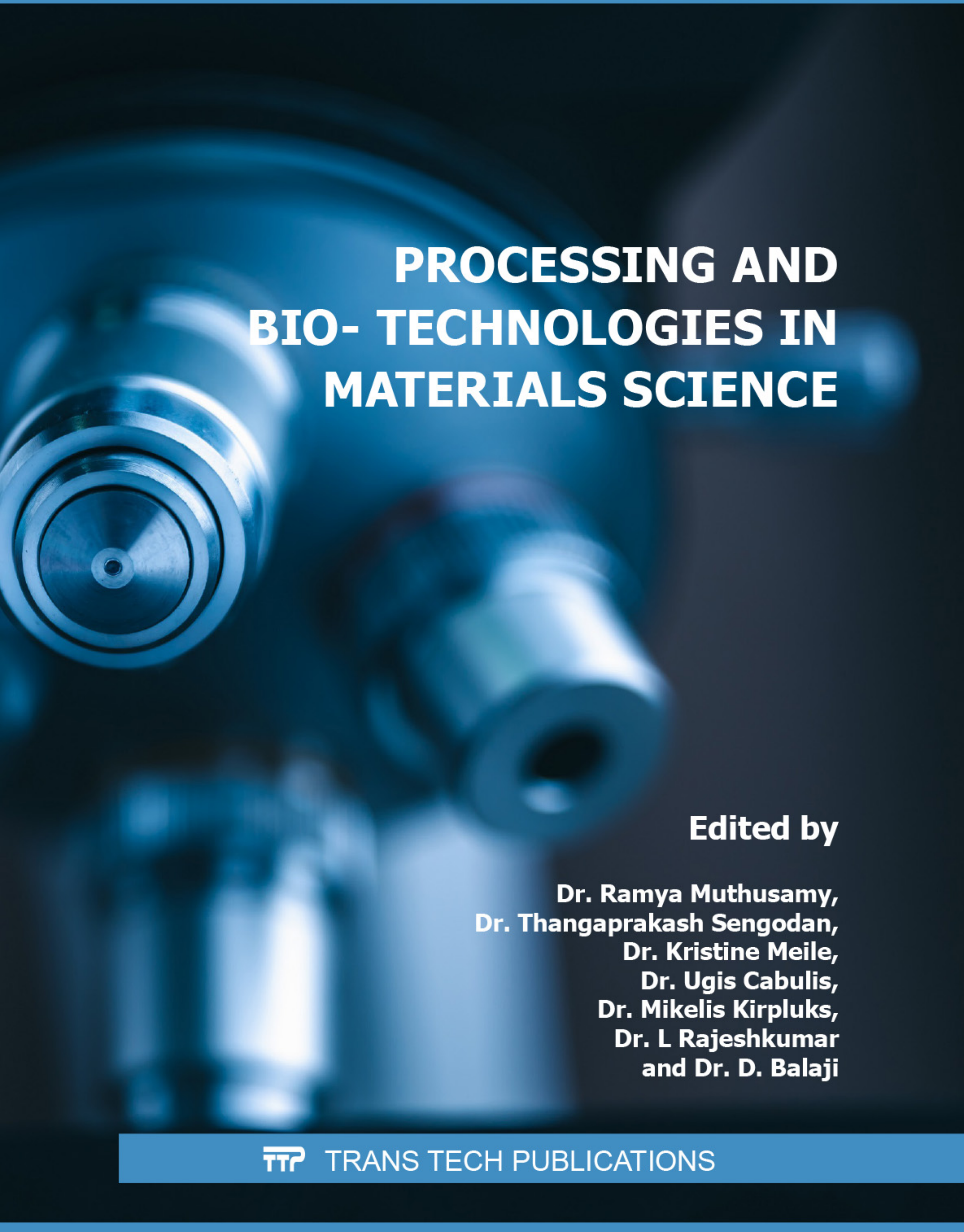

PROCESSING AND BIO- TECHNOLOGIES IN MATERIALS SCIENCE

Edited by

Dr. Ramya Muthusamy,
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Table of Contents

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Effect of Cold Work, Ageing on Hardness and Ultimate Tensile Strength of Microalloyed Steel

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Keywords: High-Strength Low-Alloy Steels, Microalloyed steels, ageing, quenching, tempering, rolling.

Abstract: Recent past witnessed the widespread use of High Strength Low Alloy steels in several structural applications, including pressure vessels, line-pipe transportation of crude oil in the oil industry and many more. API X-65 grade is widely used as a promising material for line-pipe applications in the oil industry. HSLA X-65 plate steels are produced by normalising, Controlled Rolling (CR), Direct Quenching & Tempering (DQT) or Quenching & Tempering (Q&T) techniques. These steels are characterised by their low carbon concentration while maintaining low alloy additions. Micro alloy additions such as V, Ti, and Nb provide substantial precipitation strengthening effect. Strengthening, hardness and microstructural examinations are conducted in all the stages to ascertain X-65 HSLA steel's ageing behaviour.

Introduction

High-Strength Low-Alloy (HSLA) steels are defined as a particular group of low carbon steels, with chemical composition especially developed for excellent mechanical property values. In these steels, HSLA has better resistance. Microalloying addition and thermomechanical treatment technologies have transformed metallurgy phenomenally during the past five decades. In comparison with the traditional steels HSLA attract more due to their low alloying, better mechanical properties, and least processing cost. These so-called HSLA steels and thermomechanically processed (TMP) steels are an extension of C-Mn grades and fill the gap between 250 MPa yield strength of C-Mn steels and 700 MPa yield strength for quenched and tempered alloy steels. These steels have high mechanical properties as a result with combination of least contents of C and alloy and precipitation hardening. [1-11].

According to Mileti et al., [12], a considerable steel grade with its specific properties of HSLA plays a vital role in welding constructions. Branco and Berto [13] showed that the automotive industry, including railways, is facing significant challenges in reducing fuel consumption by reducing the weight, including mechanical properties for the construction of efficient products. Kumar et al., [14] used heat treatments for vehicle components with low mechanical properties.

Fard and Kazeminezhad [15] applied electropulsing treatment (EPT) to study the effects on hardness, evolution size of precipitation and grain refinement of low carbon steel followed by cold-rolling. In results it has been shown in [15] that size of precipitation and grain increased whereas hardness decreased with continuous treatment.

Depending on the processing conditions, the optimum limit of yield strength is generally lower than cold-rolled and annealed conditions. Owing towards the varying solubility limits of carbides/nitrides in ferrite and austenite and different kinetics for precipitation, the alloy additions have vastly differing influence [16]. With adequate carbon (nitrogen with vanadium) in steels, the strength is increased by precipitation effects and grain refinement. In the presence of undissolved particles like TiN or Nb (C, N) grain growth of austenite during soaking may be restricted by more additions elements related to alloy [17]. Systematic efforts have been made to study the role of microalloying elements in steels

[18-30]. Pickering et al. pointed out that in austenite, there is a formation of precipitates that takes place. However, their presence does not play any role in final hot-rolled ferrite structure [31] via precipitation strengthening. The strong interaction of dislocation and precipitates restricts the recrystallisation and retain the higher hardness values even after prolonged ageing [32 & 33]. Many renowned researchers [32-38] have applied many techniques, e.g., heat treatment, aging, adding the alloying elements and different Thermomechanical Treatments (TMT) for improving the mechanical properties of steels. Many different production methods have also been modified. Moreover, to improve the resistance of metals, following methods, viz, cold working (CW), Solid Solution Hardening (SSH) and precipitation hardening have been applied in the literature [33-44].

The above-discussed methods can change the results of the mechanical properties of High Strength Alloy Steels. Literature review suggests that for the strengthening of high-strength alloys, the preferred mechanism is precipitation strengthening.

Alloy Composition

The commercial X65 HSLA steel in the form of a sheet with dimension 300 mm X 300 mm X 24 mm was procured. X-65 HSLA line-pipe steel was investigated. The composition (wt pct) is tabulated in Table 1.

Table 1: Chemical Composition (wt pct) of Experimental Ingots

Elements	wt %	Elements	wt %
C	0.0616	**Cr**	0.109
S	0.0046	**Ni**	0.256
P	0.0087	**Nb**	0.0594
Mn	1.66	**Ti**	0.0144
Si	0.276	**V**	0.0250
Cu	0.0597	**N**	0.0030
Mo	0.258	**Al**	0.0320
Co	0.0069	**B**	0.0016

Treatments

The steel was subjected to various thermal and mechanical treatments. Following are the treatments which are applied on as-received (AR) X65 HSLA line-pipe steel different ranges of time:

A. **Oil Quenching (OQ):** Firstly AR material austenitized for 3 hours at 1000^0C then oil quenching is applied.
B. **Quench tempered and aged (QTA):** The OQ treated material for various time ranges was aged at 700^0C followed by water quenching.
C. **Effect of Cold Work**
Cold Work with 35%, 50% and 65% rolling (TC35A, TC50A & TC65A): Following methods applied in this treatment:
    a. OQ treated material was tempered at 700^0C for 2 hours then water quenching (700^0C-2 hours-WQ) is applied.
    b. Rolled for reducing thickness by 35% reduction after cold work.
    c. Aged at 400^0C from 5 minutes to 5 hours then water quenching (WQ) is applied.

Mechanical Property Measurement

Hardness measurements were conducted for evaluating the mechanical properties. Hardness measurements were carried out on a Vickers Hardness testing machine using a 30 kg load in AR condition and all stages of various treatments. Each hardness value reported was the mean of at least five indentations. The tests were applied on AR, OQ, QTA, cold-worked (CW), peak-aged (PA) & over-aged (OA) specimens at room temperature.

Results and Discussions

Hardness

The Fig. 1 depicts the changes in hardness after various treatments. The AR steel exhibits a hardness value of 208 HV_{30}. Solution treatment at 900°C did not result in any noticeable improvement in hardness. However, solution treatment at 1000°C resulted in a significant improvement in the hardness value (222 HV_{30}). Higher solution treatment temperature (1100°C) again resulted in a drastic drop in the hardness (206 HV_{30}). The steel solution treated at 1000°C was subjected to tempering at various temperatures ranging from 500-700°C for 2 hours, followed by water quenching. Fig.2 illustrates the variation of hardness with tempering temperature. The hardness initially increases up to 600°C and then decreases drastically at 700°C.

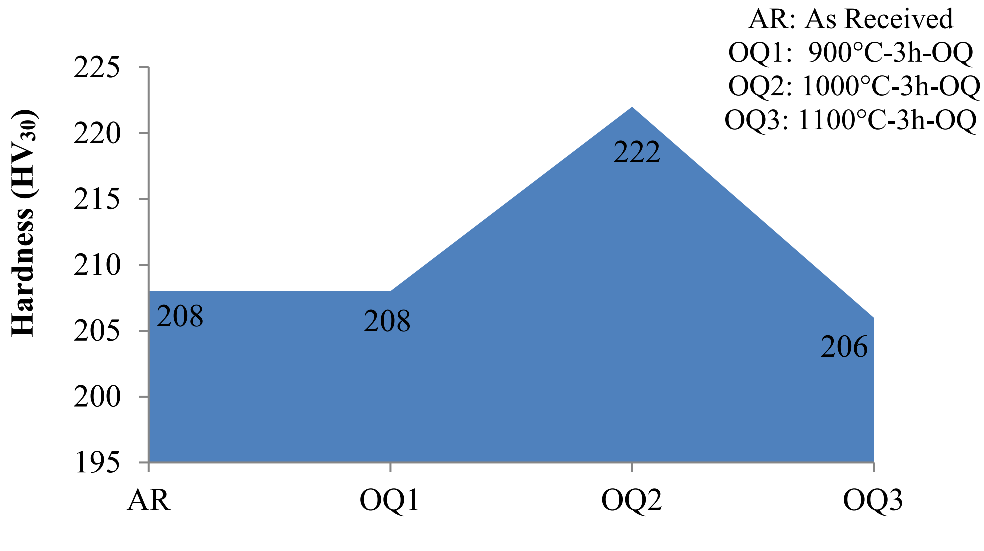

Fig.1: Variation of hardness with solution temperature (°C)

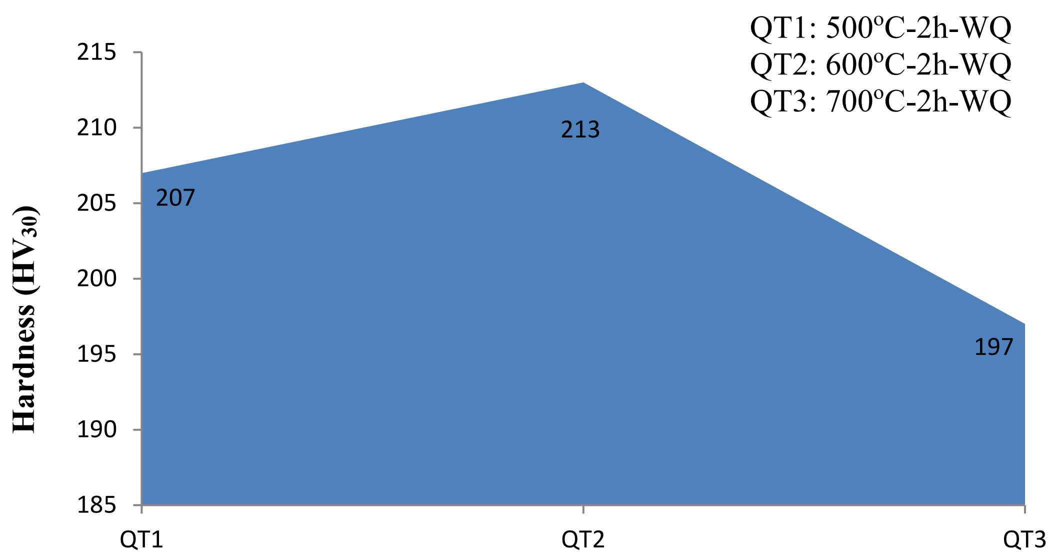

Fig.2: Effect of tempering temperature (°C) on hardness

In order to study the response to age hardening in steel, ageing treatments were carried out at 400°C and 500°C after tempering at 700°C. In general, the hardness increased after 5min but then decreased gradually at 400°C up to 120 min. Subsequent ageing at 400°C increased the hardness and attained peak values (211 HV_{30}) after 1500 min. On the contrary, ageing at 500°C resulted in a drastic drop in hardness value after 15 min. However, subsequent ageing at 500ºC beyond 15 min resulted in substantial improvement in hardness. As observed, the ageing at 400ºC exhibited a significant response to age hardening, as tabulated in Table 2 and shown in Fig.3.

Table 2: Hardness of Thermomechanically processed microalloyed X65 HSLA Steel

Condition	Hardness (HV_{30})				
	QTA		TC35A	TC50A	TC65A
Ageing Time(Min.)	400ºC	500ºC	400ºC	400ºC	400ºC
0	197	197	254	234	263
5	222	216	237	243	272
15	217	197	239	246	272
30	213	204	243	249	281
60	215	206	240	246	302
120	196	201	236	241	280
300	203	200	233	256	272
600	208	202	239	257	271
1500	211	201	262	242	275
3000	202	196	244	234	278

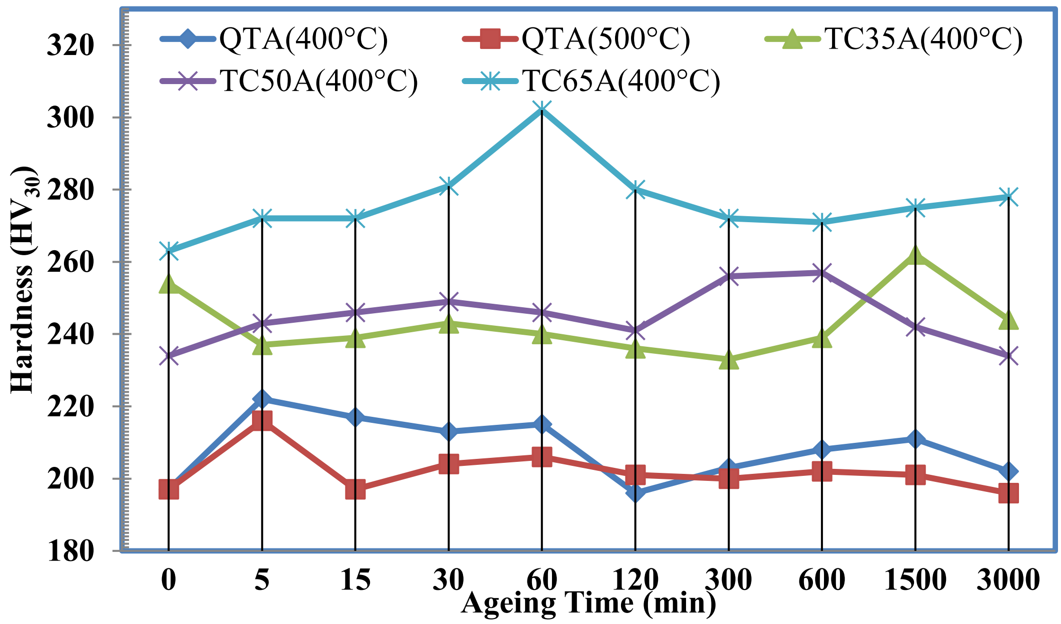

Fig.3: Hardness of microalloyed X65 HSLA steel as function of ageing time

As seen in Fig.3, the prior cold working resulted in remarkable improvements in hardness. Cold working for thickness deformation of 35% imparted a hardness of 254 HV_{30}. However, deformation of 50% resulted in a lowering of hardness (234 HV_{30}).

Further increase in the degree of deformation (65%) enhances the hardness to 263 HV30. In general, ageing after deformation of 35% and 50% by cold working resulted in gradual variation in hardness. On the other hand, a higher degree of deformation 65% accelerated the ageing process, as revealed by peaks in the ageing curve. It is evident from the ageing curve that hardness peak values are obtained after 1500 min, 600 min and 60 min after deformation of 35%, 50% and 65%, respectively. The response to age hardening also increases with the increasing degree of deformation. As a result, the maximum response to age hardening was observed after deformation of 65%. Fig.4

represents that a maximum value of hardness (303 HV_{30}) could be achieved after deformation of 65% deformation. The hardness at various stages of thermal and mechanical treatments are tabulated in Table 3.

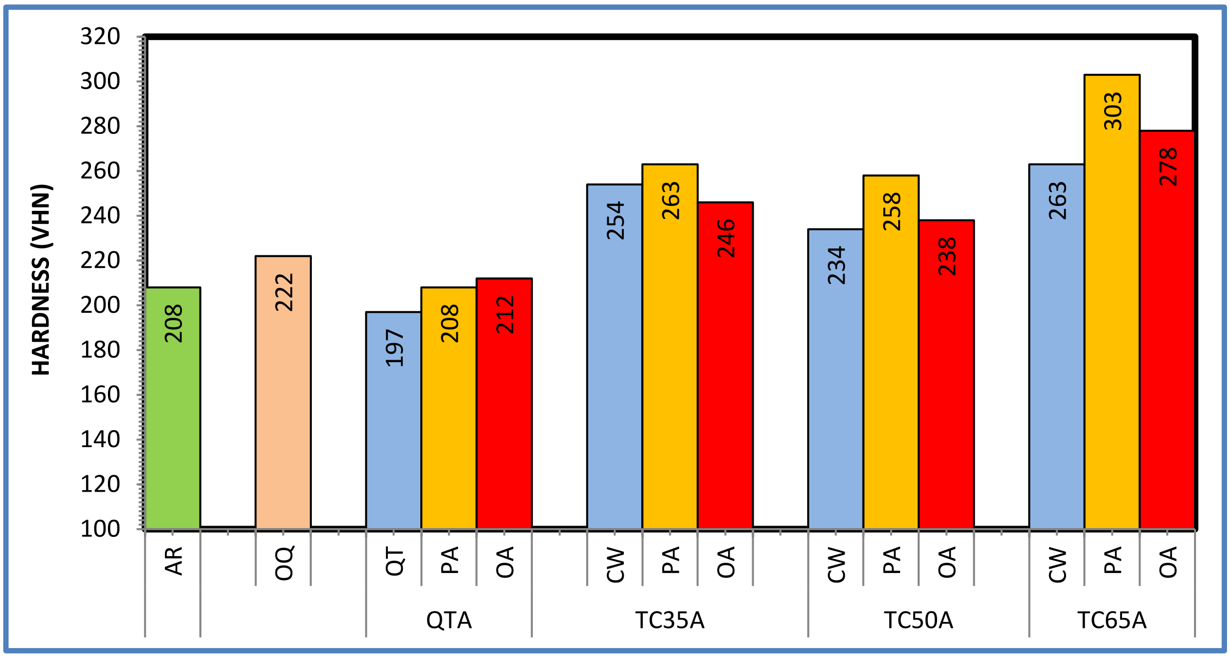

Fig.4: Hardness of Microalloyed steels in various conditions

Table 3: Mechanical Properties of microalloyed X65 HSLA Steelin various conditions

Category	Item	VHN	UTS (MPa)
AR	**As Received**	208	653.89
	1000-3H-OQ	222	550.17
	700-2H-WQ	197	606.08
QTA	**Aged-2Hr**	120	595.01
	PA-10Hr	208	836.91
	OA-25Hr	212	583.56
TC35A	**CW**	254	750.39
	PA-25Hr	263	741.97
	OA-50Hr	246	736.51
TC50A	**CW**	234	611.75
	PA-10Hr	258	821.7
	OA-50Hr	238	642.205
TC65A	**CW**	263	-
	PA-1Hr	303	-
	OA-50Hr	278	790.11

Ultimate Tensile Strengths (UTS)

Fig.5 represents the variations of UTS after various stages of thermo mechanical processing. It is observed that the UTS initially decrease after solution treatment at 1000^{o} C then oil quenching is applied. Further ageing resulted in increased values of UTS. The UTS initially increased with ageing, attained an optimum value (PA) and then dropped on subsequent ageing (OA). Fig.5 also represents the influence of tempering prior to cold working and ageing. It is seen that initially the UTS increases after 35% degree. This exhibits a drastic drop in the UTS values after 50% cold work. Accordingly, 50% cold work result in tensile strength value of 612 MPa as compared to the tensile strength value of 750MPa for 35% cold work. It can be manifested from Fig.5 that, any further increment in the degree of deformation leads to an improvement in the UTS of “Microalloyed HSLA steel”. It is also seen that the UTS varies in accordance with the variations of hardness values. In general, the lower degrees of cold work (35%) result in marginal changes in the hardness (Fig.4) and UTS (Fig.5) on ageing.

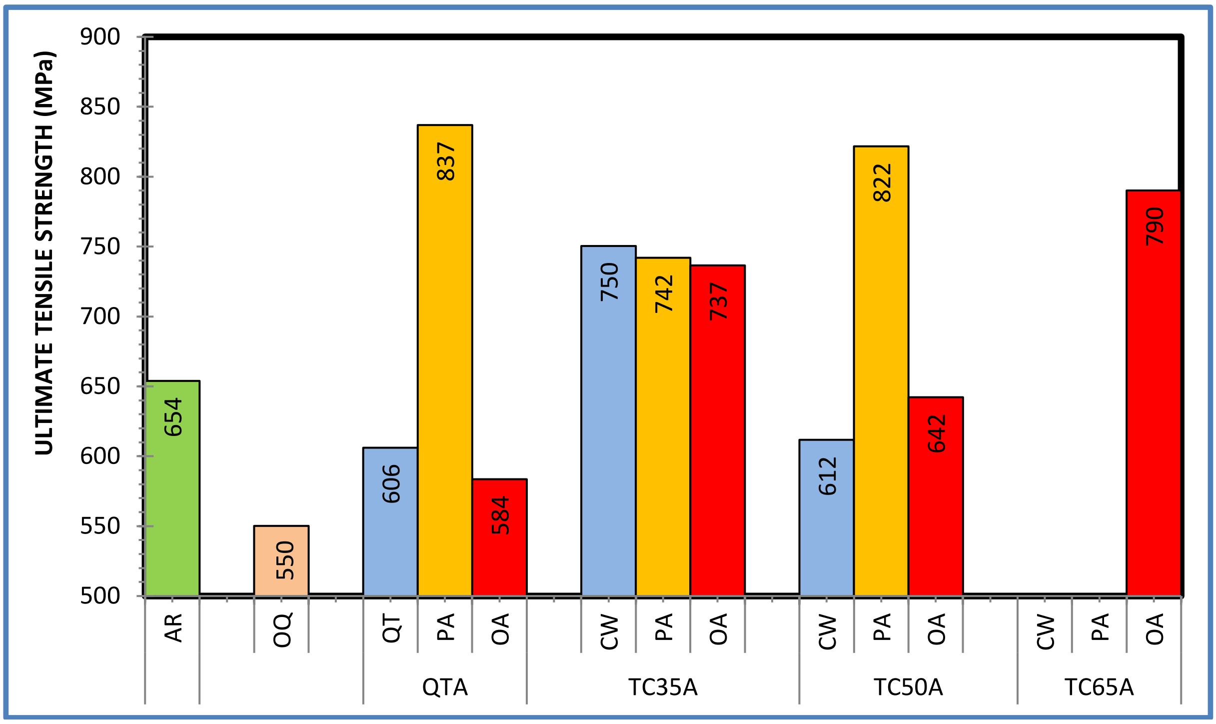

Fig.5: Ultimate tensile strength (UTS) of Microalloyed steels in various conditions

However, the higher degrees of cold working induced reasonable improvements in Hardness and UTS (Fig.4 & 5). In general, the UTS in peak aged condition increased with an increased degree of deformation. Therefore, as manifested, the hardness increased with the increased deformations. Fig.4-5, exhibit that the Hardness and UTS drop on ageing beyond the peak aged condition. It is also observed that the UTS in peak aged condition increased as the degree of deformation increased. After over ageing, the UTS values are also followed a similar trend as for the variation of hardness after cold working and ageing.

Conclusions

Thermomechanical processing of steels plays a critical role and has many practical applications in designing and developing various steels products. Mechanical properties of any material can be improved by either substantial solid solution strengthening and/or precipitation strengthening, which, in general, can be induced by both thermal and mechanical treatments. The study presents the variations in the mechanical properties i.e. hardness and ultimate tensile with the help of thermomechanical treatments. Both of these properties increased with aging and cold work. With the interaction between dislocation network and precipitation process strengthening would be increased. With the additions of microalloying elements strengthening is also increased. However, the various transformation treatments also cause increase in Hardness and UTS.

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