Development of 0.2C-CrMnMoV Ultra High Strength Steel

S. K. Maity[1], Anil Kumar Rajak[2], M. Chandra Shekhar[1], S. D. Singh[1]

[1]Metal Extraction and Forming, CSIR-National Metallurgical Laboratory, Jamshedpur, INDIA.
[2]Dept. of Metallurgical Engineering, BIT Sindhri, INDIA.
Corresponding Author: Dr. S. K. Maity, E-mail ID: maity@nmlindia.org

Abstract:

A study was carried out to develop a low alloy ultra high strength steel by induction melting and thermomechanical treatment (TMT) containing alloying elements like carbon, manganese, molybdenum, chromium and vanadium. A base alloy was prepared with 0.24%C, 1.16% Mn, 0.23% Si, 5.61% Cr, 0.42%V, 1.01% Mo, 0.026%S and 0.032%P. It showed tensile strength of 1467 MPa, yield strength of about 1180 MPa, impact strength of 6.3J and elongation of 5.9% in as-tempered condition. Other alloy was prepared by addition of 0.054% titanium with the base composition. It displayed tensile strength, yield strength, impact toughness and % elongation of 1615 MPa, 1240 MPa, 8.2J and 6.15%, respectively. The optical, SEM and TEM microstructures confirmed that the base alloy and the titanium alloy consisted with tempered lath martensites. The remaining part of the ingot was further processed by the thermomechanical treatment. The ingots were rolled in two passes, initially at 950°C and subsequently at 850°C followed by immediate cooling in oil. The TMT plates of the base alloy confirmed the tensile strength of 1755 MPa, yield strength in excess of 1460 MPa and impact strength of 9.1J. The titanium added TMT plate displayed tensile strength of 1860 MPa, yield strength of 1580 MPa and impact strength of 10.1J. Microstructures of titanium added alloy consisted finer lath martensite and precipitates of titanium carbides/carbonitrides. It was observed that the addition of titanium significantly improved the mechanical properties of 0.2C-Cr Mn Mo V alloys and the mechanical properties were also improved significantly by thermomechanical treatment.

Keywords:

Ultra high strength steel; thermomechanical treatment; mechanical properties; microstructure.

1. Introduction

Structural steels with minimum yield strength of 1400 MPa are often classified as ultrahigh strength steel (UHSS)[i]. These special steels are used for fabrication of many critical components like rocket motor casings, aircraft undercarriages, turbine motors, pressure vessels, *etc*. In addition to high strength-to-weight ratio, these steels should have good ductility, toughness and weldability. Maraging steel is mostly used for this purpose but it is highly alloyed and expensive. Development of steel with comparable mechanical properties is therefore a continuing process of investigation. The present investigation was aimed to develop indigenous steel with yield strength of 1500 MPa along with adequate ductility and impact toughness. In ultra high strength steels, several alloying elements are normally added to achieve desirable strength and toughness.

Though carbon is most important alloying element, which sharply increases the strength, but addition of high amounts of carbon results in decrease of weldability [ii] as can be seen from Equation 1.

$$CE = C+(Cr + Mo + V)/5 + (Mn + Si)/6 +(Ni + Cu)/15 \qquad [1]$$

where, CE is carbon equivalent and elements are in wt%. Based on the equation the value of “carbon equivalent” (CE) is directly proportional with increase of carbon content. Hence, the amount of carbon in the steel must be low to achieve good welding properties. Though the carbon has major effect on the strength of martensite, but good ductility can only be obtained at low carbon level. Due to the counteracting effect of carbon it has limited use as a strengthener [iii]. Generally other mechanisms adopted for strengthening of steel are: i) grain refinement, ii) precipitation hardening, iii) martensite transformation and (iv) thermomechanical treatment [iv-vi].

Grain refinement improves mechanical properties such as strength, toughness and formability[vii]. Hall gave the following relationship between yield strength and grain size which laid the foundation for the development of modern, high- strength structural steels [vii].

$$\sigma_y = \sigma_I + k_y d^{-1/2} \qquad [2]$$

where, σ_y is the yield strength, σ_I is the friction stress which opposes dislocation movement, k_y is a constant, and d is the grain size. The strengthening of the steel by alloying addition usually leads to a decrease in toughness, whereas refinement of grains results in a simultaneous improvement of strength and toughness. The Pitch equation linking impact transition temperature (ITT) and grain size is given bellow [ix].

$$\beta T = \ln B - (4qG\, \gamma' /K^{*}-K^{*}) - \ln d^{-1/2} \qquad [3]$$

where, T is the impact transition temperature, β and B are constants, q is the triaxiality factor which is 1/3 for Charpy V- notch, G is the shear modulas, γ′ is the effective surface energy, K^* is a constant, and d is the mean linear intercept grain diameter. This equation is shortened as [x]:

$$\beta T = \ln\beta - \ln C - \ln d^{-1/2} \qquad [4]$$

where, β is a constant related to the resistance of the lattice to deformation, and C is a measurement of the resistance to crack propagation. Grain refinement is achieved either by having fine precipitates of titanium carbides, vanadium carbide or other carbo nitrides which are stable at the soaking temperatures for pinning the austenite grain boundaries [xi]. Precipitation of carbides and carbonitrides both at high temperatures or during cooling and tempering provides opportunity for improving the mechanical properties [xii].

Mechanical properties of high strength low alloy (HSLA) steel are greatly influenced by the precipitation of carbides and carbonitrides. HSLA steels contain various alloying elements such as Cr, Mn, Mo, Ti and most of them are having strong affinity for carbon and nitrogen and forms their carbides and carbonitrides. The precipitates in these steels are complex in nature containing several alloying elements in the cationic sub lattice [xiii]. Ti is the strongest carbide former followed by niobium, vanadium, molybdenum, manganese and nickel. The precipitation hardening effect of carbides on yield strength can be estimated by the Orowan relationship[xiv]:

$$\sigma_y = \sigma_m + Gb/L \qquad [5]$$

$$\text{where } L = 1/6(\pi D^2/f)^{1/2} \qquad [6]$$

where, σ_y and σ_m are the yield strength in the presence and absence of the dispersion particles respectively, G is the shear modulus, b is the lattice distance, f is the volume fraction of carbides, and D is the diameter of the precipitates. It is estimated from the above equation that the increase of volume fraction and decrease of the size of the precipitates lead to improvement of yield strength.

The strength of the high strength steels is also greatly influenced by the microstructure. The relationship between composition and microstructures, tensile strength and yield strength of the steels are related with the following equations given by Irvine [xv] and Pickering [xvi] which indicate that carbon, molybdenum, titanium and others increase the strength of the steel significantly.

$$YS=15.4[4.4+23(C)+1.3(Si)+0.24(Cr)+0.94(Mo)+1.2(V) +0.29(W)+2.6(Nb)+1.7(Ti)+0.82(Al)+32(N)+0.1(\delta\text{-fe})+ 0.4d^{-1/2}] \qquad [7]$$

$$UTS=15.4[29+23(C)+55(N)+2.4(Si)+0.11(Ni)+1.2(Mo)+ 5.0(Nb)+ 3.0(Ti)+1.2(Al)+0.14(\delta\text{-fe})+0.82t^{-1/2}] \qquad [8]$$

Thermomechanical treatment normally increases the tensile properties and toughness without affecting ductility or brittle fracture resistance [xvii]. With controlled rolling it is possible to refine the ferrite structures directly after finish rolling or by using additional accelerated cooling. The processes can be divided into the following stages: i) forming in the region in which the austenite matrix recrystallizes, and/or ii) forming in a heterogeneous austenite-ferrite region after partial decomposition of austenite to ferrite followed by iii) a process of accelerated cooling after the controlled rolling. The essential hot rolling parameters of the thermomechanical process are: a) slab reheating temperature for dissolution of the precipitated carbonitrides, b) roughing phase for producing fine, polygonal austenite grain by means of recrystallisation, c) final rolling temperature, and d) degree of final deformation in the temperature range.

In the present study, high strength steel was obtained by exploiting most of the strengthening mechanisms. An attempt was made to control the chemical composition to the desired level. Carbon was restricted to 0.2%, as increase of carbon has an adverse effect on the ductility and toughness. Microalloys can control the grain size and it also provides the precipitation hardening during cooling. Chromium on the other hand gives fine precipitates during and tempering. Therefore, attempt was made to develop steel with selection of proper chemical composition during melting itself and to improve the strength of the steel by controlled thermomechanical treatment.

2. Methodology

2.1. Preparation of as-cast ingot by induction melting

The alloys were prepared in 20 Kg air induction furnace with optimized sequence of addition of ferroalloys. The scrap and ferroalloys were added in calculated amount to achieve the desired chemical composition. Ferro-titanium was added with basic steel during induction melting. The molten metal were tapped at 1600^0C and poured in preheated cast iron mould of dimension 48×52×250 mm. After solidification, the cooled ingots were taken out from the mould and were homogenized in a muffle furnace at 975°C for 8-9 hours. About 20 mm lengths were discarded from the bottom and top of the ingot. The ingots were approximately 225 mm long. About a length of 100 mm was taken from the ingots for heat treatment to study the properties in as-cast and as-tempered condition. The remaining parts of the ingots were taken for thermomechanical treatment.

2.2. Heat treatment of as-cast ingot

The specimens (10mm x 10mm) were sliced from the ingots, austenitised in oil at different temperature ranging from 850^0C to 950^0C and further quenched in oil. The maximum hardness was recorded when the specimens were austenitised at 950°C. Similar investigations were made at different tempering temperatures ranging from 400^0C to 500^0C with oil quenched specimen's austenitised at 950°C. The highest hardness was observed in the specimen tempered at 475^0C. Based on the study all the specimens of the as-cast alloys were austenitised at 950^0C and tempered at 475^0C. The as-cast heat treated specimens were prepared for mechanical properties and microstructural studies.

2.3. Thermomechanical treatment of as-cast ingot

As mentioned earlier the remaining part of the ingots were undergone for thermomechanical treatment. It was carried out in a controlled schedule of soaking, rolling and cooling. The ingots were soaked at 1100°C for about one hour and forged into 17 mm thick bars. During final rolling, the bars were re-heated at 1100°C and further transported to rolling mill and as soon as the temperature was dropped to 950°C, it was allowed to roll for first pass. The plates were allowed for second pass (final pass) at 850°C. Thereafter, immediately the samples were oil quenched. The final thickness of the plates was measured approximately 12 mm. Then the samples were prepared for mechanical properties and microstructural studies.

2.4. Characterization

Chemical analysis was carried out by atomic absorption spectroscopy (AAS) and SPECTROLAB analytical instrument. Mechanical properties were evaluated from as-cast and TMT specimens. For tensile test, round specimens of 4 mm diameter and 24 mm gauge length were prepared, as per IS: 1608 1972 and tested at room temperature using

Servo Hydraulic UTM at CSIR-NML. Charpy V-notch impact toughness specimens were prepared as per IS: 1499 1977. Hardness was measured on Rockwell C hardness tester. For optical and SEM studies the specimens were mounted and polished by conventional methods. Optical, SEM and TEM studies were carried out with standard method. Broken tensile test specimens (4 mm diameter and 10 mm long) were degreased using acetone and the fractured surfaces were examined under scanning electron microscope (SEM).

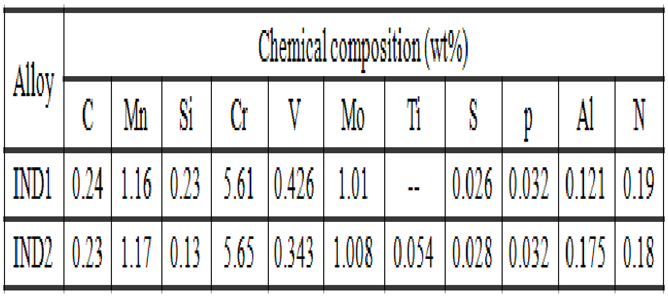
3. Results and Discussions

3.1. Properties of as-cast ingot

3.1.1. Chemical composition

As mentioned earlier, the alloys were prepared in air induction furnace with calculated amount of scrap and ferroalloys. The average recovery of alloying elements in metal was found in the range of 65-70%. The sequence of addition of ferroalloys was optimized to obtain aimed composition. It was aimed to restrict carbon of maximum 0.25%, manganese and molybdenum both should be 1%. Chromium and vanadium were maintained maximum of 5.5% and 0.4-0.5 % respectively. Out of the two alloys, IND1 was a base alloy. It contains 0.24%C, 1.16% Mn, 0.23% Si, 5.61% Cr, 0.42%V, 1.01% Mo, 0.026%S and 0.032%P. Another alloy (IND2) was prepared with addition of ~0.054% titanium in which the wt% of other elements were intentionally unchanged with the base composition. Titanium was added in the induction furnace in the form of 70% ferrotitanium. The recovery of titanium in open induction furnace was poor which was varied between 25%-30%. The chemical composition of the alloys is given in Table 1.

Table 1: Chemical composition of as-cast ingots.



Alloy	Chemical composition (wt%)										
	C	Mn	Si	Cr	V	Mo	Ti	S	p	Al	N
IND1	0.24	1.16	0.23	5.61	0.426	1.01	--	0.026	0.032	0.121	0.19
IND2	0.23	1.17	0.13	5.65	0.343	1.008	0.054	0.028	0.032	0.175	0.18

3.1.2. Mechanical properties and microstructures

The mechanical properties of the specimens of as-cast alloys were evaluated after heat treatment. The process consisted of austenitising the specimen at 950^{0}C followed by immediate oil quenching. As discussed the specimens were further tempered at 475^{0}C. The austenitising temperature was estimated from Figure 1 and found to be 950^{0}C. The tempering temperature was estimated from Figure 2 and it was around 475^{0}C.

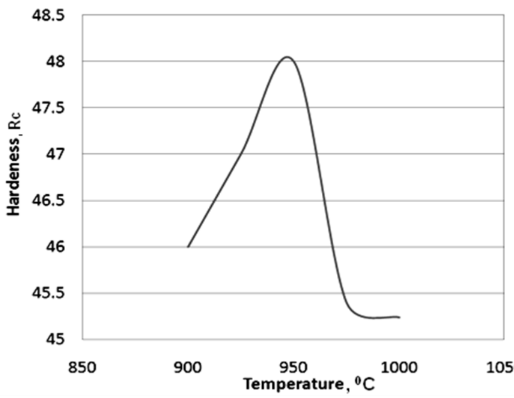


Figure 1: Hardness of the specimen austenitised at 950^{0}C and oil quenched.

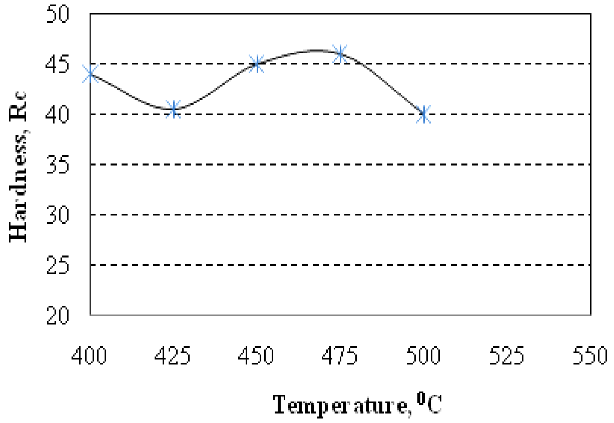


Figure 2: Hardness of the tempered specimens austenitised at 950^{0}C.

The mechanical properties of the as-cast and as-tempered specimens of the base alloy (IND1) and titanium added alloy (IND2) are given in Table 2. It can be seen that the base alloy has the tensile strength of 1467 MPa, yield strength of about 1180 MPa, impact strength of 6.3J with 5.9% elongation in quenched-and-tempered condition. While the mechanical properties of the IND2 are significantly influenced by the addition of 0.054% titanium. It displays tensile strength of 1615 MPa, yield strength of 1240 MPa, impact strength of 8.2J with elongation of 6.15%. Further, it was found that the tensile strength and the yield strength were improved by 9% and ~5% respectively after addition of titanium and there was a minor improvement in impact toughness, elongation and hardness.

Table 2: Mechanical properties of as-cast and as-tempered alloys.

Alloy	Tensile Properties			Impact strength (J)	Hardness (HR$_c$)
	UTS (MPa)	Y.S (MPa)	Elongation (%)		
IND1	1467	1180	5.9	6.3	47
IND2	1615	1240	6.15	8.2	49.4

The austenitised grain size of as-cast tempered specimens of IND1 and IND2 samples are shown in Figure 3 (a, b) and illustrated also in Table 3. The average grain size of IND1 alloy was estimated to be 65 microns which were subsequently refined to 40 microns in IND2 alloy. It seems that titanium plays an important role in the refinement of austenite grain size. The optical and SEM micrographs of the tempered specimens of IND1 and IND2 are also shown in Figure 4 (a, b) and Figure 5 (a, b) respectively. The microstructure of both alloys apparently comprised with tempered lath martensites. The laths were more finer in Ti-added alloys compared to the base alloy as it was confirmed by TEM study in the following section.

Table 3: Austenite grain size of as-cast and as-tempered specimen.

Alloy	Average grain size	
	ASTM no	Absolute value (μm)
IND 1	5	65
IND 2	7	40

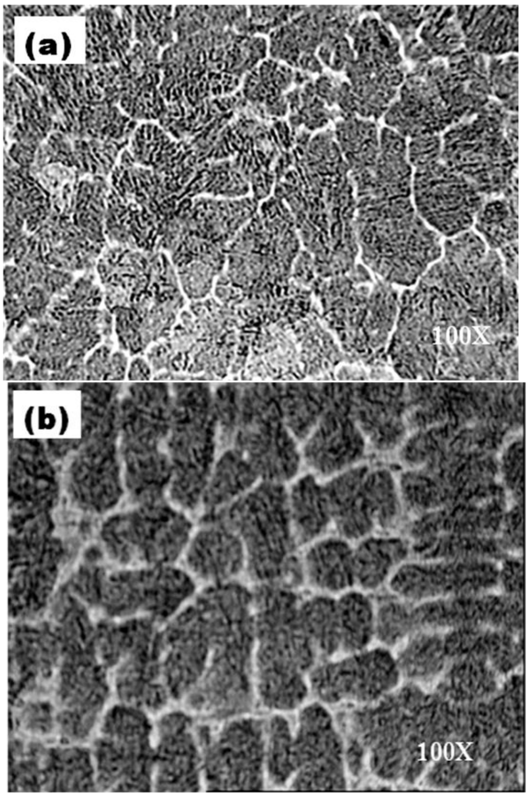
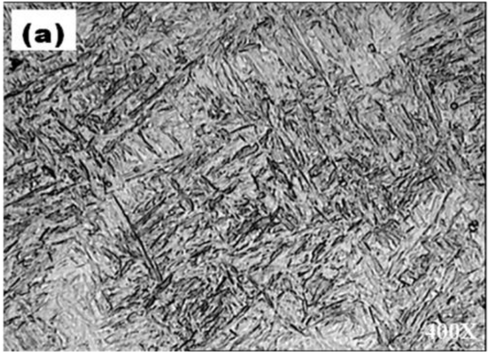


Figure 3 (a, b): Optical microstructure pertaining to the grain size of base alloy (IND1) and titanium alloy (IND2) in as-cast and as-tempered condition.



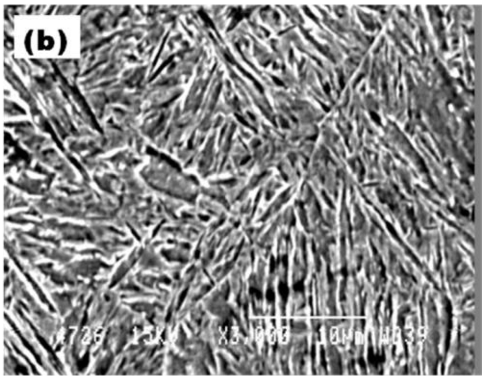


Figure 4 (a, b): Optical and SEM Micrographs of tempered IND1 specimen showing predominantly tempered lath martensite structure.

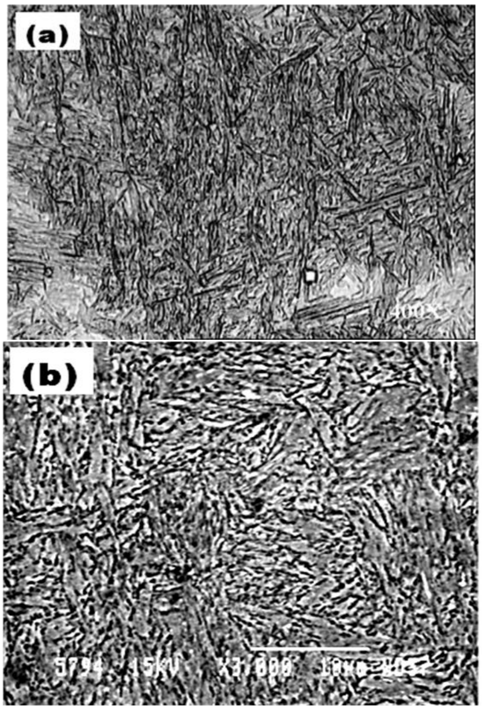


Figure 5 (a, b): Optical and SEM Micrograph of tempered IND2 specimen consist of finer lath tempered martensite structure.

3.2 Properties of TMT plates

3.2.1 Mechanical properties

For further improvement of mechanical properties of as-cast alloy, thermomechanical process was applied to the remaining part of the ingot prepared by induction melting. During the thermo-mechanical treatment the ingots were forged to bars and soaked at 1100^0C and allowed for rolling at two passes. In each pass about 25% reduction was given in the cross-sectional area. The final pass was at 850^0C followed by oil quenching. It allowed to obtain predominantly martensite microstructures [xviii]. The mechanical properties of as-TMT specimen is shown in Table 4.

Table 4: Mechanical properties of TMT alloys.

Alloys	Tensile properties			Impact strength (J)	Hardness (HR$_c$)
	UTS (MPa)	Y.S (MPa)	Elongation (%)		
IND1	1755	1460	NA	9.1	48
IND2	1860	1580	NA	10.1	51

It can be seen that the tensile strength, yield strength, impact toughness and hardness values were were 1755 MPa, 1460 MPa, 9.1J and 48 Rc respectively of the base alloy (IND1). It can be seen from Table 2 and Table 4 that the tensile strength and yield strength of the TMT specimens were increased by 288 MPa (19%) and 280 MPa (23%) respectively compared to as-cast tempered condition. Similarly, significant improvement of mechanical properties were observed in TMT specimens of titanium added alloy (IND2) as compared to the corresponding as-cast tempered specimens. The titanium added TMT plate displayed tensile strength, yield strength and impact toughness of 1860 MPa, 1580 MPa, 10.1J respectively. In this case the tensile and yield strength were improved by 245MPa and 340MPa as compared with as-cast alloy. On the other hand similar trends of improvement of mechanical properties was found in TMT specimens of base alloy and titanium.

3.2.2 Microstructure

The optical and SEM microstructures of the TMT specimens of IND1 and IND2 alloys are shown in Figure 6 (a, b) and Figure 7 (a, b) respectively. The micrographs reveals that the microstructures of the TMT specimens of the both alloys consisted with fine tempered lath martensite as it was seen in as-cast tempered alloys. It seems that the laths were relatively finer after thermomechanical treatment. Similar effect was observed in TMT specimens in titanium alloy compared to the basic steel. The TEM micrographs of TMT specimens of IND1 and IND2 are shown in Figure 8 (a, b) and Figure 9. TEM micrographs of IND1 indicates the presence of retained austenite in the predominantly martensite matrix. The average inter lath spacing of the martensite is measured to be 890 nm and ranging from 750nm to 920nm. The TEM micrographs of IND2 alloy is shown in Figure 9. The micrographs reveals that the microstructures were mostly finer lath martensites in which inter lath spacing's were measured in the range of 220nm to 400nm averaging to be 300nm. This study indicates that the addition of titanium resulted in refinement of martensite laths, which is in line with optical and SEM micrographs as discussed earlier.

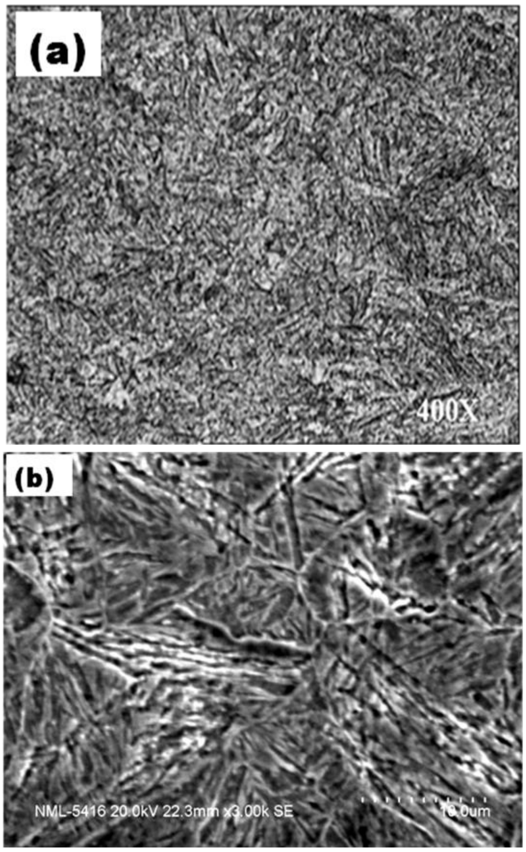


Figure 6 (a, b): Optical and SEM micrographs of TMT specimen of IND1 alloy.

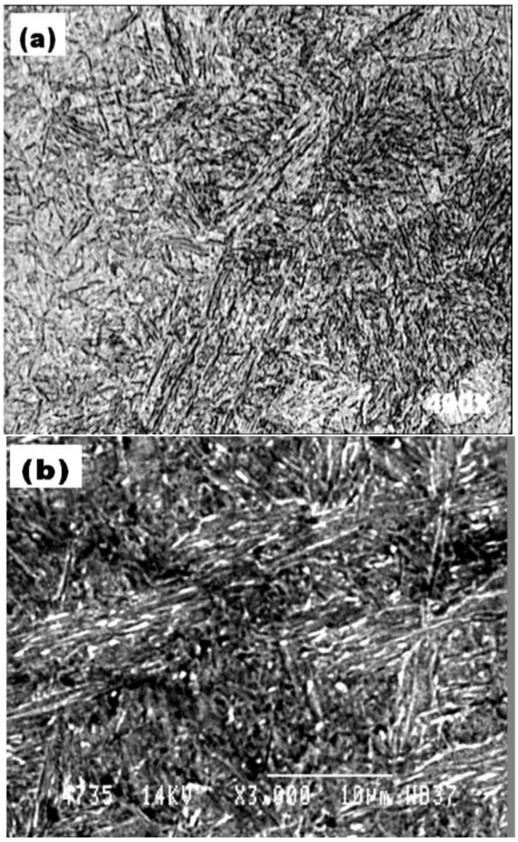


Figure 7(a, b): Optical and SEM micrographs of TMT specimen of IND2 alloy.

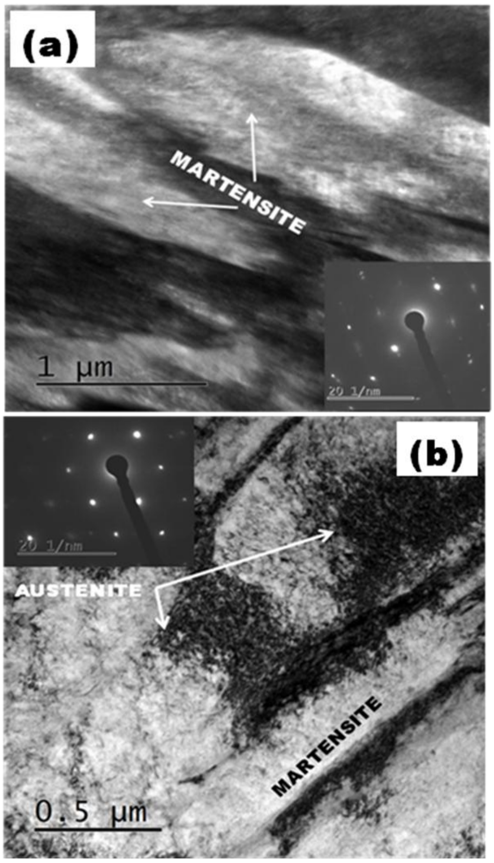


Figure 8 (a, b): TEM micrographs of TMT specimen of IND1 alloy shows the presence of lath of martensite and retained austenite.

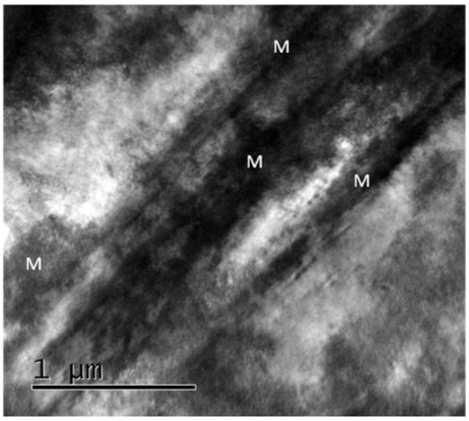


Figure 9: TEM microstructure of TMT specimen of Ti-inoculated alloy (IND2) shows lath of the martensites.

The fractrographs of the broken TMT tensile test specimens of IND-1 and IND-2 alloys are shown in Figure 10 (a, b). It can be seen from the micrographs of the IND2 that the fracture surface of the titanium alloy consisted of cup and cone appearance and central zone of the fractured surface has irregular fibrous appearance with numerous dimples. This structure might be characteristics of fracture resulting from uniaxial tensile failure of a ductile material. The fractrographs of IND1 has relatively less or no dimples. It possibly indicates that the materials were failed largely in cleavage mode and has characteristic of brittle materials. In this context, it can be seen from Table 2 and Table 4 that the value of elongation in IND1 alloy was relatively lower than IND2 alloy in both as-cast and as tempered and TMT specimens.

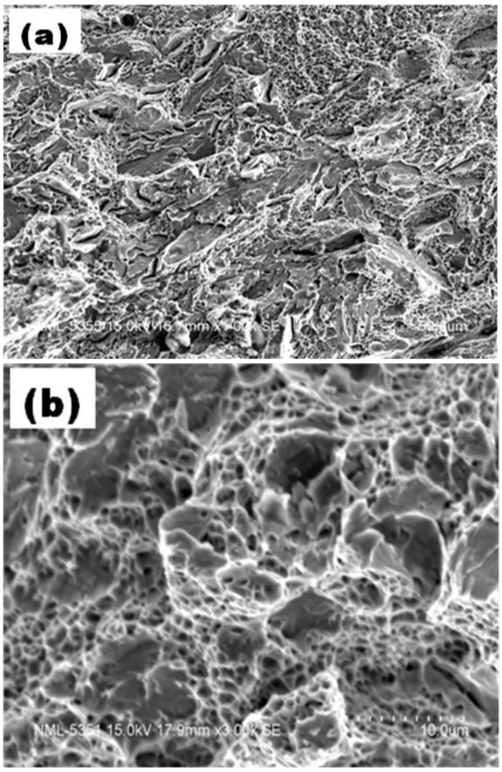


Figure 10 (a, b): Fractrographs of broken tensile specimen of TMT plate of IND1 and IND2 alloys.

3.3 Discussions

In the present investigation an effort has been made to develop an alloy having yield strength 1500Ma with adequate ductility and toughness. Available commercial steel are made of either high carbon (>0.4%C) or with high expensive alloying elements (> 10-15%). Sometimes high carbon structural steel find difficulty in its application due to its poor weldability. On the other hand, addition of high alloying elements especially Ni, Co results in the increase of cost of the steel. Therefore, an effort has been made to develop an alloy steel with addition of carbon in the range of 0.2% to 0.25% and other relatively low cost alloying elements like Cr and Mn. Apart from above, other alloying elements like Mo, V and Ti are added to the steel to increase the beneficial effects of precipitation hardening and grain refinement. In one hand C, Cr and Mn increase the hardenability of the steel to a great extent and on the other hand presence of strong carbide formers like Ti, V and Mo helps in increasing of the precipitation hardening. Titanium not only gives the precipitates of titanium carbide/ titanium carbonitrides but also restricts the grain growth at the austinitising/ soaking temperatures because of the stability of its carbide at higher temperature (< 1250^0C) [xix] by zinner pinning effect [xx]. The titanium carbides act as a grain refiner leading to the improvement of mechanical properties [viii]. Whereas the application of thermomechanical treatment to the steel results in improvement of mechanical properties, but, application of this technique to ultra high strength steel (UHSS) is merely reported. In the present study this technique was adopted in this alloy to investigate the extra beneficial effect in the mechanical properties. For this reason optimized and control process parameters need to be applied during the experiments. An attempt was therefore made to incorporate all the strengthening mechanism to develop these alloys.

The tensile strength and yield strength of the steels prepared in this study was found to be higher than the value specified for ultra high strength steel [i]. It can be seen from Table 3 that titanium addition in base alloy composition leads to decrease of austenite grain size from 67 µm to 40 µm. The comparative study between Figure 8 (a) and Figure 9 shows that addition of titanium increases the degree of refinement of inter lath spacing from 899nm in IND1 and 400nm in IND2 alloy steel to a great extent and possibly increase of volume fraction of martensite as no retained austenite could be seen in titanium alloy. It has also reported that addition up to 0.1% titanium leads to increase the hardenability and mechanical properties and beyond this limit it affects adversely [xix]. Due to this fact in this investigation the amount of titanium was restricted to 0.054% which resulted in increase of volume fraction of martensite in titanium alloy improving its strength and hardness. The precipitates of titanium are normally stable at higher temperature which may restrict the grain growth of austenite leading to the formation of finer martensite during rapid cooling. The appearance of finer lath martensites in titanium alloy as compared to the base alloy noticed in the micrographs in Figure 8 (a, b) and Figure 9 is clarifying the above.

The precipitates of base alloy and titanium alloy are revealed in TEM micrographs as shown in Figure 11 (a, b). It can be seen from Figure 11(a) that the precipitates in base alloy consisted mixed (Cr, Mo, Si, V) carbides in which the cationic sub-lattice were filled with Cr, Mo, Si, V, etc. These precipitates are distributed longitudinally niddle shaped structure and randomly placed in the matrix. Whereas spherical shaped TiC/ Ti (C, N) precipitates were observed in titanium alloy (IND2) as shown in Figure 11(b). The size of the precipitates was measured and found to be in the range of 15-30nm. Due to smaller in size and its stability at higher temperature it can restrict the grain growth and helps for grain refinement. The precipitation hardening may follows Orowan relationship [xiv]. According to Orowan equation the beneficial effect of the precipitation hardening and grain refinement may be obtained from the fine precipitates of TiC/Ti(C.N) and its homogeneous distribution [xiv], which improves the mechanical properties. Moreover, this effect can be obtained when the titanium in the steel is maintained in preferably in the range of 0.05% to 0.07% [xxi]. The entrapment of carbon due to the formation of titanium carbides is estimated to be about 0.01% (Ti:C :: 4:1 by weight %) which is very marginal compared to the total amount of residual carbon (0.22%) and apparently it has no influence on the martensite transformation during rapid cooling.

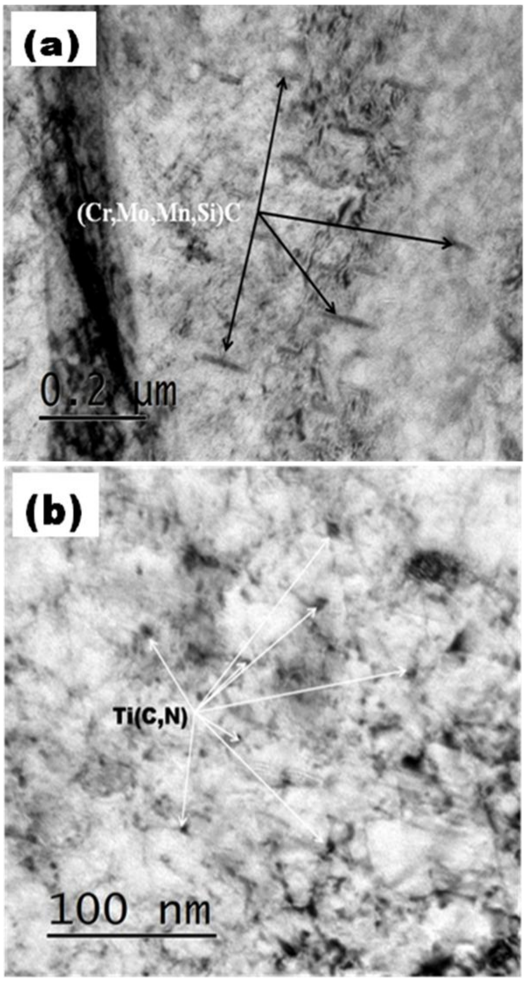


Figure 11 (a, b): TEM micrographs showing precipitates of (Cr, Mn, Mo, Si)C in IND1 alloy and Ti(C, N) in IND2 alloy.

In addition to the above, thermomechanical treatment by controlled rolling and accelerated cooling plays an important role in the modification of final microstructures. The first pass rolling helps to increase the yield strength and toughness. It is attributed to the resultant fine grain microstructures. In the second pass rolling followed by rapid quenching, the increase of mechanical properties is caused not only by refining of grain size, but also by the change of the morphology of the various phases in the (bainite or martensite) ferrite matrix. It is reported that if rolling is completed at a relatively high temperature (in the high temperature austenite range) and the sample is cooled faster resulting in the formation of mostly martensite phase [xvii]. Although, the TMT specimens of both alloys confirm the strength values of UHSS, however, many more studies are still needed to understand the other properties suitable for critical applications. It is noticed that addition of titanium in 0.2C-CrMnMoV steel results a significant improvement in tensile strength, yield strength, toughness and hardness. As the carbon equivalent is higher in these steels the welding may be an anticipated problem. The comprehensive study is required to find out the suitable welding process for these alloys. The technique of the thermomechanical treatment adopted in the present study requires further optimisation of process parameters for better yields.

4.0 Conclusions

1. The tensile strength and toughness of thermomechanically treated alloys prepared by induction melting meet the strength requirement of ultra high strength steel.
2. Addition of small amount of titanium in 0.2C-CrMnMoV steel results in significant improvement in tensile strength, yield strength, toughness and hardness by reducing the grain size and refines the martensite laths.
3. Titanium in the range of 0.054% reduces the retention of austenite during quenching and helps in decrease of the grain size significantly due to precipitation of finer titanium carbide or titanium carbonitrides.
4. Thermomechanical treatment in this kind of steel results in increase of tensile strength and yield strength by 15% and 27% respectively in compared to as-cast and as-tempered specimen. It does not only increase the strength but also improves the toughness and hardness. After thermomechanical treatment, the base alloy resulted UTS:1755 MPa, Y.S.:1460 MPa, impact toughness: 9J and Ti-added alloy displayed UTS of 1860 MPa, Y.S. of 1580 MPa, impact toughness 10.1J.

References

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