Effect of Flame Straightening on Through Thickness Properties of TMCP Steel Plate

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Abstract— Thermo-mechanical controlled process (TMCP) steel plates are used in manufacturing of steel structure. Welding distortion is a perennial problem during fabrication. Flame straightening method is adopted for removing distortion. In this paper, the effect of flame straightening on mechanical properties of TMCP steel plate across the thickness has been taken up for investigation. A test specimen having yield strength 450MPa-TMCP steel plate was heated to 800 °C on the surface using oxy-acetylene flame by line heating method. The material properties at different zones of heat imparted location was studied. The test results were analyzed and observed that the variation in mechanical properties were due to changes in microstructure. The yield strength, toughness and ductility of the TMCP steel plate got reduced by 17.33%, 23.42% and 12.87% respectively along the thickness of heat imparted zones.

Key words: Distortion; Flame straightening; Mechanical properties; TMCP steel

I. INTRODUCTION

In structural steel fabrication, distortion is a perennial problem observed when steel structure is welded by Submerged Arc Welding process (SAW). Distortion cannot be eliminated but controlled by design of welds, process parameters and welding sequence. Shape control by flame straightening is a common practice in steel fabrications. Establishing a process to meet the rationalized fabrication practice is based on the reliability of the structure and fabrication cost. During welding, complex strains occur in the solidified weld metal and base metal regions. The complex strains may be accompanied by plastic upsetting due to temperature gradient. The stresses resulting from these complex strains react and produce internal forces that cause deformation. To remove the unacceptable deformation and to maintain the integrity of the product, flame straightening is used.

Burbank [1], investigated the flame-heated un-welded sections of 'HTS' steel plate, 10 mm thick, in the range of temperatures between 525°C-800°C and water-quenched. There was a decrease in impact strength when they were tested immediately after straightening; a further decrease was noted, when they were tested after six months. Nippes and Savage [2], reported the variation in notch toughness, when the specimen was subjected to several cycles of flame straightening. Low notch toughness was noted beyond the heat imparted zone. Canonico et al. [3], found out the effect of accelerated cooling on the properties of steel. The notch toughness is based on temperature field beyond the heat imparted zone in which steel experience the magnitude used while flame straightening. Studies on flame straightening by Harrison [4], indicated the variation in the mechanical properties of the steel plate.

TMCP steels are characterized by micro alloying elements (Nb, V, and Ti), alloying elements (Mo, Cr, Ni) and parameters of hot rolling process [5]. The desired mechanical properties of the steel plate are obtained by rolling at prescribed temperature and cooling after rolling either in air or through accelerated cooling [6,7]. Strength and toughness of the plate are influenced by their microstructural phase transformation [8, 9]. During flame straightening, heat is applied over the plastically deformed regions of the welded parts, which is proven process for correcting the weld distortion [10]. The flame straightening process is characterized by thermal cycles viz. local heating and cooling like welding. Different types of microstructures such as spheroidzed zone, partially transformed zone, grain refined zone and coarse grained zone are formed in the base metal during flame straightening [11]. The microstructures formed at the heat imparted zones tend to change the properties of the base metal. Depending upon the cooling rate, especially below Ar_3 temperature typical microstructure such as ferrite, acicular ferrite, pearlite and bainite are formed [12, 13] across the plate thickness. The yield strength and toughness are the critical parameters which need to be compared with mill test certificate to assess the material properties after flame straightening. TMCP steel behaves like a poor material due to its rolling characteristics while flame straightening [14]. The literatures reveal that the superficial heating up to 950°C does not influence the mechanical properties, if the temperature at mid thickness is kept below 700°C [15].Frank Hanus et al. [16] found that the TMCP steel with high yield strength might be prone to softening by flame heating. The recent investigation on flame straightening revealed that the penetrative reheat temperature 800°C and higher, the mechanical properties are satisfied but the average decrease of yield strength below 7% [17]. The effect of flame straightening on mechanical properties were analyzed so far on full thickness plate. The aim of this investigation is to find out the mechanical properties of the TMCP steel plate at various regions of heat imparted zones due to flame straightening and its suitability in the steel fabrication used for dynamically loaded structures.

II. EXPERIMENTAL PROCEDURE

Flame straightening process was carried out on High tensile low carbon TMCP structural steel plate specification to IS 2062-E450BR of the size 300x300x 56 mm. The correction process was simulated in a separate plate. Plate was heated to 800°C on surface in pre-defined direction using oxy-acetylene gas by line heating method. The heating torch was oscillated to a width of 40 mm and it travelled to the length of 300 mm.The experimental set up is shown in Fig.1.The temperature was checked with the thermal crayons and the plate was allowed to cool in still air. The chemical composition and mechanical properties of the plate are given in table 1 and 2 respectively.

III. TEST SPECIMEN PREPARATION AND TESTING

Test specimens from the heat imparted zone at different depths of the steel plate were identified by etching. A soft zone at a depth of 8 mm and width of 35 mm with semi-circle profile was identified after etching and shown in Fig. 2. Test specimens for all test were prepared and tested at respective heat imparted zones of 8 mm, 13 mm, 17 mm and 23 mm depths from the top surface.

Using Vickers hardness tester, hardness test was conducted as per IS1501-2002 on the sample by applying load 10 kgf for 10-15 seconds duration. Hardness values were measured at different depths from the top surface across the section thickness. The impact test samples were prepared at different depths and with the size of 10x10x55 mm, 45 degree V notch of 2 mm depth and with a root radius of 0.25 mm. The notch was made on the heated top side.

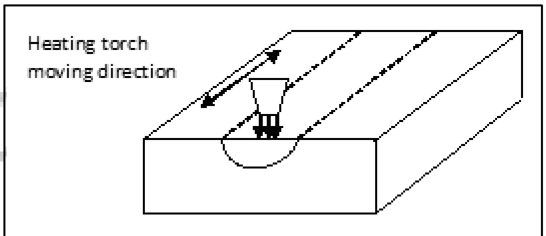

Fig.1. Experimental set up


Fig. 2: Macro- Heat imparted zone

C	Mn	S	P	Si	V
0.18	1.48	0.003	0.011	0.36	0.050
Nb	Ti	Mo	Cr	Ni	--
0.035	0.017	0.040	0.116	0.005	--

Table 1: Chemical composition (mass %) of the steel plate

Material specification	Yield strength MPa,	Tensile strength MPa	% Elongation	Impact Value (J) at 25 °C
E450 BR	506	634	26	143

Table 2: Mechanical properties-Mill certificate

Charpy impact test was carried out as per ASTM E23-16B on samples. Transverse Tensile (10x20 mm) test specimens were prepared in the heat imparted zone of the plate at different locations across the section thickness. The values of impact energy, yield and tensile strength were recorded. The heat imparted zone of the base metal was prepared for microscopic examinations as per ASTM E407-07e1 after polishing with different grades of emery papers and etching by 2 % Nital solution. The microstructure were captured by Leica-optical microscope with 200X magnification at different depths of heat imparted zones.

IV. TEST RESULTS AND DISCUSSION

A. Flame Straightening

The effect of flame straightening process depends upon on the thermo-physical properties of the plate metal and heat density of the flame. The oxy-acetylene flame is most suited for distortion correction owing to high heat density. Flame straightening process parameters such as peak temperature, temperature gradient, cooling rate and frequency of heating cycles, affect the metallurgical and mechanical properties of the base metal. Further microstructure transformation occurs in the base metal leading to the decrease in tensile and impact strength. Fig.3, shows a schematic representation of the deformation flow process on flame straightening.

TMCP steel billets are usually heated to temperature of 1200°C and rolled above Ar_3 temperature. The optimum precipitate size and dispersion are obtained when the finish rolling temperature is around 775°C. The schematic diagram Fig.4, represents the rolling parameters of TMCP steel. The final rolling passes of TMCP plate promote plastic deformation at lower temperature. The rolling passes below Ar_3 temperature which enhance austenite to ferrite transformation resulting in fine grains of ferrite and fine dispersed precipitates. Flame straightening is conducted at temperature range of 600-650 °C with variation of 100 °C for “As rolled” or “Normalized” low carbon steel plate. Temperature control is the main factor to decide flame straightening process. The plastic rotation while heating is directly proportional to the heating temperature, up to at least 870°C. High temperatures may result in greater rotation but likely damage the surface and alter the material properties after cooling. The flame straightening process may yield the desired results at temperature of 950°C leading to thermal upsetting. The stress developed due to heating should be in the yield limit of the base material and be slightly exceeding the elastic limit. These inter connecting limits are represented in Fig. 5. Generally, yielding occurs at a stress where the average dislocation sources create slip bands. The general yield stress (σ_0) can be expressed [18] by the relation:

$$\sigma_0 = \sigma_s + \sigma_i \qquad (1)$$

Where, σ_s is the stress to operate the dislocation sources and σ_i is the friction stress.

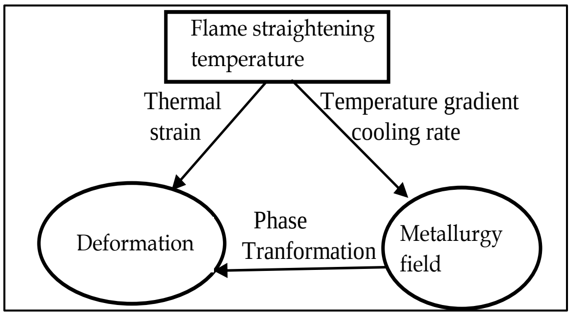

Fig. 3: Deformation flow process

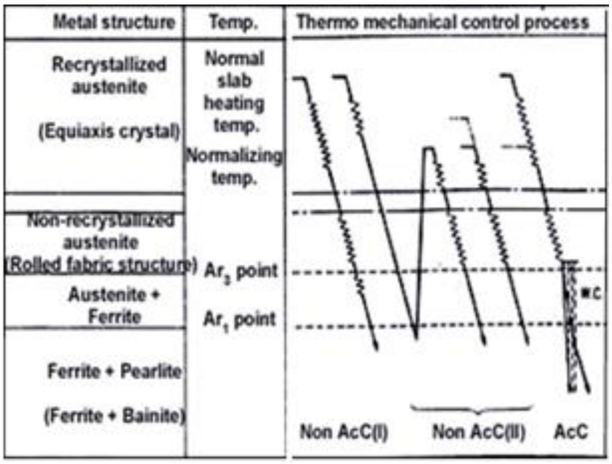

Fig. 4: Schematic diagram for TMCP-rolling parameters

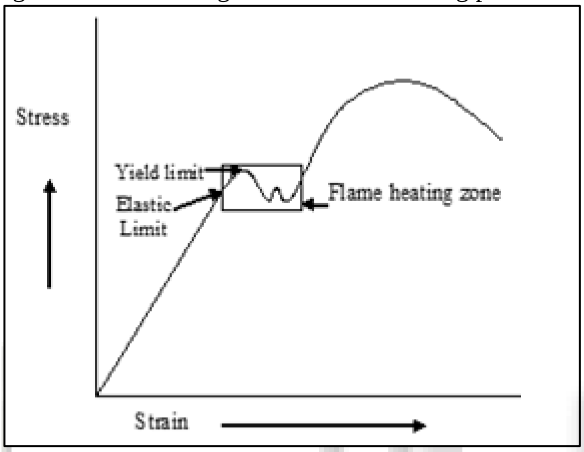

Fig. 5: Schematic representation of flame heating zone

B. *Hardness*

Many factors are responsible for the hardness variation across the thickness on flame straightening, one of the major factor is phase transformation. Reduced work hardening in the plate occur due to grain nucleation and growth of austenite. The annealing effect while cooling has distinct impact on the phase contents. Therefore, the net effect is reduced hardness. Despite the cooling rate being high, the nucleation of fine grains structure exhibit low inter-granular spacing. The stress (τ_o) for dislocations to cross grain can be calculated by [18].

$$\tau_o = (Gb)/\lambda \qquad (2)$$

Where G is shear young modulus, λ is inter-particle spacing and b is dislocation Berger's vector. The hardness value of the test plate across the thickness is graphically represented in Fig. 6. Hardness value is found to be in the order of 202 Hv in the heat imparted zone up to the depth of 8mm from top surface. This is due to fine grains of ferrite and spheroidzed pearlite. The hardness is 196Hv at a depth of 8 to 13mm due to coarse grained pearlite microstructure on nucleation and fast heat dissipation in the base metal. The coarse grained pearlite and ferrite with high volume fraction of pearlite microstructure is observed between the depths 13 and 17 mm and the hardness value is found to be in the order of 185Hv. The hardness value measured between 17 and 23 mm is 189Hv and the microstructure is found to be fine grains of ferrite and pearlite with widmanstatten ferrite. Hardness in the base metal beyond 23 mm is measured and found to be the order of 197 Hv, in which the microstructure is equiaxed ferrite and pearlite with widmanstatten platelets of ferrite and pearlite viz. base metal. Therefore the variation in hardness is due to the different types of microstructure across the section thickness. Empirical relations are used to estimate the strength from bulk hardness measurement [19]. An empirical equation between hardness and strength has been determined as

$$H = cS \qquad (3)$$

H, is the hardness (Kg/mm^2) and S is the uniaxial flow strength (MPa). The factor c is elastic constant and has a value approximately 3.16 for ferritic steel [20, 21]. The hardness values are validated with the actual test values of the tensile strength.

C. *Toughness*

The energy absorption during dynamic loading of a structural member is determined by the toughness of the material. The impact energy observed at various locations are plotted and shown in Fig. 7. The energy observed at the location up to 8 mm from the top surface is 172 joules. This is attributed to the cooling process similar to the TMCP rolling. Beyond 8 mm and up to 13 mm, the impact energy is found to be 152 joules and after 13 mm and up to 17 mm, is 134 joules.

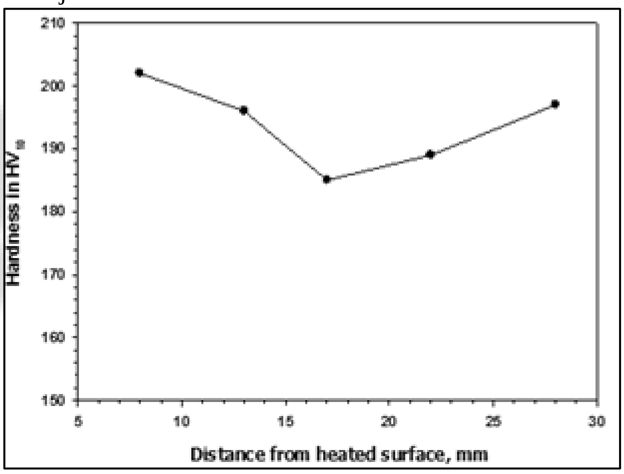

Fig. 6: Hardness at different location

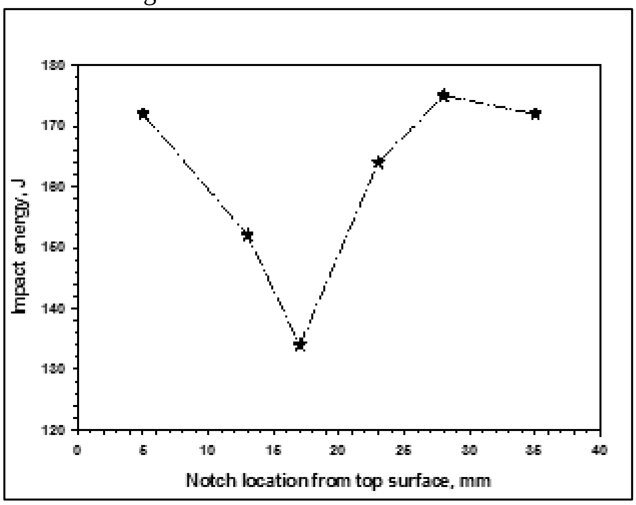

Fig. 7: Impact energy at different location

Fig. 8: A. Dimple ductile fracture Fig. 8: B. Cleavage fracture

At the depth of 23 mm, impact energy is 164 joules and beyond 23mm the impact energy is 175 joules in unaffected base metal. The impact test specimen fracture pattern is represented in Fig.8a and 8b. A dimple ductile fracture occurred at 8 mm depth from the heated surface. This is due to the presence of fine grain structure of equi-axed ferrite and spheroidzed pearlite. Cleavage fracture occurred where the impact energy is 134 Joules at a depth of 17 mm. The surface exhibited a brittle fracture behavior and relatively flat surface. The reduction in impact energy between the depth of 13 and 17 mm is promoted due to coarse pearlite with ferrite prior to austenite grain boundary observed at that location. The impact energy absorbed at heat imparted zone is 134 joules, whereas the impact energy absorbed at un-affected base metal is 175 23.42% against base metal impact strength. The grain growth of coarse pearlite due to phase transformation can increase the crack initiation and it can be adversely affect the fracture toughness. This behavior is related to the non-uniform distribution of carbides.

D. Strength

The mechanical properties of TMCP products are determined by the rolling sequence and microstructure. Plate E450BR includes the micro-alloy elements Nb, V, and Ti. The strengthening effect depends on the content and distribution of the micro-alloy elements. The flame straightening process can affect the kinetics of the precipitation of the alloy carbonitrides, the recovery and recrystallization. Mechanical test has been conducted to find out the yield, tensile strength, percentage elongation and strength ratio. The tensile and yield strength values at different locations are plotted and are represented in Fig.9. The tensile and yield strength values at a depth of 10 mm are better where the presence of spheroidzed pearlite and fine grained equiaxed ferrite microstructure.

The tensile and yield strength are comparatively low at the depth of 13 to17 mm. This is due to formation of coarse pearlite with ferrite. High temperature transmission enhances slow nucleation with cooling rate and the growth of the nuclei leading to such types of microstructure. The yield strength at the depth of 17 mm is 415 N/mm^2 whereas the yield strength at the un-affected base metal is 502 N/mm^2. The reduction in yield strength is 17.33%.This variation is owing to heat dissipation and change in microstructure across the thickness.

The ductility is the critical parameter considered for TMCP material and it is intended for higher ductility along the rolling direction. Z quality across thickness is to encounter lamellar tear during welding. "Z" quality plates are used to endure the high level of stresses, particularly where heavy plate section is used. The ductility is experienced in terms of percentage elongation. The percentage elongation versus strength ratio is shown in Fig.10. The percentage elongation and strength ratio at the depth of 13 mm is 18.66.0% and 79.37% respectively. Beyond 13 mm and within 17 mm, the strength ratio is drastically reduced to 68.7%, whereas the strength ratio at un-affected base metal is 79.68%. The strength ratio of the TMCP steel (E 450 BR) is usually in the range of 75-85%. Therefore strength ratio is reduced by 13.78%. Percentage elongation at heat imparted zone is 17.6%, whereas at unaffected base metal zone is 20.2%. The reduction in percentage elongation is 12.87% with respect to unaffected base metal at the depth of 17mm is due to coarse pearlite with ferrite microstructure.

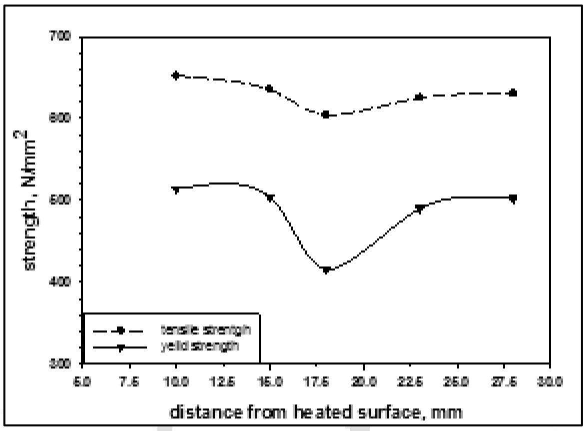

Fig. 9: Tensile-yield strength variations

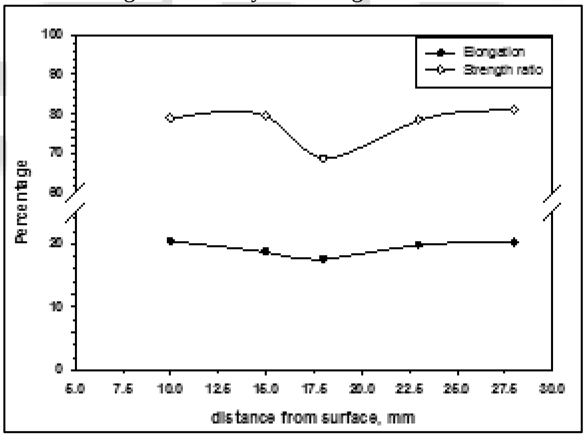

Fig. 10: Percentage elongation-Strength ratio

E. Microstructure

During flame straightening, the temperature in a localized area may exceed the lower critical temperature and even approach upper critical temperature. In either case, the mechanical properties of TMCP steel rolling treatment may upset. TMCP steel plate microstructure is composed of ferrites and pearlites. The grains were elongated along the rolling direction and these grains recrystallized to a certain extent and that they grew during flame straightening process.

Fig. 8.a, represents the formation of fine grains of ferrite and spheroidzed pearlite up to the depth of 8 mm. This is due to the surface temperature gone above 720 °C and allowed to cool in still air, it is like TMCP rolling process. This has resulted in fine grains of ferrite and spheroidzed pearlite microstructure. The mechanical properties for the said microstructure is in good agreement

with analysis carried out by M.C Zhao et al. [22, 23]. The microstructure captured beyond 8 mm and up to 13 mm is shown in Fig.8.b. The microstructure is dominated by coarse pearlite and ferrite along the prior austenite grain boundaries. In contrast, ferrite has irregular shape, since the heat is dissipated quickly along the thickness to the adjacent part of the material. The formation of pearlite is at inter-critical temperature and controlled by rate of nucleation above 680°C. The diffusion permits larger grain growth and resulted in an increase in the volume fraction of pearlite and the boundary between ferrite and pearlite became blurrier with increased temperature. The micro structure captured at a depth of 17mm is shown in Fig.8.c.The microstructure is coarse pearlite and ferrite along the prior austenite grain boundaries and typical structure such as proeutectoid ferrite, polygonal ferrite and acicular feerite were revealed. The characteristics of acicular ferrite in the microstructure depend on the cooling rate in the temperature range 800 to 500° C. The formation of acicular ferrite in heat imparted zone by multiple nucleation at intragranular sites, At low temperatures, nucleation occurs fast and ferrite grain growth is reduced leading to pearlite microstructure. The micro structure captured at a depth of 23 mm shown in Fig.8.d is fine grains of ferrite and pearlite with widmanstatten ferrite and pearlite.

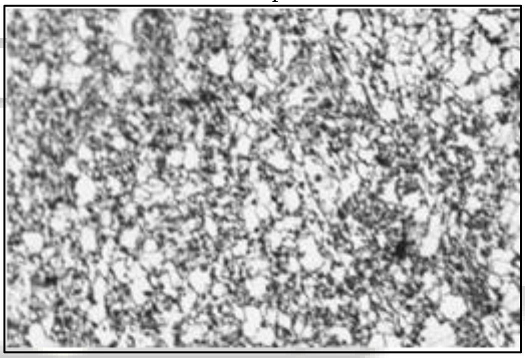

Fig. 8: a. Fine grains of ferrite and spheroidzed pearlite

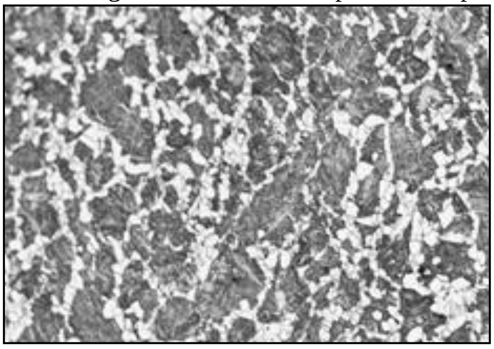

Fig. 8: b. Coarse pearlite and ferrite

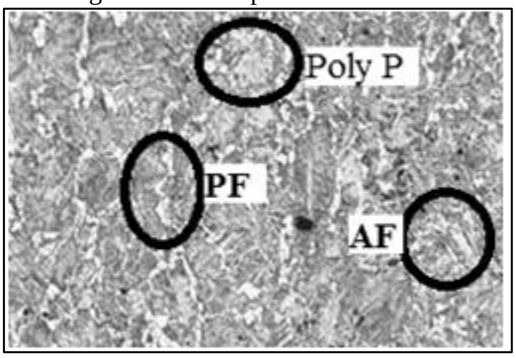

Fig. 8: c. Acicular ferrite (AF), Proeutectoide ferrite (PF), Polygonal ferrite (poly F) at depth 30 mm

Fig. 8: d. Fine grains of ferrite and pearlite

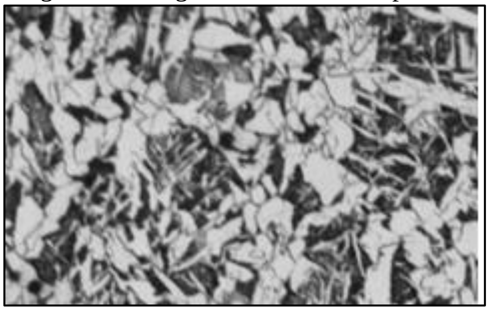

Fig. 8: e. Equiaxed ferrite and pearlite

The grain structure shown in Fig.12.e is equiaxed ferrite and pearlite with some widmanstatten platelets of ferrite and pearlite. Beyond depth of 23mm, transmission temperature is around 350°C where microstructural changes do not occur.

The temperature range for precipitation of carbonitrides is shown in Fig.8. The precipitation temperature of Nb carbonitrides is at about 800°C-1200°C, and of V occurred at about 700°C-900°C. Any micro additive beyond 0.04% under goes segregation at particular temperature.Niobium (0.04 % given in Table 2) segregation happens at grain and sub-grain boundaries, promotes the formation of coarse grained carbonitrides particles. Some of these particles remains undissolved during welding cycles. When the temperature is cooled to 760°C, the heated zone enters the two-phase region. At faster cooling, the microstructure will be composed of proeutectoid ferrites. The proeutectoid ferrites occur along the austenite grain boundary, and this causes a decrease in the strength. The precipitation of the carbonitrides has an impact on the recovery and recrystallization of the deformed austenite and this further affects the mechanical properties of the TMCP steel plate [25, 26].

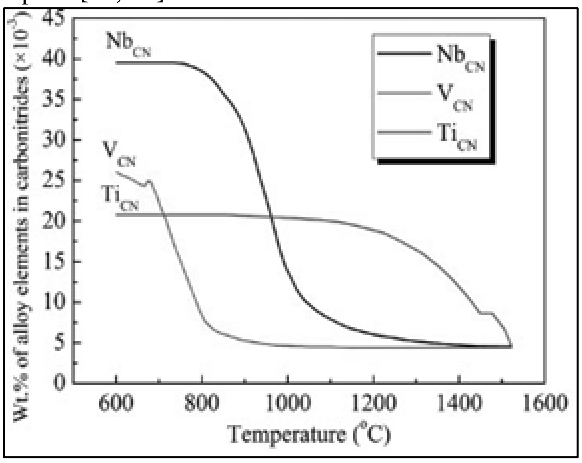

Fig. 8: Equilibrium chemistry of complex carbonitrides Nb, V and Ti steel 600°C-1600°C.(Calculated using thermo calc) [28]

V. CONCLUSION

The effect of flame straightening on base metal properties was investigated. Based on investigations, the following conclusions could be drawn and summarized.

1) Tensile, yield strength and strength ratio of the steel plate gets reduced by 4.1%, 17.33% and 13.78% respectively. The toughness and ductility of the steel plate get reduced by 23.42% and 12.87% respectively.
2) Flame straightening process can affects the precipitation of alloy carbonitrides and blurs the boundary between ferrite and pearlite. The proeutectoid ferrite occurs along the grain boundary result in degradation of properties between 13-17mm.
3) For full load bearing capacity for dynamically loaded structure, uniform properties are desired. The non-uniform mechanical properties across the thickness can have an adverse effects on fracture toughness.

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NOMENCLATURE

- TMCP : Thermo-mechanical controlled process
- AcC : Accelerated cooling
- Ar_3 : Upper critical temperature, °C
- Ar1 : Lower critical temperature, °C
- WC : Water cooling
- Hv : Vickers hardness
- Cr : Chromium
- Mo : Molybdenum
- Nb : Niobium
- Ni : Nickel
- V : Vanadium

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