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Development of API X70 Grade Hot Rolled (HR) Coils for Spiral Welded (SW) Pipes

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Abstract In this paper, efforts made at BSL, SAIL towards developmental of API X70 grade HR coils intended for SW pipes, have been presented. Two trial heats with Nb-Cr-V and Nb-Cr-V-Mo based chemistry aiming (a) ferrite-pearlite and (b) ferrite-pearlite-bainite microstructures respectively were made and cast into 1400 x 210 mm slabs. These trial slabs were processed under suitably designed process variables. Acicular ferrite microstructure engineered through Nb-V-Cr-Mo alloy design has been found more suitable to achieve requisite strength level (in 45° direction) and impact toughness properties consistently in API X70 HR coils. All the properties requirements like, Yield Strength (YS): 515-536 MPa, Ultimate Tensile Strength (UTS): 590-610 MPa, Percentage elongation (%El) in 50mm GL: 25-35%, YS/UTS: 0.86-0.88, Hardness: 184-218 HV_{10} and Impact toughness (at -5°C): 305-328 J were successfully achieved in HR coils of Nb-V-Cr-Mo heat. Performance trial for three number of coils of Nb-V-Cr-Mo heat were conducted at customer's end. The coils were rolled into 28 mm OD x 7.1 mm thick Helical Submerged Arc Welded (HSAW) pipes and forty numbers of pipes were successfully made. Mechanical properties requirements like YS : 511-550 MPa, UTS: 589-646 MPa, %El: 34-38%, YS/UTS: 0.84-0.87), impact toughness in base (280-296 J), weld (184-196 J) and HAZ (184-236 J) and 100% shear area in Drop Weight Tear Test (DWTT) at 0°C were successfully met in all the pipes. Surface of the rolled pipes were found free from any defect. All the pipes passed the hydraulic, ultrasonic and radiography tests.

Keywords APIX70 grade, Acicular microstructure, Spiral welded pipes

1. Introduction

The ever increasing demand for energy word wide requires the construction of high-pressure gas transmission lines with the greatest possible transport efficiency, so that the cost of pipeline construction and gas transportation is minimized. Therefore there is a trend towards using line pipe of larger diameter and/or increasing the operation pressure of the pipeline. This, in turn, necessitates the use of higher strength steel grades (API X70 and above) to avoid a large wall thickness that would otherwise be needed. Large pipeline systems that are installed on land with operating pressures in the range of 70-100 bars are typically constructed from API X65 or X70 grades. However, if the operating pressure requirement is more, higher strength grades like API X80 and above are used for pipeline construction [1]. These steels combine high strength, high impact toughness and outstanding weldability.

There are basically two different processes to produce pipes from hot strips i.e Longitudinally Electric Resistance welded (ERW) pipes and Helically or spirally welded pipes. Production of ERW pipes is carried out in a continuous forming and longitudinal welding operation. The most common welding process is the High Frequency Induction (HFI) welding. A major advantage is the high productivity attainable due to the high welding velocities of HFI process. The pipe diameter depends critically on the strip width and very tight tolerances apply. Spiral pipes are produced from forming and welding of strip. Some pipe producers may use a tack welding operation, whereby the pipes are formed and tack welded in one step and the submerged arc welding is done in another operation. A major advantage of spiral pipe production is its high versatility. Various pipe diameters can be produced from the same strip width by changing the forming angle. The forming angle is defined as the angle between the incoming strip and the leaving pipes [2].

Thermomechanically processed hot strip displays anisotropic mechanical properties. This phenomenon can be explained by the elongated grain structure in the austenitic phase that transforms into a textured ferritic phase. Therefore, thermo mechanically rolled material possess long grain boundaries in rolling direction. Pipes are usually tested with samples from the circumference of the pipe.

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These specimens, transverse to the pipe axis, correspond to a completely different location within the strip material depending on the pipe production process used. A transverse or longitudinal sample in a ERW pipe corresponds with the transverse or longitudinal sample in the strip. However, the location of a transverse sample in a spirally welded pipe compared to the hot strip depends on the forming angle and the pipe diameter. In the hot strip a transverse sample in the pipe is located approximately in a 30 to 45° angle from rolling direction. A pipe made from the same strip material will show different properties depending on the production process. The ERW pipe will display higher YS compare to spiral welded pipe, as the YS values are lowest in this angle range.

In the recent past [3], API X70 grade HR coils for ERW pipes were successfully developed at BSL based on ferrite-pearlite microstructure having Nb-V-Cr based steel chemistry, where the required tensile properties need to be achieved in transverse direction (at 90°) of the strip. Since the demand of API X70 grade HR coils for making SW pipes in India is also quite substantial, it was felt worthwhile to initiate efforts for making API X70 HR coils for SW pipes, keeping in view that properties requirements (YS values required to be achieved in 45° direction) for this application shall be different as explained above.

Keeping above factors in mind, two different microstructures i.e (i) ferrite-pearlite and (ii) ferrite-pearlite-bainite having Nb-V-Cr and Nb-V-Cr-Mo steel chemistry respectively were targeted in the present work to achieve requisite properties in the API X70 grade HR coils (intended for SW pipes). The objective was to examine effect of different microstructures on the properties of API X70 grade HR coils as well as on pipes.

2. Alloy Design & Processing Considerations

Alloy design considerations for production of defect free slabs involved control of C ≤ 0.06% and N ≤ 50 ppm and addition of higher (~0.018%) Ti addition to avoid chances of peritectic reaction and to improve hot ductility of steel [4]. Mn content was kept in the range of 1.4 - 1.5% keeping in view the customer specification, strength requirement of API X70 grade and solid solution strengthening on one hand and the strong tendency of Mn to segregate on the other. S & P was restricted below 0.010% and 0.020%, respectively for enhancing impact toughness and DWTT results. Nb addition was made to achieve refinement of ferrite grains. Addition of V aimed at engineering precipitation hardening without increasing the mill load. Further, small amount of Mo was also added to achieve bainitic microstructure in HR coils [5]. Mo alloying helps to promote a continuous yielding curve and avoid the so-called Bauschinger effect, which is important when strain-based design codes are specified [6].

Concept of thermo-mechanically controlled processing (TMCP) has long been employed for high strength micro-alloyed line-pipe steels. In order to control grain refinement and fine dispersion of precipitates, dissolution of coarse primary carbides and carbo-nitrides present in the slab needs to be ensured. Accordingly, the temperature of soaking in reheating furnace was selected on the basis of the temperature of dissolution (Tsol.) of primary Nb(CN) precipitates. Sufficient holding time at temperatures above Tsol. ensured Nb & V in solution. Austenite grains undergo two processes during rough rolling, viz. (a) grain refinement through the process of recrystallisation after each pass, and (b) grain coarsening during inter-stand time or any holding on the roller table. Temperature control and distribution of draft during each rough rolling pass was adjusted accordingly for austenite conditioning in order to obtain a fine-grained microstructure. Finish rolling was carried out by processing austenite below the temperature of non-recrystallisation (Tnr). High deformation (~70%) during finish rolling was ensured to achieve enhanced number of nucleation during γ to α transformation which in turn results in a very fine, homogeneous ferrite grain structure [7].

3. Experimental

Basic Oxygen Furnace (BOF) – Ladle Furnace (LF) – Continuous Casting (CC) Route was followed for making of API X-70 grade steel. Two trial heats were made and cast into 1400 x 210 mm slabs. Typical casting parameters comprised casting speed of 1.2 M/min., super heat < 200°C and soft secondary cooling practice. These slabs were stack cooled for 60 hours.

Slabs were reheated to 1250°C (which was about 50°C above Tsol.). Soaking of a minimum period of 2 hours was ensured. The slabs were processed into 7.1 mm thick HR coils under suitably designed process variables. During hot rolling, thickness of slab was reduced from 200 mm to ~38 mm in 5 roughing-passes. Temperature at the end of roughing (R_5 Temp.), finish rolling temperature (FRT) and coiling temperature (CT) varied in the range of 1016 – 1054°C, 834- 917°C, and 538– 679°C respectively.

Samples were drawn from HR coils of two trial heats. Tensile properties, impact toughness, hardness and microstructure of these samples were evaluated. Tensile testing was carried out in a 100 kN capacity INSTRON, UK make 1195 model screw driven mechanical testing machine using flat test specimens of 50 mm gauge length (GL) and 12.5 mm gauge width as per ASTM A 370. The tests were carried out in accordance with ASTM E-8 specification while maintaining cross-head speed of 2 mm min^{-1} during the testing. Hardness measurements were carried out by Rockwell indentation method using an Instron Wolpert make (Model: Series R-Testor®600) hardness testing machine with 100 kg load.

Charpy impact tests were conducted using V-notched (2 mm deep notch) with sub- size specimens of 55 x 10 x 5 mm size as per ASTM E - 23 specification. The tests were conducted at ambient and sub-zero (–5°C & –10°C) temperatures. Microstructural examination of the steel was conducted on longitudinal section in an Olympus make metallurgical microscope. The samples were ground and mechanically polished by conventional metallographic procedures. The polished samples were etched in 2% nital solution for microstructural examinations.

Performance trial for three number of HR coils (of Nb-V-Cr-Mo heat) were conducted at customer's end. All the pipes were subjected to hydraulic, ultrasonic and radiography tests. Samples from pipes corresponding to three coils were collected and tensile, hardness, impact & DWTT properties were evaluated.

4. Results & Discussion

4.1. Steel Chemistry

Chemistry of the two trial heats made against a customer specification is shown in Table 1. In order to achieve high Mn level (1.40-1.50%) along with low carbon content (0.06% max.), high purity Mn metal was added in the heat. Re-blows were avoided to achieve low N level in the steel. Nitrogen level was also controlled within 50 ppm in both the heats. Ti addition was targeted in the range of 0.015-0.020% to tie up any free nitrogen to improve hot ductility of steel. S and P were controlled within 0.005 and 0.015% respectively to improve ductility and impact toughness of steel. Nb and V were maintained as per customer specified limit of 0.05% max. and 0.08% max. respectively to achieve requisite strength level in HR coils. Cr addition was controlled in the range of 0.25-0.30% to achieve required YS/UTS ratio. Mo addition of 0.14% was made in steel-2 to achieve ferrite-pearlite-bainite structure in HR coil.

4.2. Properties of API X70 HR Coil

4.2.1. Tensile Properties & Hardness

Details of processing parameters along with tensile properties and hardness achieved in the HR coils of two trial heats are shown in Table 2 & 3. It may be noted from the Table 1, that in case of Nb-V-Cr HR coils, YS (at 0.5% El), UTS and %El (G.L=50mm) varied in the range of 498-546 MPa, 538-587 MPa and 31-46%. Customer Specified YS value were achieved in all the coils (except one), however, UTS requirement could not be achieved in any of the coils for Nb-V-Cr HR coils. This may be attributed to insufficient solid solution strengthening and precipitation strengthening in case of Nb-V-Cr HR coils due to lower amount of Si, restricted Mn addition (1.5% max.) due to customer specification and absence of Mo. However, due to sufficient refinement of ferrite grain size, YS value of 510 MPa min, could be achieved in most of the coils. Hardness of the HR coils varied between 184-201 against the requirement of 248 max.

In case of Nb-V-Cr-Mo HR coils (Table 2), YS (at 0.5% El), UTS and %El (G.L=50mm) varied in the range of 515-536 MPa, 590-610 MPa and 25-35% respectively. YS, UTS, %El and YS/UTS ratio could be achieved successfully in all the coils. In case of Nb-V-Cr-Mo HR coils, hardness varied in the range of 184-218 VHN. In most of the coils, it was on the higher side (202-218 VHN), except for last two coils (2G and 2H) which were processed at higher finishing (898-917°C) and coiling temperature (664-679^{o}C) resulting in relatively coarser ferrite grain size (~ 5.6 µm).

4.2.2. Impact Toughness

Impact toughness (shown in Table 4) of both Nb-V-Cr and Nb-V-Cr-Mo HR coils was found much superior to specified value of 100 J at -5°C. In case of Nb-V-Cr HR coils, it varied from 208 J at room temperature to 196 J at -5°C. Even at -10°C, drop in impact energy was marginal (~10 J). The superior impact toughness is attributed to formation of very and uniform ferrite grain structure (3.0-4.0 µm) in Nb-V-Cr HR coils due to their processing at lower roughing exit temperature (~1035°C) as well as lower finish rolling (~840°C) and coiling (~570°C) temperatures during hot rolling. Impact toughness of Nb-V-Cr-Mo was much superior to Nb-V-Cr HR coils owing to formation of acicular ferritic grain structure. It varied from 331 J at room temperature to 300 J at -10°C.

Table 1. Steel chemistry (in wt.%) achieved in two trial heats

Heat	C	Mn	P	S	Si	Al	Nb	V	Ti	Cr	Mo	N (ppm)
Nb-Cr-V (Steel-1)												
Achieved	0.052	1.45	0.013	0.005	0.26	0.03	0.047	0.05	0.016	0.28	-	47
Aimed	0.06 max.	1.45-1.50	0.015 max.	0.005 max.	0.22 -0.25	0.02 -0.04	0.047 -0.050	0.048 -0.050	0.015 -0.020	0.25 -0.30		50 ppm max.
Nb-Cr-V-Mo (Steel-2)												
Achieved	0.057	1.41	0.012	0.002	0.31	0.03	0.049	0.05	0.017	0.25	0.14	45
Aimed	0.06 max.	1.40-1.45	0.015 max.	0.005 max.	0.30 -0.35	0.02 -0.04	0.047 -0.050	0.048 -0.050	0.015 -0.020	0.25 -0.30	0.12 -0.15	50 ppm max.
Customer Spec.	0.12 max	0.8 - 1.50	0.015 max	0.010 max	0.35 max.	0.04 max	0.05 max	0.08 max	0.02 max	0.30 max.	0.25 max.	100 max.

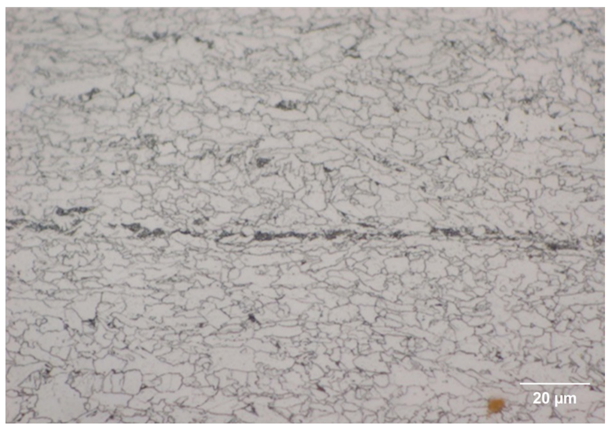
Table 2. Tensile properties of Nb-Cr-V HR coils

HR No.	Roughing exit Temp., °C	Finish Entry Temp. °C	Finish Rolling Temp., °C	Coiling Temp., °C	YS, MPa (0.5%El)	UTS, MPa	%El (50 mm GL)	YS /UTS	Hardness, VHN
1A	1033	962-894	837	548	520	563	40	0.95	190
1B	1044	981-931	834	554	546	573	39	0.90	188
1C	1029	957-886	853	578	530	587	31	0.96	-
1D	1027	973-903	840	579	535	553	39	0.94	192
1E	1038	977-921	836	574	544	580	41	0.94	198
1F	1030	971-893	848	576	516	550	36	0.93	185
1G	1037	915-860	850	579	498	538	46	0.94	184
1H	1030	966-908	856	579	537	568	41	0.92	201
Customer Spec.	-	-	-	-	510 min.	590 min.	25 min.	0.90 max.	248 max

Table 3. Tensile properties of Nb-Cr-V-Mo HR coils

HR No.	Roughing exit Temp., °C	Finish Entry Temp., °C	Finish Rolling Temp., °C	Coiling Temp., °C	YS, MPa (0.5%El)	UTS, MPa	%El (50 mm GL)	YS /UTS	Hardness, VHN
2A	1047	982-912	856	574	536	603	28	0.88	218
2B	1046	974-919	853	566	533	600	25	0.88	210
2C	1052	990-916	851	564	527	610	28	0.86	217
2D	1034	965-910	853	564	515	595	35	0.86	210
2E	1044	918-869	858	590	516	595	35	0.87	202
2F	1029	965-920	844	562	525	608	27	0.86	198
2G	1045	954-927	917	679	520	590	31	0.88	187
2H	1016	947-946	898	664	521	600	35	0.87	184
Customer Spec.	-	-	-	-	510 min.	590 min.	25 min.	0.90 max.	248 max

(a) Coil No. 1E



(b) Coil No. 1G

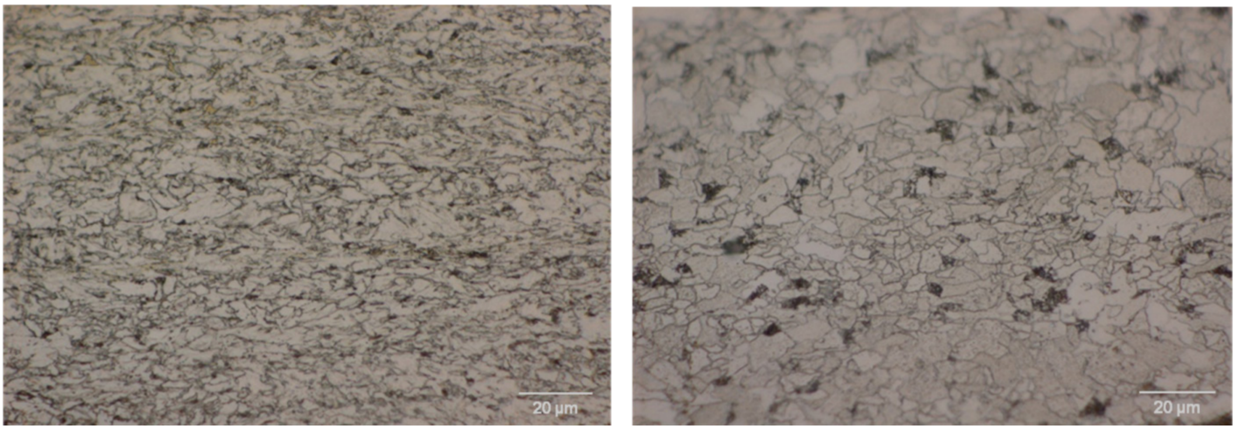
Figure 1. Microstructures of Nb-V-Cr HR coils

4.2.3. Microstructures

Microstructures of HR coils are shown in Fig 1 and 2. Typical ferrite-pearlite microstructure, with very fine ferrite grain size (3.0-4.0 μm) was observed in most of the Nb-V-Cr HR coils (Fig.1). Nb-V-Cr-Mo HR Coils mostly manifested acicular ferrite grain structure, as shown in Fig. 2a, however, coil processed at higher finishing (898°C) and coiling temperature (664°C) manifested typical ferrite-pearlite structure even in case of Mo added HR coils (Fig.2b).

Table 4. Impact toughness of Nb-V-Cr and Nb-V-Cr-Mo HR coils

HR Coil	RT	-5°C	-10°C
Nb-Cr-V	208 J	196 J	185 J
Nb-Cr-V-Mo	331 J	328 J	300 J
Specified		100 J min.	



(a) Coil No. 2B (b) Coil No. 2H

Figure 2. Microstructures of Nb-V-Cr-Mo HR coils

Table 5. Chemical analysis of HR coils

C	Mn	P	S	Si	Al	Nb	V	Ti	Cr	Mo	N
0.062	1.30	1.302	0.001	0.285	0.03	0.045	0.050	0.009	0.27	0.12	0.007

Figure 3. Fractured surfaces of DWTT tested specimens

5. Performance Trial at Customer's End

Three coils (Coil No. 2B, 2D and 2H) of Nb-V-Cr-Mo Heat were evaluated for HSAW pipe performance at customer's end. Chemical analysis and properties evaluated for the these coils at customer's end are shown in Table 5 and 6 respectively. The values were found acceptable.

Table 6. HR coil Properties (in transverse direction)

Coil No.	YS, MPa	UTS, MPa	% EL	YS / UTS
2B (TR-1)	565	653	39	0.87
2D (TR-2)	582	653	28	0.89
2H (TR-3)	559	649	34	0.86

These three coils were rolled into 28 mm OD x 7.10 mm WT HSAW pipes of API 5L Gr X70 M PSL2. Forty numbers. (13 + 13 + 14) pipes were made from these three coils. Surface of the rolled pipes were found free from any defect. No incidence of edge lamination was observed. All the pipes passed hydraulic, ultrasonic and radiography tests. Samples from three pipes corresponding to above three coils were evaluated for tensile, hardness and impact properties. Properties achieved in pipes corresponding to three HR coils are given in Table 7 and Table 8. Bauschinger gain observed as tensile properties of pipes are comparable or better than those achieved in 45^o angle in HR coils.

DWTT tests were carried out at 0^oC. Percentage Shear Area of fractured surfaces was found 100% in all the three test-cases, as shown in Fig.3. 4t bend test (Mandrel dia.: 28 mm) results were also satisfactory in all cases. Pipes made from two coils (2B and 2D) manifested very high tensile properties which are close to the specified values of API X 80 i.e. YS: 555–705 MPa and UTS: 625–825 MPa. All the requirements of properties of formed pipes of API X70 grade have been met satisfactorily. As per trial results, Mo bearing HR coils of API X70 have been found suitable for making of HSAW pipes in every respect.

Table 7. Tensile and impact toughness properties of pipes

Coil No.	YS, MPa	UTS, MPa Base(weld)	%El	YS / UTS	Impact Toughness (J)*		
					Base	Weld	HAZ
2B (TR-1)	546	646 (665)	34	0.84	140	92	92
2D (TR-2)	550	638 (670)	37	0.86	140	98	118
2H (TR-3)	511	589 (652)	38	0.87	148	96	110

*Minimum values of half size Charpy impact toughness at 0 °C

Table 8. Hardness (in VHN) after pipe forming

Coil No.	Base	Weld	HAZ
2B (TR-1)	242-268	238-274	232-264
2D (TR-2)	245-274	236-281	227-262
2H (TR-3)	228-233	224-251	215-238

6. Conclusions

- Control of carbon (< 0.06%) and nitrogen (< 50 ppm) is must to produce defect free slabs of API X70 grade
- Nb-V-Cr-Mo alloy design is more suitable to achieve requisite strength level (in 45°) and toughness properties consistently in API X70 HR coils intended for SW-pipe making.
- Control of R_5 temperature, FRT and CT to less than 1040°C, 850°C and 600°C respectively results in achieving consistently very fine and uniform ferrite grain structure leading to superior impact toughness properties in HR coils of both Nb-V-Cr and Nb-V-Cr-Mo heats.
- Performance trial results of 40 pipes made from 3 HR coils of low carbon Mo bearing API X70 grade supplied by BSL have been found satisfactory in terms of surface inspection, ultrasonic testing, hydraulic testing, radiography and all other metallurgical quality requirements of HSAW pipes of API X70 grade.

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