further enhancement of the strength, toughness and weldability of HSLA steels through newer alloy design and varying processing techniques [2–8]. A few attempts were also made to replace the next in HY series, i.e. HY-130 grade steel with lower carbon content [9]. Lower carbon content in these steels was compensated by adding higher amount of Ni, however, the target strength was not achieved due to the lack of sufficient hardenability of austenite. Another category of low carbon ultrahigh strength steel is HY-180 or AF-1410 type steel where carbon is reduced to 0.1–0.16 weight percent (wt.%) to improve the toughness and weldability [10]. However, a large amount of alloying elements ($\geq$10 wt.%) such as Ni, Cr, Mo and Co are added to these steels to achieve an increased strength level. Misra et al. [11] have reported another approach to develop ultrahigh strength microalloyed hot rolled steel as an alternative to the quenched and tempered product. This type of steel has minimum yield strength of 100 ksi with ferrite–bainite microstructure.

Recently, a development of a new category low carbon microalloyed ultrahigh strength type steels has been reported by the present author [12–15]. These are copper bearing steels and ultrahigh strength properties have been achieved by newer alloy design and controlled thermomechanical processing. However, the ageing behavior of this type of steels has not been explored yet. The present paper reports the ageing behavior of the new type of copper bearing ultrahigh strength steel.

2. Experimental work

The steel used for this study was melted in an air induction furnace and the chemical composition is given in Table 1. The cropped ingot was hot forged to 16 mm × 16 mm bar and reheated to 1200 °C soaking temperature for 50 min. Finally the forged bar was rolled down to 6 mm thick sheet at 800 °C finish rolling temperature (FRT) and subsequently quenched in water. The detailed rolling schedule has been reported in the earlier

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Table 1
Chemical composition (wt.%) of the steel

C	0.045
Si	0.21
S	0.01
P	0.01
Mn	1.79
Ni	3.43
Mo	0.79
Cu	1.96
Nb	0.06
Ti	0.08
Al	0.03
N	0.008
C.E.	0.86
A_{c1} (°C)	685

investigation [12]. Specimens for the heat treatment were cut from the rolled plates and ageing was performed in the temperature range of 200–700 °C. After heating at different temperatures for 1 h, the specimens were taken out of the furnace and cooled in air. Hardness, tensile and Charpy impact testing were carried out to evaluate the mechanical properties of the aged specimens. The hardness was measured in a Vickers's hardness tester using a 30 kg load and an average hardness of 10 indented fields for a particular sample was reported. The error in hardness measurement was ±3 Vickers hardness numbers (VHN). The tensile and subsize Charpy samples (4.5 mm × 10 mm × 55 mm in dimension) conforming to the ASTM standards were machined from the rolled plate with their long axis parallel to the rolling direction. Tensile testing was carried out in an Instron tensile testing machine at a constant cross head speed of 8.3×10^{-3} mm/s and Charpy impact testing was carried out in a AVERY impact testing machine at room temperature (RT). Three specimens for tensile testing and six specimens for impact testing were tested for each condition and the average values were reported. The error in ultimate tensile strength (UTS), yield stress (YS) measurement was ±10 MPa. The error in percentage elongation (%EL) and percentage reduction in area (%RA) measurement was ±1 where as for Charpy V-notch (CVN) values it was ±2 Joules (J).

Transmission electron microscopy (TEM) was used for microstructural characterization. Thin foils for TEM were prepared by twinjet polishing in an electrolyte of 90% acetic acid and 10% perchloric acid and energy-dispersive spectroscopy (EDS) was carried out to determine the chemical composition of various phases and precipitates. The lath spacing, precipitate size were measured from the micrographs using an image analyzer. The mean values of at least 300 readings with standard deviation (S.D.) have been reported. Scanning electron microscopy (SEM) was used to evaluate the fracture surfaces of impact specimens tested at room temperature.

3. Results and discussion

3.1. Microstructure

On water quenching from 800 °C FRT microstructure obtained in the hot rolled (HR) and water quenched (WQ) steel is predominantly lath martensite, with interlath dark region (arrowed) (Fig. 1(a)). Precipitation of copper (Cu) particles was not observed in the lath. In the WQ steel, it is expected that all the Cu would be in solution. The average lath width, measured by linear intercept method was found to be 400 nm (S.D. 65). During ageing of lath martensite, supersaturated with Cu, two phenomena are expected to occur together, i.e. tempering of lath martensite and precipitation of Cu in the lath. The low temperature tempering of martensite is associated with the relieving of internal stress, precipitation of fine carbides. High temperature tempering process is associated with annihilation of dislocations, decrease in dislocation density and increase in grain/lath size resulting in a decrease in strength properties. On the other hand, in Cu bearing steels Cu precipitates out of the solution during ageing process causing a rise in strength.

It is noticed that, after ageing at 550 °C the average lath width has been increased to 540 nm (S.D. 82) and the lath structure shows predominantly lath martensite (Fig. 1(b)). A noticeable increase in average lath width was observed at 700 °C ageing temperature (759 nm, S.D. 74) (Fig. 1(c)). It is also noticed that the interlath dark regions have been increased at 700 °C ageing temperature in comparison to that of the HR and WQ steel. Mujahid et al. [16] have also found similar dark phase at the martensite lath boundaries in HSLA-100 steel. They have observed new austenite started to form beyond heating above the A_{c1} line (635 °C) and the transformation behavior of this new austenite is very much dependent on the solute concentration. At the early stage of development this new austenite is enriched in solute elements like nickel (Ni) and Cu (mainly austenite stabilizer) and it remains stable upon cooling at room temperature leaving behind a substantial amount of retained austenite, which appeared as a dark phase at the lath boundaries. The EDS anal-

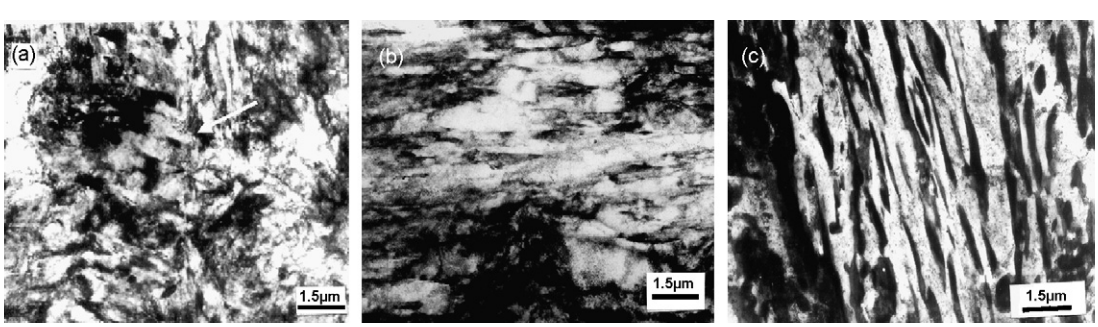

Fig. 1. Lath structure at different processing conditions. (a) HR and WQ, (b) HR and WQ + aged at 550 °C and (c) HR & WQ + aged at 700 °C.