Effect of welding heat input on through thickness properties of TMCP steel plate

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***Abstract*—Thermo mechanical controlled process (TMCP) steel plates are characterized by high strength and enhanced toughness with excellent weldability due to its rolling sequence and chemical composition. Welding heat input has great influence on recrystallization and change in microstructure resulting in degradation of base metal properties across the thickness. In order to evaluate the effect of welding heat input on through thickness properties, a weld pad was welded by using SMAW, SAW and GMAW process with TMCP steel plate having yield strength of 450MPa. The effect of heat input on microstructure, hardness, toughness and strength across the thickness of the base metal for the above three welding processes were analyzed. It was observed that, SAW process caused maximum reduction of 16.63 % in yield strength compared to the unaffected base metal. This reduction is due to appearance of coarse grained proeutectoid ferrite microstructure across the thickness.**

Keywords: Heat\input; Mechanical Properties; TMCP steel; Welding process

I. INTRODUCTION

TMCP steels are used for construction field such as bridges, cranes, boiler supporting structure, pipeline and ship building. The high strength and toughness of TMCP steels are due to its micro alloying elements (Nb, V, and Ti), alloying elements (Mo, Cr, Ni) and parameters of hot rolling process. It is well known fact that the strength and toughness are due to refinement of grain size. The desired mechanical properties of the steel plate is obtained by rolling at prescribed temperature and cooling after rolling either in air or through accelerated cooling [1, 2]. Strength and toughness of the plate are influenced by their microstructural phase transformations [3-6]. High strength and low alloy TMCP steel plates are characterised by high strength [7], high toughness [8] and weldability [9-11].The welding process is characterized by thermal cycles viz. local heating and cooling. Different types of microstructures such as spheroidized zone, partially transformed zone, grain refined zone and coarse grained zone are formed across thickness in the base metal during welding [6]. The microstructure 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 on cooling route.

The role of the micro additives in these steels, the creation of appropriate dispersion of carbides, nitrides and carbonitrides of niobium and vanadium, during the controlled rolling process, which increase the strength properties through micro phase reinforcement and limited size of the grains [14]. Several investigation have been made on behaviour of TMCP steel subjected to welding and their weldability [15-17]. TMCP rolled plate have excellent fabrication properties instead of conventional grades [18]. Microstructure and mechanical properties had a greater effect on quenched process route than on normalized TMCP steel plate on reheating [19]. Investigations revealed that reheating is able to change the temperature distribution and the cooling route [20-22]. Muljono et al. [23] investigated the effects of the heating rate on the isothermal recrystallization of low and ultra-low-carbon steels. The thermal cycle involved during welding has an effect on recrystallization and grain growth across the plate thickness. The aim of this investigation is to find out the effect of heat input of SMAW, SAW and GMAW (FCAW) process on the mechanical properties of the TMCP steel plate at various regions of heat imparted zones due to welding heat input and recommend the welding process which suits best for TMCP steel fabrication.

II. EXPERIMENTAL PROCEDURE

A 40 mm thick High strength and low carbon TMCP steel plate to specification IS 2062 E450 BR, with specimen size of 400x 380 mm was taken for experiment. Weld layers were laid over the surface of the plate using Shielded Metal Arc welding (SMAW), Submerged Arc Welding (SAW) and Flux cored arc welding (FCAW) in a separate test specimen for each of the welding process. Welding was carried on test plate by laying three layers one over other with overlapping 30-40% to the width of 30 mm and to the length of 380 mm. The schematic diagram is shown in Fig. 1.

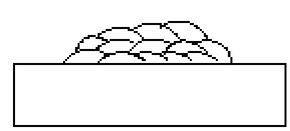

Fig.1. Schematic diagram of test specimen

The weld metal was completely removed from base metal by machining and test specimens from the heat imparted zone at different depths of the steel plate were identified by etching. Test specimens were prepared and tested at respective heat imparted zones of 10 mm, 20 mm and 30 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. Charpy impact test was conducted as per ASTM E23-16B on samples. Transverse tensile (10x12.5 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 and tensile strength were recorded. The heat imparted zone of the base metal was subjected to microscopic examinations as per ASTM E407-07e1 after polishing with different grades of emery papers and etching by 2 percent Nital solution. The microstructure were captured by optical microscope at different depths of heat imparted zones.

III. TEST RESULTS AND DISCUSSION

A. Welding heat input

Welding process is based on melting faying surfaces of the base metal using heat produced by a welding arc, established between base metal and a consumable electrode. Welding current determines the rate at which the electrode is melted, base metal fusion and dilution. Welding voltage which governs the length of the arc column. High voltage increases the dilution of base metal. Welding speed is inversely proportional to heat input, which usually control the bead width and penetration. The effective heat input can be determined on process parameter such as voltage, current and welding travel speed. For seam welding, the heat input (q_w) is determined by heat input per unit length (KJ/ mm).

$$q_w = (VxIx0.06)/v \quad (1)$$

Where V is welding voltage, I is welding current, welding speed, v (mm per minute) and process efficiency is neglected. The micro structure at various cross section in TMCP steel depends on peak temperature and cooling rate. Welding heat input was calculated based on equation 1 for SMAW, SAW and FCAW and values were recorded in Table I.

TABLE I. Welding parameters

Process	Electrode Specn.	Dia in mm	Current (A)	Volt (V)	Speed mm/s	Heat input kJ/mm
SAW	EM12K	Ø 4.0	420	29	6.2	1.96
SMAW	E7018-1	Ø 4.0	170	22	2.08	1.79
FCAW	E71T1	Ø1.6	240	24	4	1.44

B. Hardness

Many factors are responsible for the hardness variation across the thickness during welding heat input, 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 [24].

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

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 2. Hardness value is found to be in the range of 202-206 HV10 in the heat imparted zone up to the depth of 10 mm from top surface. This is due to fine grains of ferrite and spheroidzed pearlite. The hardness is found in the range of 177-186 HV10 at a depth of 10 to 20 mm due to coarse grained pearlite microstructure. At the depth of 20-30mm, hardness value is found to be in the order of 172-182 HV10 and the microstructure is coarse grained pearlite and ferrite with high volume fraction of pearlite. Hardness in the base metal beyond 30 mm found to be the order of 191-202 HV10, in which the microstructure is equiaxed ferrite and pearlite with widmanstatten platelets of ferrite and pearlite.

C. Strength

The mechanical properties of TMCP steel products are determined by the rolling sequence and microstructure. There is a heat input restriction and that will experience strength reduction upon welding; typically a maximum heat input of 2.5kJ/mm. This value is dependent on the steel grade, and is more critical for higher strength steels that have had more rapid cooling. Plate E450BR includes the micro-alloy elements Nb, V, and Ti and shown in Table II. The strengthening effect, depends on the content and distribution of the micro-alloy elements. Mechanical test has been conducted to find out the yield, tensile strength, percentage elongation and yield ratio.

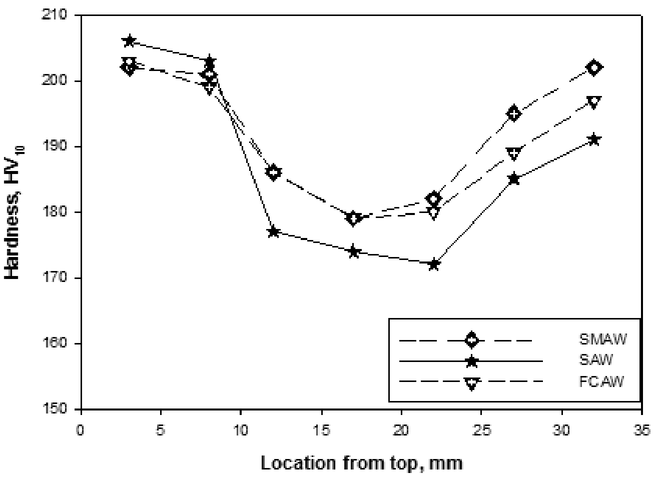

Fig.2. Hardness at different location

TABLE: II. Chemical composition (wt%) of the TMCP steel plate

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	-

Empirical relations are used to estimate the strength from bulk hardness measurement [25]. An empirical equation between hardness and strength has been determined as

$$H = cS \tag{3}$$

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 [26, 27].The tensile and yield strength values at different locations are plotted in Fig. 3 a, b and c for different welding process. 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 20 to 30 mm. From the Fig. 4a-c, SAW process have represented by yield strength as 461 N/mm^2, which is comparatively lower than the SMAW and FCAW welding process. This is due to formation of coarse grained 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 reduction in yield strength is owing to heat dissipation and change in microstructure across the thickness.

The yield ratio of the TMCP steel (E 450 BR) is usually in the range of 75-85%. The yield ratio for different welding process is shown in Fig. 4 and the yield ratio is observed for SAW is 76.57% where as SMAW and FCAW are 77.3% and 77.5% respectively. The variation in yield ratio is due to change in microstructure.

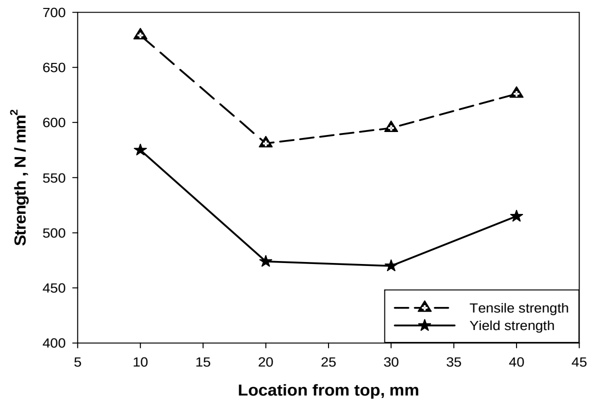

Fig.3.a. Strength at different location @ SMAW

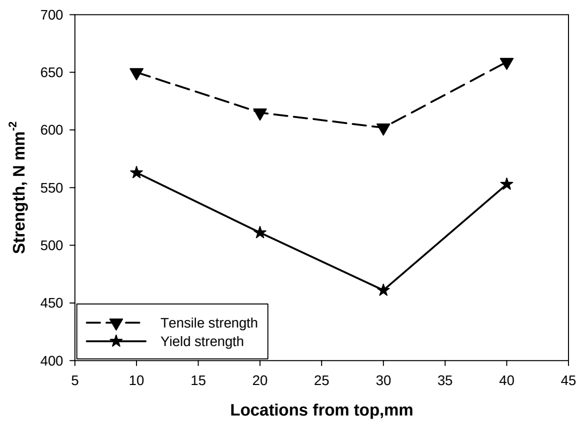

Fig.3.b. Strength at different location @ SAW

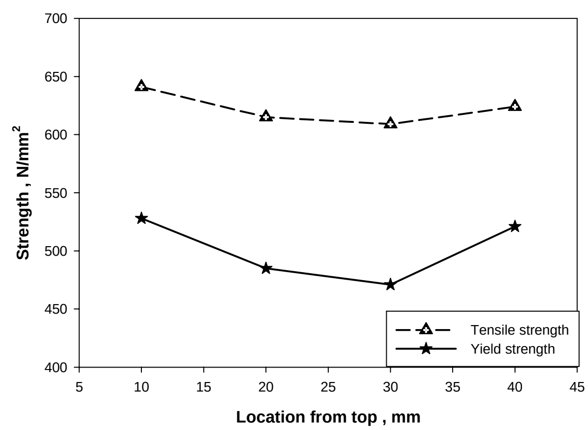

Fig.3.c. Strength at different location @ FCAW

The ductility is the critical parameter considered for TMCP material and it is intended for higher ductility along the rolling direction and across the thickness. 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.

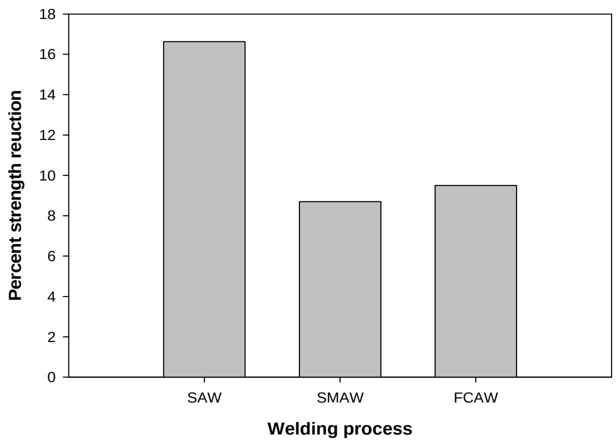

Fig.3.d. Strength reduction for different welding process

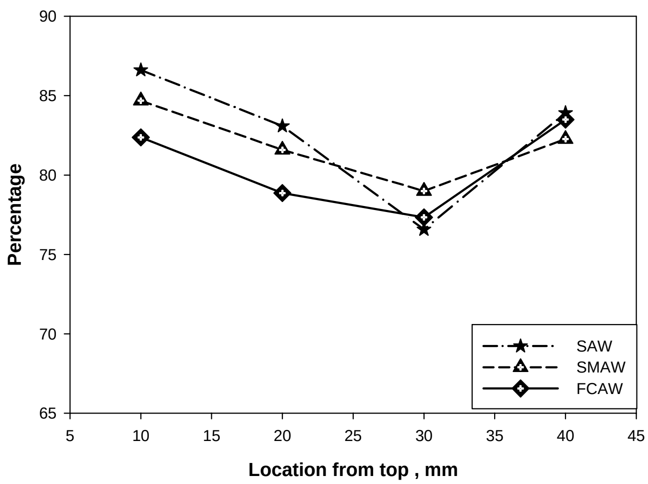

Fig.4. Yield ratio for different welding process

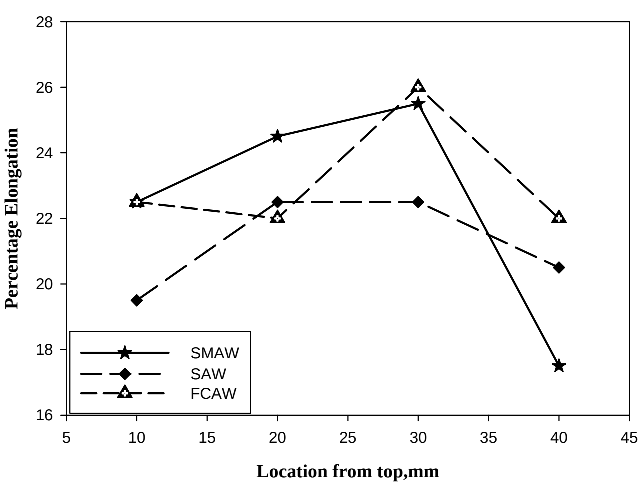

Fig.5. Percentage elongation for different welding process

The Fig. 6 is represented for percentage elongation for SAW, SMAW and FCAW. The percentage elongation for SAW is observed 17.5, whereas the percentage elongation for SMAW and FCAW are 20.5 and 22.0 respectively at the depth of 30mm. Percent elongation for SAW is low when compared to SMAW and FCAW.

D. Toughness

Softening can occur in TMCP steels on welding, as the cooling rate of welding is usually slower than that of the TMC processing. Grain coarsening due to heat input can result in reduced toughness.The impact energy observed at various locations are plotted and shown in Fig. 7. The energy observed at the location up to 10 mm from the top surface in the range of 266-280 joules. Beyond 10 mm and up to 20 mm, the impact energy is found to be 248-260 joules and after 20mm and up to 30mm, is 206-244joules. Beyond 30 mm the impact energy is in the range of 265-284 joules.

The reduction in impact energy between the depth of 20 and 30 mm is promoted due to coarse pearlite with ferrite prior to austenite grain boundary observed at that location. The lowest impact energy absorbed at heat imparted zone between 20-30 mm is 206 joules for SAW process, whereas the impact energy at these zone for FCAW process is 244 joules. This behavior is related to the non-uniform distribution of carbides and nitrides due to temperature gradient during cooling.

The base metal undergoes uncontrollable intermetallic phase's separation on fine grain segregation of carbides/carbonitrides. {Nb(C, N), V(C,N)} and others, which significantly lower the impact energy of the base metal. A high heat input promoted grain growth and have an adverse effect on toughness.

E. Microstructure

TMCP steel plate microstructure is composed of ferrites and pearlites. During welding, 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. The grains were elongated along the rolling direction and these grains recrystallized to a certain extent and that they grew during the welding. Fig 8.a, represents the formation of martensitic structure at HAZ. This is due to the surface temperature gone above 900 °C.

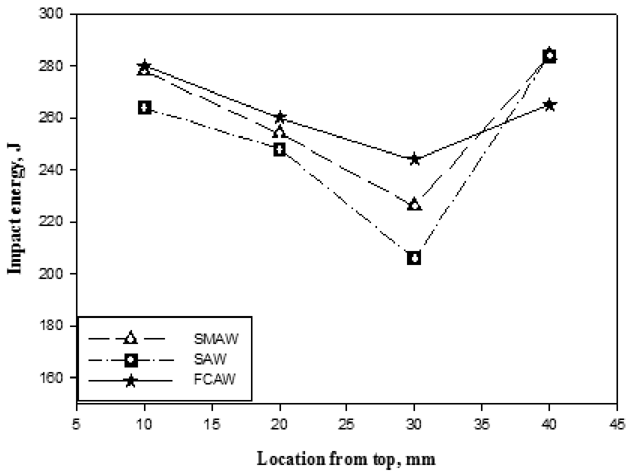

Fig.7. Impact energy at different location

Adjacent to HAZ region and depth up to 10 mm from top surface, the bae metal subjected to peak temperature between upper and lower critical temperature typically 910°C and 720°C. The partial transformation to austenite occurs within inter-critical range during heating. The austenite decompose to different transformation product. This has resulted in fine grains of ferrite and spheroidzed pearlite microstructure and represented in fig.8.b. The mechanical properties for the said microstructure is in good agreement with analysis carried out by M.C Zhao et al. [28, 29].

The microstructure captured beyond 10 mm and up to 20 mm is shown in Fig.8.c.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 micro structure captured at a depth of 30 mm is shown in Fig.8.d. At low temperatures, nucleation occurs fast and ferrite grain growth is reduced leading to pearlite microstructure. The metallurgical analysis revealed that the yield strength of the base metal was dependent on the acicular ferrite, proeutectoid ferrite and polygonal ferrite. The diffusion permits larger grain growth and resulted in an increase in the volume fraction of pearlite. These microstructures are due to high heat input revealed that SAW process is the main feature for development of degraded microstructure. The micro structure captured at depth beyond 30 mm is shown in fig.8.e. As the transmission temperature is around 350°C, microstructural changes does not occur.

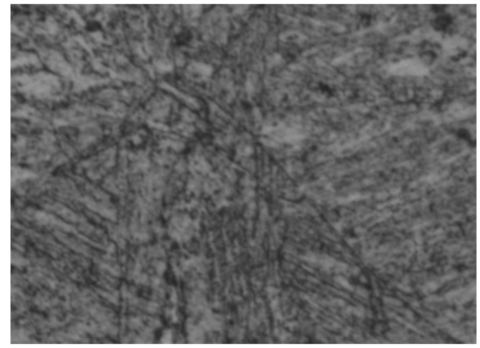

Fig.8.a.Fine grain martensite structure @HAZ

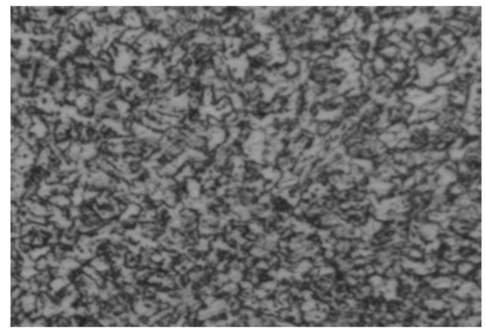

Fig.8.b.Microstructure at depth 10 mm

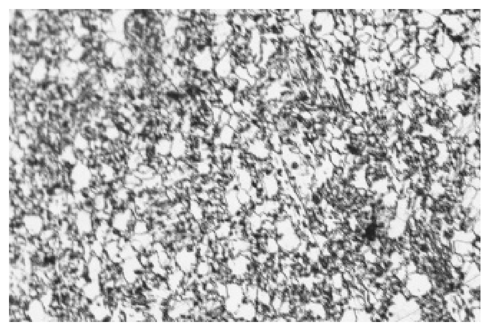

Fig.8.c. .Microstructure at depth 20 mm

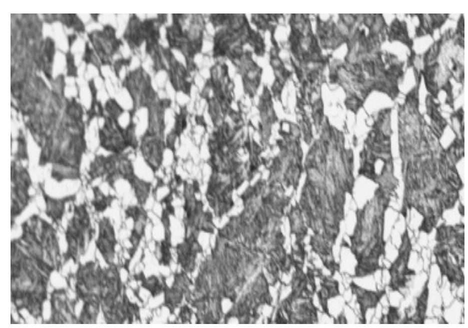

Fig.8.d. Microstructure at depth 30 mm

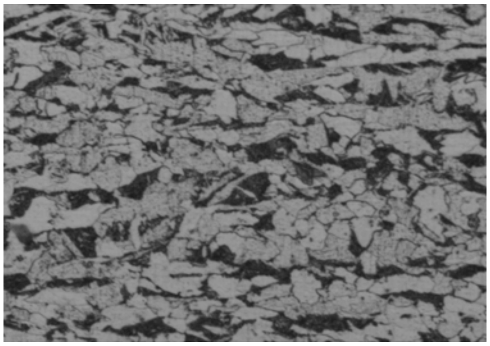

Fig.8.e. Micro structure of base metal

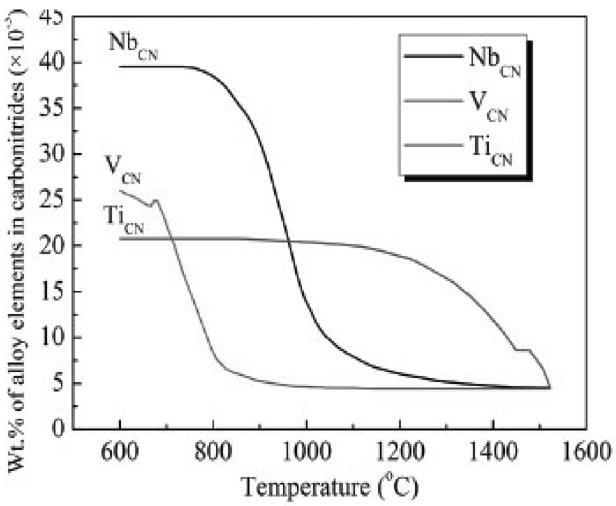

Fig.9. Equilibrium chemistry of complex carbonitrides Nb, V and Ti steel 600°C-1600°C (Calculated using thermo calc)[30, 31]

The temperature range for precipitation of carbonitrides is shown in Fig. 5. 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 II) 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.

IV.CONCLUSION

The effect of welding heat input for SMAW, SAW and FCAW on base metal through thickness properties were investigated. Based on investigations, the following conclusions were drawn and summarized.

1. Heat delivered to base metal due to welding has significant effects on recrystallization and grain growth. These effects depend on heat input with respect to welding process. The precipitation of the alloy carbonitrides during cooling has an impact on the recovery and recrystallization of the deformed austenite.

2. The microstructure of TMCP steel plate arranged by ferrite and pearlite alternatively along the rolling direction to improve mechanical properties. Reheating the base metal due to welding heat distorted the preset microstructure and induces non-uniformity in microstructure.

3. The proeutectoid ferrites occur along the austenite grain boundary, which results in the degradation of the mechanical properties gained during the thermo mechanical treatment of the plate.

4. The yield strength gets reduced by 16.6% due to high heat input in SAW process. In case of FCAW the heat input to base metal was low among the three welding processes. Hence from the above analysis FCAW process is best suited for TMCP steel fabrication.

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