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HIGH PERFORMANCE MICROALLOYED LINE PIPE STEEL CHINA

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The demand for energy has become a bottle neck for development of China. Economical delivery of natural gas through pipelines is an urgent problem that needs to be solved. Gas pipeline construction has stimulated development of high performance pipe steels since 2000 in China. The super tough X-70 Acicular Ferrite/Bainite pipe steel with yield strength YS≥530 – 630 MPa used in the West – East gas transmission project, essentially corresponds to X80 grade steel elsewhere. However, to delivery natural gas from the Western most reservoirs to Eastern China using the present pipe steel cannot be competitive as compared with practices overseas. Recent research elsewhere gives us inspiration. Exxon Mobil and BP redesigned the pipeline to operate at higher pressure using Grade X 100 or X 120 high strength pipe steels to achieve comprehensive cost savings. A series of development works was done before applying this new idea. Research on the steel went going deeply into the relationship between the substructure domain size, high angle boundaries and the TMCP schedule. This innovation on high grade pipe steel also involved new types of welding consumables and welding techniques special for the high strength steel. In order to assure the integrity of pipelines laid in geologically unstable regions, the pipeline was designed using based strain principles and special pipe having higher deformability. Research on ductile fracture prevention of the steel pipe considered toughness and the installation of composite crack arresters. Developments concerning oxide metallurgy to dramatically improve the toughness of the pipe girth welding joint is worthy of mention.

Introduction

As a response to the significant development of the social economy, the demand for crude oil increased rapidly in 2004 to as high as 290 million tons, i.e., 170 million tons of local production plus 120 million imported. It has been forecast that imported. crude oil will increase over 130 million tones in 2005. Supplementing petroleum products has become one of the bottlenecks restricting China development. China was forced to adjust the energy sources from chiefly coal to natural gas both for energy efficiency and reducing environmental pollution in Table 1 [1 – 3].

Table 1. Forecast of Demand for Crude Oil and Gas in China

Year	Crude Oil 0.1 Billion tons / year		Natural Gas 0.1 Billion m^3/year	
	Demand	**Import**	**Demand**	**Import**
2000	**2.1**	**0.696**	**20**	
2004	**2.9**	**1.2**	**40**	
2005	**3.0**	**1.3**	**50**	
2010	**3.8**	**1.87**	**100**	**20**
2020	**4.9**	**2.95**	**200**	**40**

The problem that needed to be solved before natural gas became available was how to economically transport large quantities of natural gas from the remote Western China or neighboring countries to the Eastern economic regions in Figure 1 [3 – 7].

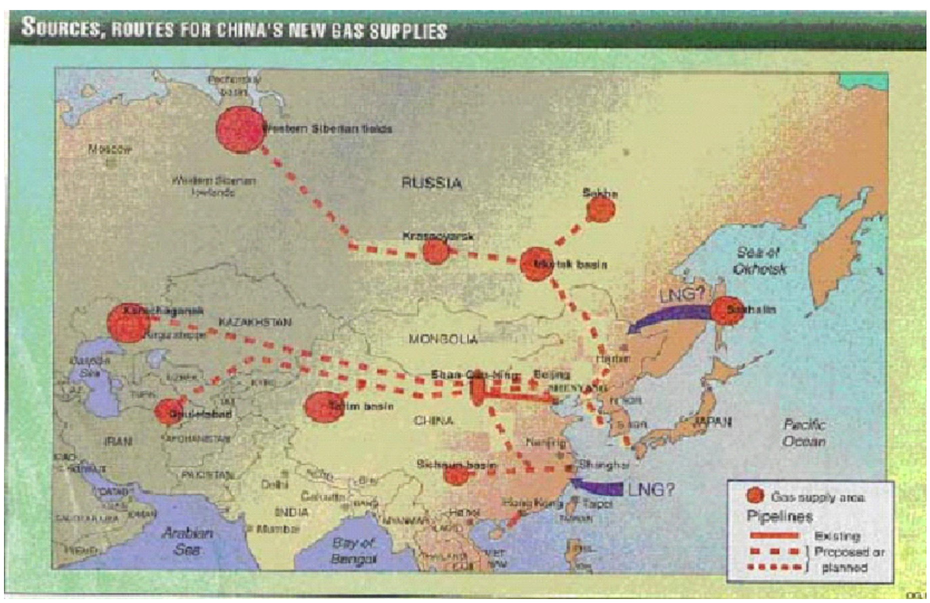

Figure 1. The prospective resources of natural gas from Western China, Russia, Middle Asia and LNG by barging.

Since the beginning of this century, 2000 AD, the long distance large volume gas transmission project, i.e., The West-East Gas Pipeline has started the tide of using high performance linepipe steels.

Figure 2. The 4000 KM natural Gas Trans China Pipeline Routes from Tarim Basin in Western China to economy developing Yangzi delta in the eastern coastal regions [7].

API Grade X-70 Acicular Ferrite / Bainite high strength pipe steel has been developed and applied in two long distance high pressure natural gas transmission pipelines in this country [9 – 13]. One is the 4000KM West-East gas transmission pipeline (Figure 2) to transport natural gas from the Tarim basin in Xinjiang and the Ordus basin in Shaanxi in far Western China to the Yangze river delta in the East coast regions, i.e., Shanghai, etc. The pipeline was finished and has operated since 2004 [4,7]. The next large gas transmission pipeline will be the Second 860 KM Shaanxi – Beijing gas transmission pipeline (Figure.3) which links the West-East gas transmission pipeline to Beijing – Tainjin – Tongshan delta [5]. All pipes are 1016mm, diameter and 14.6 – 26.2 mm thick with operating pressure of 10 MPa and transportation capacity of 12 billion cubic meters / year.

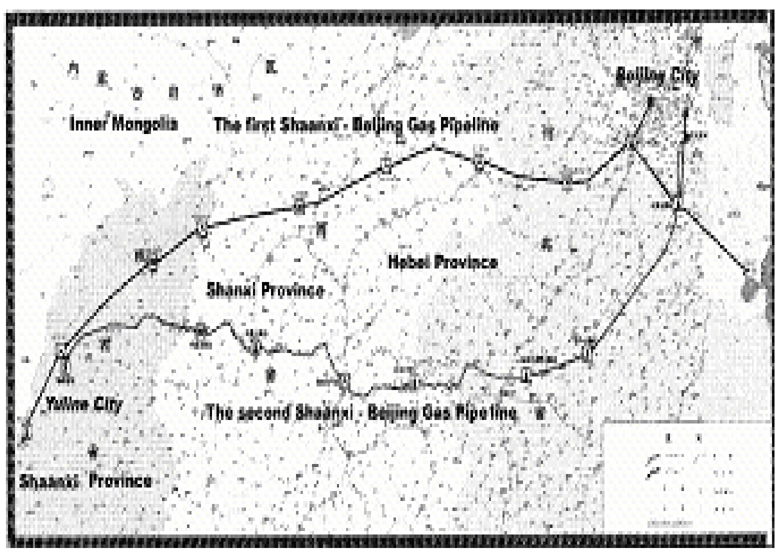

Figure 3. The 860 KM Second Shaanxi- Beijing natural Gas Pipeline from Ordus Basin in Western China to the economy developing regions of BEIJING- TAINJIN- TONGSHAN delta [5].

Figure 4. The planned gas transmission pipeline project, i.e., 4887 KM Gas Project, with capacity of 30 billion cubic meters / year from Siberia, Russia to Northeastern China and South Korea.

The large expense to delivery large volumes of natural gas by X70 grade pipeline from the remote reservoirs in West China or overseas, i.e., Russia and middle east (Figure 1, 4) to the eastern, and southeast and Northeastern China could not be competitive compared with gas from offshore or from imported LNG without development of new steels to attract investment. This is the background behind development of high performance pipe steel in China. Recently, API Grade X80 pipe steel has been developed by domestic steel plants [55 – 58]. However, we are especially inspired by Exxon Mobil's and BP's research [6, 60 – 68], which is directed to largely reducing the cost of long distance natural gas delivery by using Grade X-100 and Grade X-120. Particularly their experience in delivering gas from the Arctic North slope of Alaska through the permafrost and geologically unstable regions along that route, i.e., the pipeline must exhibit good strain performance to tolerate the frost heave and thaw settlement, etc. These technologies will allow us to exploit the natural gas reservoirs in the high and cold plateaus in Western China [69 – 78]. This paper presents a view of the achievement of high performance line pipe steels in China and comments on the developing targets for the next phase of exploration of natural gas.

The Situation of Line Pipe Steels in China

The X-70 Grade Acicular Ferrite Pipe steel:

The great improvements in pipe steels in the 21st century in China can be traced to the development and utilization of acicular ferrite/bainite (AF) pipe steel in gas transmission trunk pipe lines. Until 2000 ferrite – pearlite steel were conventionally used for gas transmission pipelines, e.g., the first Shaanxi–Beijing gas pipeline constructed in the 1990s. Since then we have noticed the excellent performance of Acicular ferrite / Bainite steel, which already was specified for the major gas pipelines in overseas [8, 14 – 18, 23]. The decision to apply the Acicular ferrite/ Bainite (AF) pipe steel in the West-East Gas Transmission Project **WEGP** in 2000 was inspired by the Alliance Pipeline in North America, which is similar to **WEGP** in terms of the delivery volumes, transportation distance, and engineering environment [19 – 22]. We found in addition to good weld-ability for infield girth welding, AF steel was successfully used to make large diameter and thick walled spiral welded pipe for high pressure natural gas transmission pipelines in CANADA. This was particularly meaningful because in China only spiral-weld pipe mills were available for manufacturing linepipe for petroleum trunk pipeline construction. Therefore, the X70 grade Acicular Ferrite / Bainite (AF) steel became the major candidate for executing this project. The design of the AF steel for the domestic steel industry was according to the Graville relationship for girth weldability. (Figure 5) [9 – 13, 24 - 26]. About one half of the X70 Grade AF line pipe steel, or one million tons, used in the **WEGP** were supplied by overseas steel plants, namely, Sumitomo, POSCO and Euro Pipe [8, 27,28].

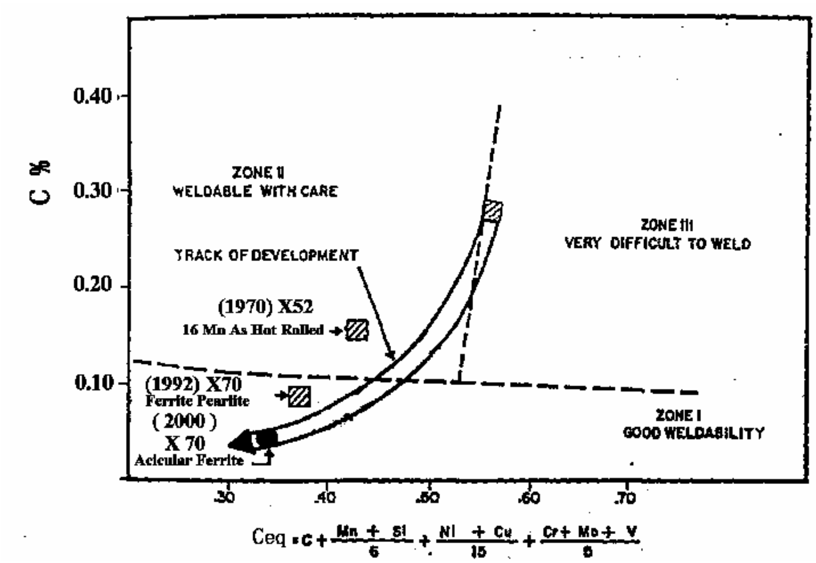

Figure 5. The historical development of pipe steel in China according to the Graville diagram

This AF steel was melted then ladle refined with calcium powder injection for deep desulphurization, sulfide shape control and vacuum degassing. Later controlled rolling using TMCP (thermo-mechanical control process), was applied with a finishing temperature just above Ar_3. Thereafter the steel strip or plate was accelerated cooled at rates between 3.5°C/s – 35°C/s to coiling or ageing temperatures between 600°C and 450°C, depending on the capacities of the cooling, coiling and hot leveling facilities respectively (Figure 6). Up to the present, both X70 Grade steel coil and plate have been developed and produced by domestic steel plants and welding into spiral and longitudinal seam pipes in Table 2 – 6 [11 – 13, 24 – 26, 41, 42].

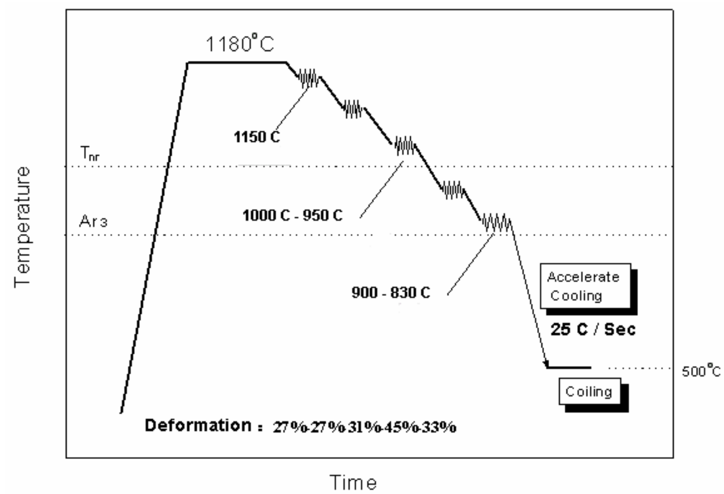

Figure 6. TMCP parameter for X70 AF Steel [39].

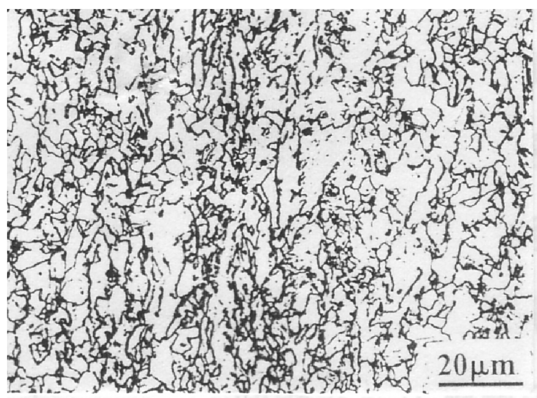

Figure7. Microstructure of Acicular Ferrite / Bainite Steel Specimen taken from Trial melt by Institute of Metal Research. Consists of Acicular Ferrite+ Granular Ferrite + Polygonal Ferrite + M/A Optical Microscopy 1000 × [11-13].

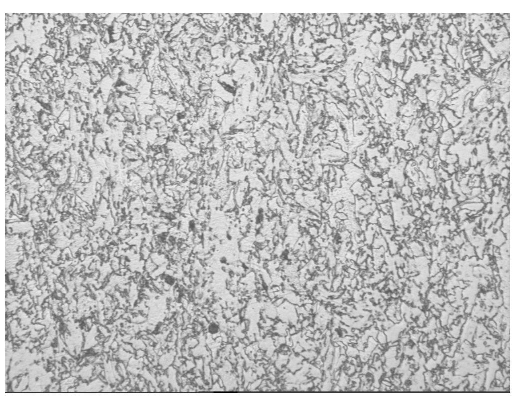

Figure 8. Microstructure of Acicular Ferrite/Bainite X70 Pipe Steel (14.7mm) Coil Strip from Domestic Steel Plant, showing Acicular Ferrite+ Granular Ferrite + Polygonal Ferrite + M/A [11].

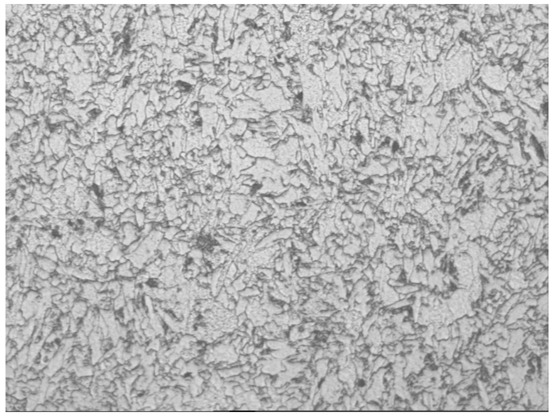

Figure 9. Microstructure of Acicular Ferrite/Bainite X70 Pipe Steel (14.7mm) Coil Strip from another Domestic Steel Plant, consists of Acicular Ferrite+ Granular Ferrite + Polygonal Ferrite + M/A [11].

Figure 10. Microstructure of X70 Acicular Ferrite / Bainite Pipe Steel 17mm Plate from a third Domestic Steel Plant (Acicular Ferrite+ Polygonal Ferrite + M/A, Grain Size ASTM 10). Optical Microscopy 500 × [10,11]

According to the results obtained by microstructure analyzer, the matrix of so-called Acicular ferrite/ Bainite steel consists of acicular ferrite/bainite (30 – 55%), polygonal or granular ferrite (30 – 55%) and retained austenite/martenite (6 – 16%) which is consistent with the results obtained by Korean scientists [53,54] and similar to those of the so called residual – austenite (RA) steel which is part of the family of multiphase steels [43] used for automobile manufacture.

Spiral Saw Pipe Utilizing AF Steel

In order to manufacture X70 Grade large diameter and thick wall spiral pipe, new spiral pipe welding facilities were designed, manufactured, installed and were put into routine production in the major pipe factories, i.e., BAOJI, HUABEI, ZIBO, and SHASHI, etc. (Figure. 11), The mechanical properties of spiral welded pipe and weld seam manufactured by the domestic BAOJI pipe mill from coils made by domestic steel plants are shown in Table 5. The impact toughness of the pipe is shown in Figure. 12.

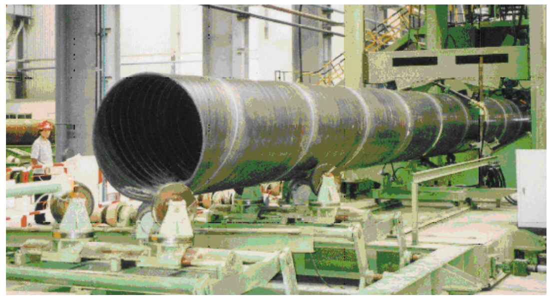

Figure 11. The domestically build new spiral welding pipe facility in BAOJI pipe mill.

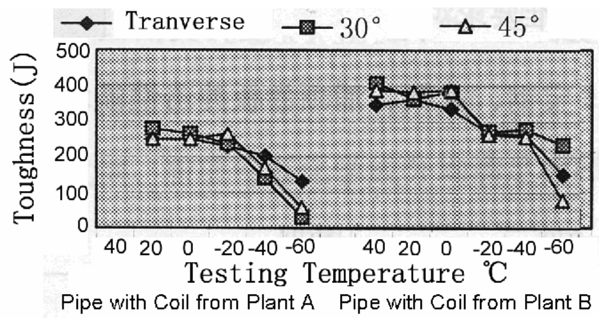

Figure 12 Toughness of Spiral Welded Pipe Body Using X70 AF Steel Coils from Domestic Steel Plants.

The data demonstrate that spiral welded pipes made from domestic coils can fully meet the demands of the specification for the West–East Gas Transmission Pipeline Projects **WEGP** (Table 5 & 6). The data show that the mechanical behavior of spiral welded pipe from domestic pipe mills has reached a relatively high level.

Longitudinal Seam Saw Pipe

To meet the increasing demand for longitudinal submerged arc welded (LSAW) pipe in higher thicknesses, which are prescribed for high pressure gas transmission pipeline construction in the 2nd, 3rd and 4th Class regions (i.e. , the dense population, industry and traffic zones), LSAW pipe mills have also been installed in China since 2003. A photograph of the LSAW pipe production facilities in Julong steel pipe factories is shown in Figure 13.

Figure. 13. The imported JCO forming machine for longitudinal saw pipe production in Julong (Huabei) Steel Pipe Co.

LSAW pipe manufactured in China commenced and was supplied to the West-East Gas Transmission Project **WEGP** since May 2002. AF steel plates for LSAW pipe manufacture were made from plates domestic from steel plants or from plates imported from overseas. These steel plates possess high purity and excellent mechanical properties (Table 2 – 4). The steel plate is welded by 4-wire submerged arc welding into LSAW pipe. The experimental data show that the properties of LSAW pipe can fully meet the specifications of the West–East Gas Transmission Pipeline Projects.

Experimental data show that the Yield/Tensile strength ratio of the LSAW pipe decreases slightly (around 0.02 %) relative to that of the original steel plates. Evidently, there is no yield strength loss during the LSAW pipe manufacture process.

Resistance to Ductile Fracture

One of the reasons to select Acicular Ferrite/ Bainite steel as the major candidate for the West-East gas transmission pipeline construction is its significantly superior crack resistance needed to prevent the fast propagation of ductile fracture compared with conventional ferrite-pearlite line pipe steel. Until 2000, pipeline designers in China have not had direct experience on such mechanism of failure. They knew however from overseas experience that as the operating pressure of the gas pipeline increases the stored energy in the contained gas increases. Once a crack of critical length occurs, such a crack may initiate a long ductile fracture, i.e., running shear fracture, which may lead to catastrophic failure of the pipelines. Since the pipeline for **WEGP** was designed as 1.016 meter in diameter with 10MPa operation pressure, whether this design could prevent ductile fracture occurrence in burst accidents was one of the prerequisite questions to be answered in advance of authorizing the project scheme. In the initial design phase of this **WEGP**, there had been quite a strong controversy on whether or not to build a full scale burst testing site in China with considerable budget, corresponding to millions of US Dollars in order to determine the minimum threshold toughness value of the pipe necessary to prevent running ductile fracture, in order to obtain the data before the decision of this **WEGP.**

In order to solve this controversy within a short period, the authors suggested and assisted the headquarters of **WEGP** to host an international seminar concerning "Ductile Fracture and Prevention in High Pressure Gas Pipelines" and invite the top scientists and engineers in this field in order to hear overseas specialist's opinions.

This seminar was held between 25- 27, Oct. 2000 in Langfang, China. With the help of Dr. William Warke from AMOCO and Dr. Tamatsu Hashimoto of SUMITOMO, Dr. Brian Leis, Mr. Robert Eiber, Dr. Gery Wilkowski, Mr. Gerald Wilks from USA, Dr. Izumi Takeuchi and Dr. Hiroyuki Makino from Sumitomo Japan were invited to attend and make presentations to about 80 attendees including the designers of this project and the senior staff from relevant departments concerning this project as well as representatives of the Authorities, and regulators.

Figure. 14 Some of the foreign scientists who made incisive and penetrating presentations in the International seminar on ductile fracture and prevention, 25 – 27 Oct. 2000, Langfang China (The center is author).

From their incisive and penetrating presentations, the audience became aware that construction of a full scale burst test facility in China would involve a lot of know how with a total cost of around 10 millions US dollars, which would also delay the schedule for the **WEGP**. The audiences were advised that the toughness needed for X70 grade steel pipe to prevent ductile fracture had been widely examined elsewhere using full scale gas pipeline burst testing. As the operational parameters of **WEGP** involve lean gas transmission through 1,016mm diameter x 14.7 mm pipeline made by X70 grade steel with operating pressure of 10MPa (0.7 SMYS). According to the opinion from Dr. Brian Leis and Mr. Robert Eiber, et.al., the minimum Charpy impact toughness needed to arrest a ductile fracture within one pipe length is estimated to be 90 – 110 Joules. The conditions of the estimate is the pipe's toughness CV100 / CVP ratio 0.8 which is used as an index of separation defect on the fracture surface of impact specimen, because the scientists from North America think that separation defects may be detrimental for crack arrest capacity of the steel plate. However, according to the opinion of

Dr. Izumi Takeuchi and Dr. Hiroyuki Makino the arrest value could be 120 Joule Charpy V-notch energy without the limitation of CV100 / CVP ratio $\geq$0.8, based on the fact that Japanese scientists could not find any relationship between propagation speed of ductile cracks and separations in their tests. Concerning the weld seam and heat affected zone, the scientists believe that a low toughness (around 30 Joule) is required to prevent the initiation of cracking. Therefore, it became clear that establishment of a full scale burst test facility in China as a pre-phase requirement for this project was unnecessary. This International seminar therefore resulted in quite large saving both in financial terms and the time schedule for the **WEGP** [29 – 36].

Through this seminar and a series of surveys made afterwards overseas the minimum toughness required to prevent the initiation and propagation of running ductile fracture in the pipeline, were authorized and issued (Table 6)[37]. Comparing the data in Table 4 and in Figure 12, it is evident that high strength pipes made from Acicular Ferrite/Bainite steel can fully meet the requirements without the need for crack arrestors installed in the pipeline.

In the summer of 2000, one experimental pipeline section of AF steel pipe was constructed in a steep terrace of desert regions. Because there was insufficient water for hydro testing, the pressure tests were performed using compressed air instead of water without incident. According to the estimation of Dr. Izumi Takeuchi and Dr. Hiroyuki Makino, for the case of compressed air pressure testing at around 13 MPa (0.8 SMYS), the minimum toughness needed to arrest a ductile crack for a 1016 diameter X 17 mm Grade X70 pipeline, within one pipe length should be 200 – 250 Joule [38]. This estimate also verified the integrity of pipeline made by the AF line pipe steel.

Construction of the West-East gas transmission pipeline using AF steel

Through years of hard work the, **WEGB**, the longest gas pipeline in the World has been completed. It stretches from the gas fields around Korla, in the Northern edge of the Tarim desert in western China to the costal region of the Eastern China sea.

Figure 15. Infield pipe laying and girth welding in the GOBI desert of the West – East Gas Project.

This construction began from the unpopulated GOBI desert (Figure 15) in Western China, where the windy and sandy environment and continental climate made the girth welding pipe work very difficult.

Figure 16. The tests for infield automatic girth welding in the windy and sandy region of the West – Gas Project**.**

Figure 17. The West- East Gas Project pipeline climbs up the steep hill [7]

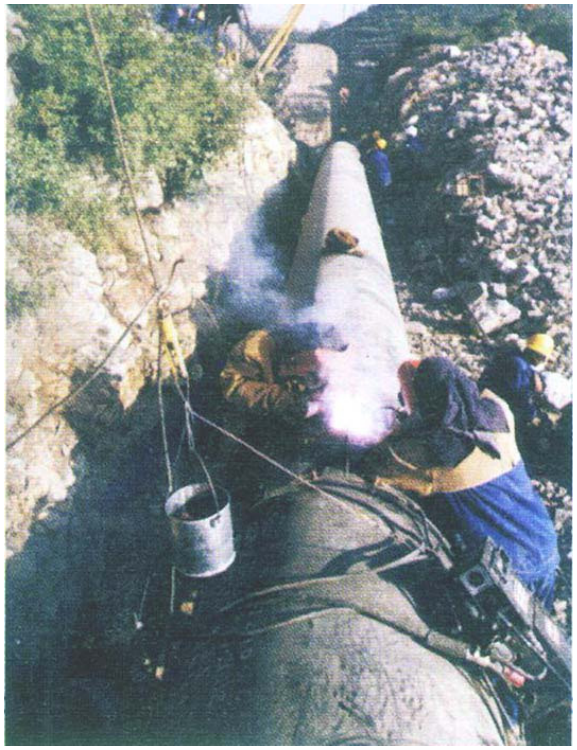

Figure 18. Manual girth welding in a steep terrace

This pipeline crossed three mountain ranges, where the slopes ranged between 60 and 70 degrees with frequent gullies and ridge top elevations of 250 – 300 meters [7]. Where the girth welding pipe could not be done by automatic process manual welding, under poor working condition for girth welding was used (Figure 17,18).

Figure 19. The 540 meter aerial crossing in the upper Yellow River [7].

Figure 20. Tunneling machine specially designed for the 1,992 meters long underground crossing of the Yangzi river which is 42 meters beneath the water level and 12 meters under the river bed [7].

The pipeline construction included 16 tunnels and 16 aerial crossings. Other crossings were 517 roads, 335 smaller rivers and 441 ponds. There were various types of crossings, such as aerial crossings, tunnel crossings, horizontal directional drilling, mooring crossings, etc. All of these have a unique crucial problem, i.e., how to guarantee the quality of the girth welded joints to bear various loads.

Figure 21. The mooring pipeline traverses the 900 meters swamp in the low and damp region of Eastern China.

The complete success of the **WEGP** pipeline, in which about two million tons of Grade X70 AF steel pipes were used with the completion of more than 300,000 infield girth welding joints, indicates the superior behavior of AF pipe steel for gas pipeline construction.

Microstructure, Strengthening and Toughening of AF Steel

Since 2000, the successful application of AF pipe steel in **WEGP,** has aroused strong interest in the pipeline industry, amongst pipe manufacturers, the steel industry and material research institute in China. Research on the strengthening and toughening mechanism of AF steel and microstructure observation with sophisticated technical apparatus has been carried out.

Microstructure shows that the so called "Acicular Ferrite" is a special morphology of ferrite – bainite transformation product formed during continuous cooling after controlled rolling below the non re-crystallization temperature of low carbon ($C \leq 0.06\%$) niobium containing steels [41,42, 44, 45]. Consistent with the classification and terms by Krauss and Thompson [39, 40], the microstructure of the acicular ferrite / bainite steel consists of fine tangled acicular ferrite lath bundles, fine equiaxed granular ferrite (Figure 23) , some polygonal ferrite and widely dispersed M/A with discontinuous and non distinct prior austenite grain boundaries (Figure 7 – 10, 22).

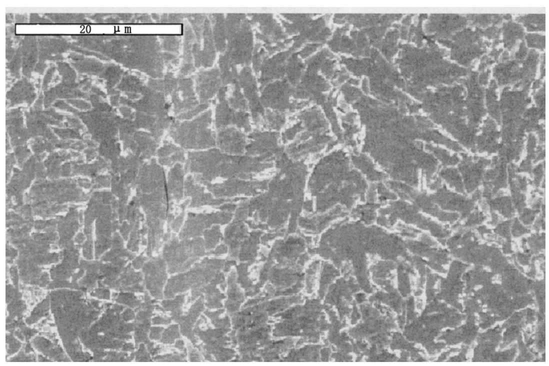

Figure 22. Acicular Ferrite Laths + Granular ferrite + Polygonal Ferrite+ MA .
Microstructure of Acicular Ferrite/ Bainite X70 Pipe Steel. Scanning Electron Microscopy

The microstructural features of acicular ferrite can be easily distinguished from the polygonal ferrite formed in non deformed, i.e., non control rolled simply continuously cooled steels. The latter possesses parallel lath ferrite with clear original austenite grain boundary and clear sparse dislocation network, with carbide precipitation either along the lath boundary or on the prior austenite grain boundary [44,45].

The morphology of acicular ferrite / bainite consists of acicular ferrite lath with inter-lath dislocations and precipitates (Figure 24, 33), acicular ferrite laths with inter-lath films (Figure 27), and the acicular ferrite lath with discrete-island constituents, i.e. M/A (Figure 26) plus degenerate pearlite (Figure 25).,which are consistent with the predecessors [39,40].

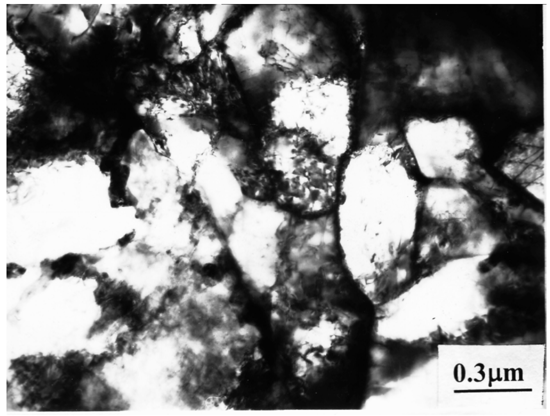

Figure 23. The ultra fine axial granular ferrites by control rolled with dense precipitate along their boundary.

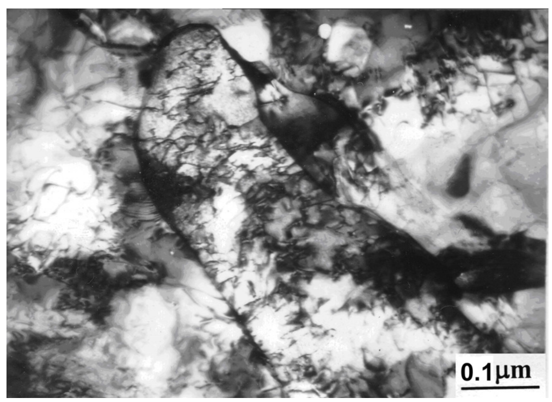

Figure 24. Dense dislocation networks in the Acicular Ferrite Lath. Transmission Electron Microscopy

The acicular ferrite lath bundles with low angle boundaries are composed of interwoven nonparallel ferrite laths (Figure. 22) with dense dislocation net works (Figure 24) and precipitated carbonitrides less than $\leq$10nm, along the dislocation lines, which tie the dislocations (Figure 33) [45]. There are ultra-fine dark etching particles or islands among the laths (Figure 7 – 10, 25, 26), indicating that the carbon content is higher than that of the matrix, which indicates that they are either Pseudopearlite-degenerated pearlite (Figure25) or Martensite / Austenite (M/A) islands (Figure 26). Which are the consequence of the carbon partition. The mechanism of such microstructure formation must be related to the nucleation rate of acicular ferrite from the deformed austenite in the non-recrystallization region which accelerates, the diffusion of carbon to the coherent or semi-coherent γ / α interface. Thereafter the un-decomposed austenite is enriched with carbon, in the later cooling and ageing process, part of the austenite will transform into martensite (Figure. 27) or separate the carbon to form Pseudopearlite (Figure. 26) which then coexists with the retained austenite to form the dark etched spots under the low magnification optical microscopy (Figure 7 – 10).

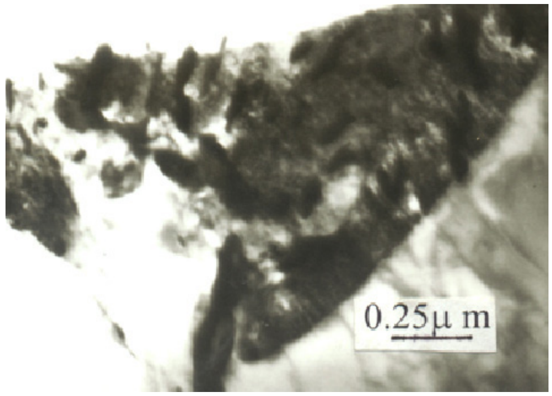

Figure 25. Pseudopearlite along the ferrite boundary Transmission Electron Microscopy

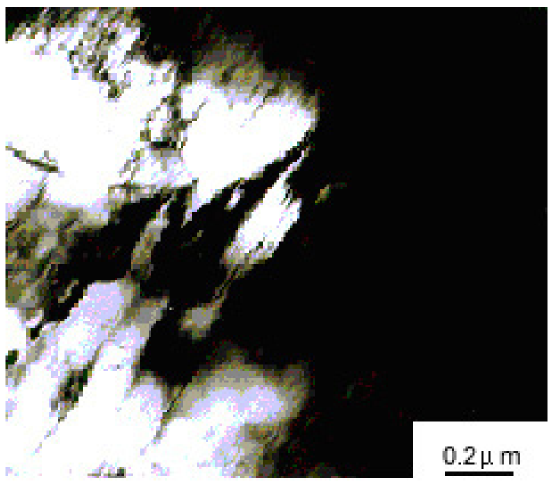

Figure 26. Martensite / austenite phases between the ferrite laths

The 10 – 200 nm thick film of retained austenite-martensite structure (M/A) present between the ferrite laths (Figure 27 – 29), was thought to act as a barrier to micro–crack propagation.

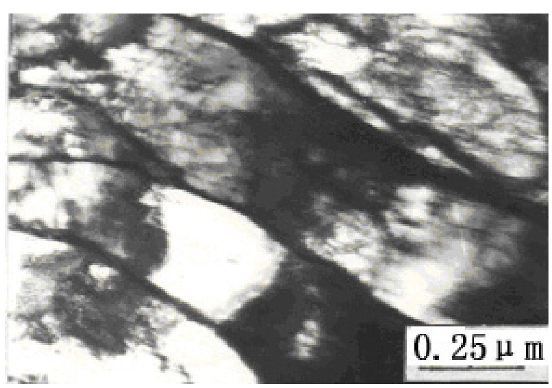

Figure 27. Thick M/A film along the ferrite lath boundary and dense dislocation network inside the ferrite lath. AF X70 Steel (Transmission Microscopy)

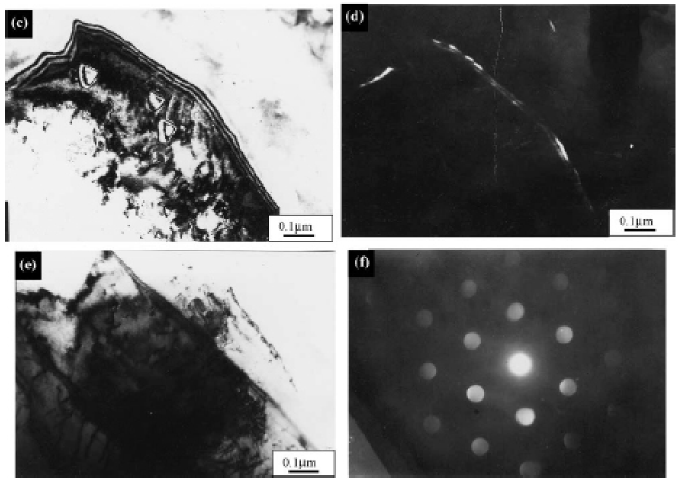

Figure 28. Thick M/A film along the ferrite lath boundary under optical microscopy（c). Bright field image (d) Dark field image (e) Bright field image (f) Microdiffraction pattern of (e) [46]

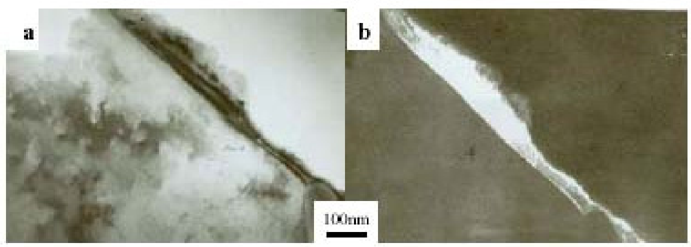

Figure 29. Thick M/A film along the ferrite lath boundary inside the AF steel under optical microscopy.(a)Bright field image (b)Dark field image [48].

Micro Crack Propagation Behavior of AF Steel [48]

Micro crack propagation behavior of acicular ferrite steel under loading was investigated by directly observing tensile strained sheets or foils with TEM (Transmission Electron Microscopy of Hitachi H800 200KV) [48]. The results show that as the micro- crack occurs and develops under tensile strain it meets the high angle boundary (about 30°) to the ferrite lath, it passes through the boundary with a dislocation free zone in front of its tip and gradually changes its direction to the slip direction of the latter grain (Figure 30).

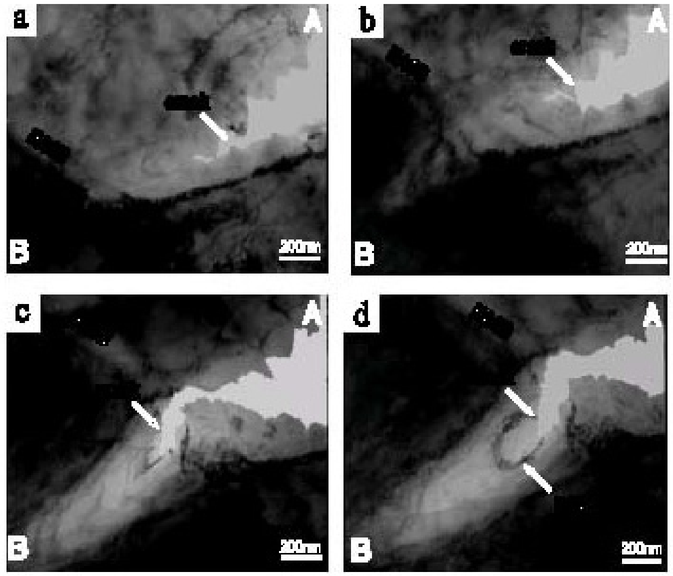

Figure 30. The in situ TEM study of propagating crack meeting high angle grain boundary (HAGB) between grains A and grain B. (a) Crack propagating inside A toward B, (b) The dislocation in B are moving under loading, (c) The crack passed through HAGB with changing propagating direction, (d) Crack changing direction inside A, i.e., along the slip direction of dislocations with dislocation free zone in front of the crack tip.

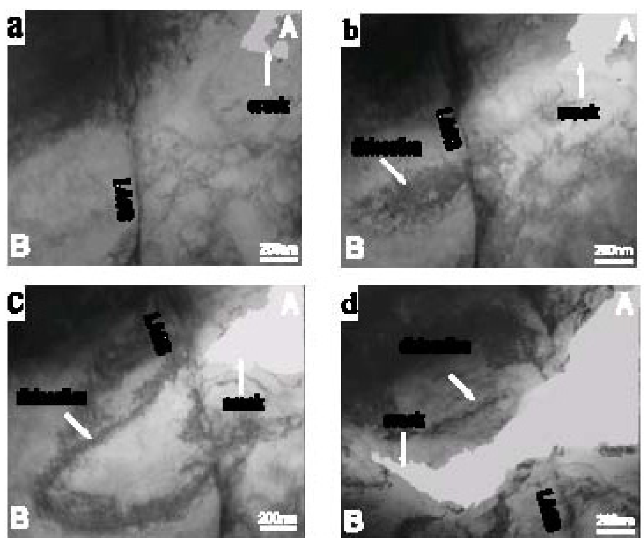

Figure 31. The in situ TEM study on the crack propagation meeting low angle grain boundary (LAGB) between grain A and grain B. (a) Crack propagating inside A toward B, (b) The boundary emitting dislocations toward B under loading, (c) The crack approach the LAGB, (d) the crack passed through LAGB without or small changing its propagating direction.

When the micro–crack under loading moves near the low angle lath boundary, between grain A and B, dislocations are gradually generated at the low angle boundary between grain A and B, where they pile up and finally the at last, this crack "slips into grain B" with almost the same propagation direction in grain A (Figure 31).

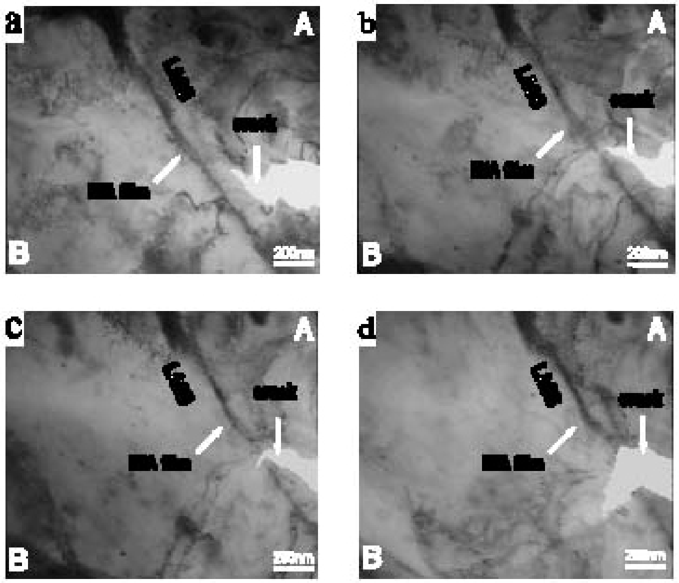

Figure 32. In situ TEM study of crack propagation meeting low angle grain boundary (LAGB) between grain A and grain B with thick M/A film. (a) Crack propagating inside A toward B, (b) The crack approach the boundary without apparent dislocations inside B under loading, (c) The crack passed through the LAGB, (d) the crack propagating inside Grain B with changing direction.

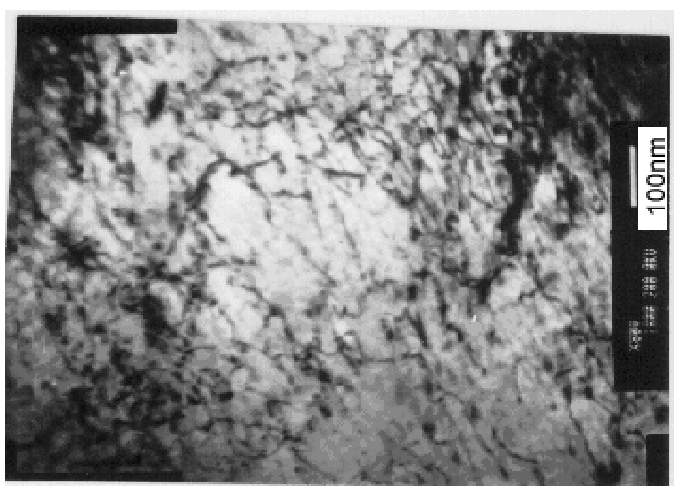

Figure 33. The Dislocation Network in AF lath pinched by Ti–Nb (CN) precipitates. Transparent Microscopy.

In the case where there exists a thick film of retained austenite and martensite (M/A) at the low angle boundary between grain A and grain B, the micro-crack moves towards the boundary without apparent changes in dislocation state and after passing through this low angle boundary with a remarkable deflection in its propagation direction. Finally the misorientation of crack direction can be up to as large as 90 degrees (Figure 32) [48].

Micro-crack propagation behavior in AF steels under low frequency loading [47].

In order to investigate micro crack initiation and propagation behavior in AF steel under 10 HZ sine wave low frequency fatigue loading, i.e., simulating the daily pressure fluctuations of the gas pipe line under start and stop conditions, specimens of Grade X70 AF steel and X60 Grade ferrite – pearlite steel were taken from industrial production to make fatigue tests comparing specimens from laboratory made Grade X70 AF steels having a better microstructure and toughness. Composition and mechanical properties of all the tested specimens are shown in Tables 7 and 8.

From Figure 34, the fatigue resistance of AF steel is evidently higher than that of the ferrite-pearlite Grade X60 pipe steel. There a linear relationship between the micro-crack propagation rate, i.e., da / dn value and the impact toughness of the tested steels (Figure 35). The specimen life under fatigue loading of Grade X70 AF steels also exhibited a linear relationship with the specimen's toughness (Figure 36, Table 9).

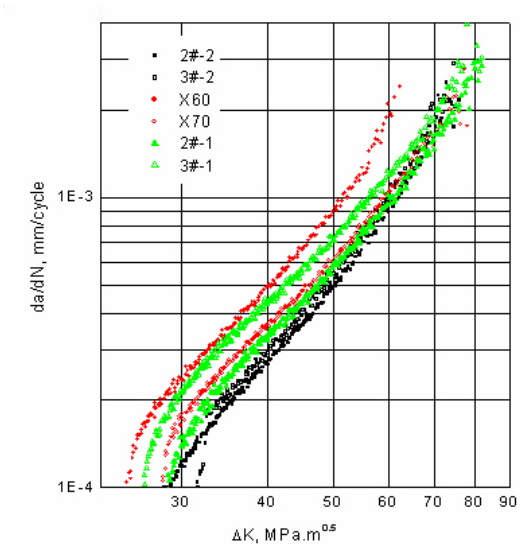

Figure 34. Fatigue crack propagation rate comparisons between the line pipe steels.

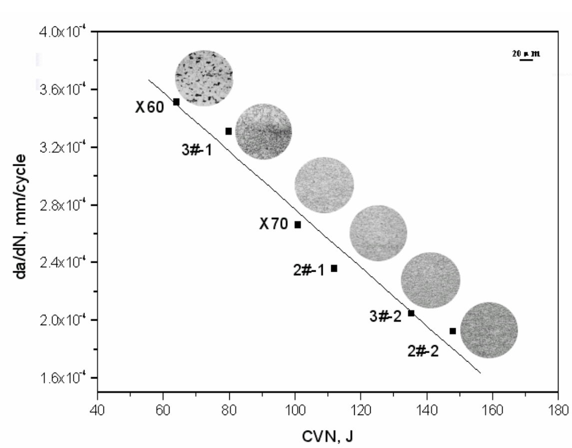

Figure 35. Relation of fatigue crack propagation rate da/an with the toughness CVN value of pipe steels.

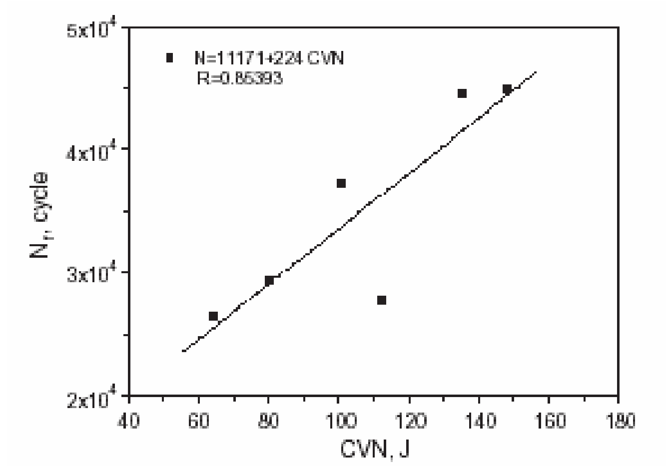

Figure 36. Relation of specimen's testing life under low frequency fatigue loading with their impact toughness

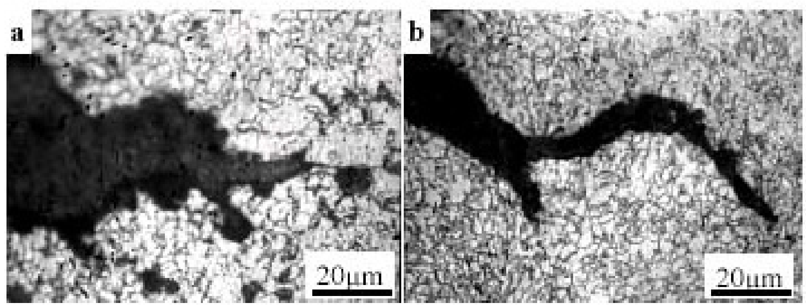

Figure 37. Trajectory of the crack tip

(a) X60 grade ferrite and pearlite pipe steel

(b) X70 grade acicular ferrite pipe steel

The merits of Grade X 70 AF over ferrite-pearlite steels can be intuitively explained from the direct observation of the micro crack tip by optical .microscopy (Figure 37). [48]

Anti sour resistance of AF steels [49].

The anti-sour resistance of the micro-structure of the acicular ferrite was investigated by taking specimens from the same steel melts, (Table 7. No.2 # melt), let producing a acicular ferrite microstructure or ultra-fine ferrite microstructure by rolling with different TMCP schedules (Table10) respectively, but obtaining similar mechanical properties (Table 11). The anti-sour behavior was compared by SSC testing. The results show that the steel with acicular ferrite micro-structure possesses the highest Sc value (≥1,260 MPa) compared with ultra-fine ferrite micro-structures where the Sc value is 1190 MPa (Table 12) despite the latter possessing finer grain size than the acicular ferrite steel (compare Figure 38 with Figure 7-10).

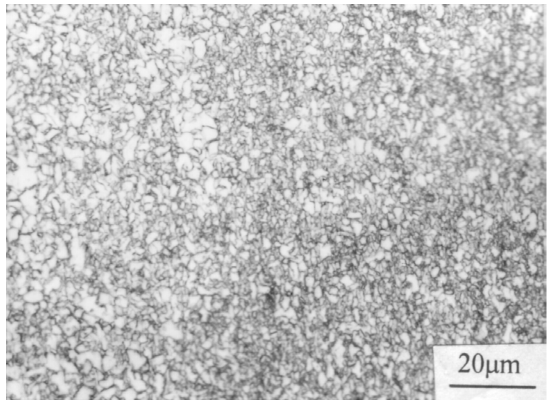

Figure 38. The micro-structure of ultra-fine ferrite steel showing fine equiaxed ferrite grains by optical microscopy. [49]

The above comparison shows that the fine interlocking characteristics of acicular ferrite make the crack propagation difficult due to the presence of dense precipitation of carbonitrides and the M/A film islands which might punch the dislocation to arrest or deflect the cracks, this plays a significant role in enhancement of strength and toughness of AF steel. In a nutshell, these characteristics are responsible for the excellent weldability, high strength and superior toughness of the acicular ferrite steels, with the finer the microstructure the better the strengthening and toughening effects.

Grade X 80 AF steel.

Since 2004, Grade X80 pipes having both spiral and longitudinal seams have been developed in China. To compare the mechanical property data of Grade X80 steel coil (Table14) with those used in the present West-East gas project as Grade X70 line pipe steel (Table 2, 3, 4, 15), one can see that the strength range of the pipe used in present **WEGP** has entered the range corresponding to Grade X80 pipe but still only using Grade X70 strength (490MPa) as the design criterion. The microstructure of Grade X80 steel also exhibits an acicular ferrite morphology but shows more AF and less polygonal ferrite and dark precipitates, i.e., M/A or Pseudopearlite than the Grade X70 steel (compare the microstructure in Fig. 39, 40 with Figure 7 & 8).

The above comparison shows that the strength fluctuations of Grade X70 and X80 pipe steels are mutually interlaced with the same microstructure morphology, i.e., acicular ferrite, etc. Therefore, strictly speaking, the so called Grade X70 steel used in WEGP with strengthYS≥530-630MPa is essentially corresponding X80 grade steel. Only because of yield strength lost due to Bauschinger effects in pipe forming was X-70 taken as the design strength. ,

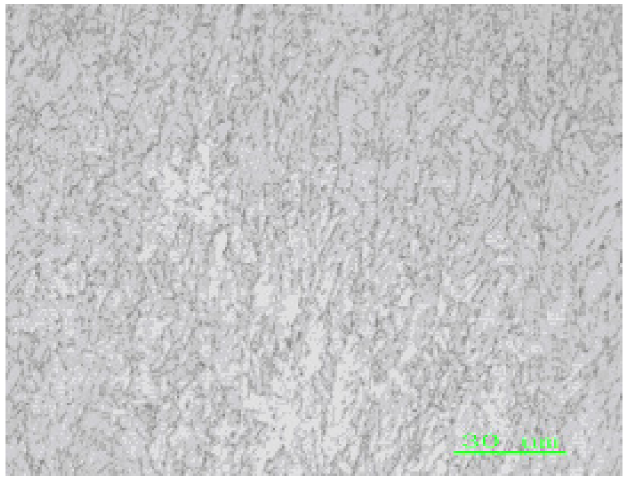

Figure 39. Microstructure of X80 Acicular Ferrite / Bainite Pipe Steel 18.4 mm Plate from Domestic Steel Plant D, [Acicular Ferrite+ Polygonal Ferrite + M/A,, Grain Size ASTM 12-13 Optical Microscopy.

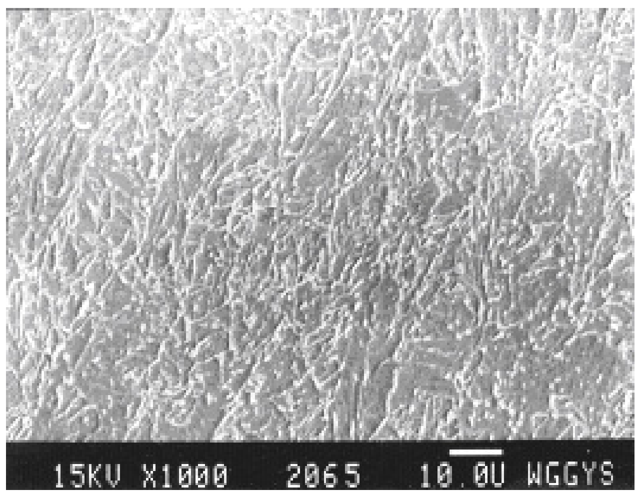

Figure 40. Microstructure of X80 Acicular Ferrite / Bainite Pipe Steel 18.4 mm Plate from domestic Steel Plant D, [Acicular Ferrite+ Polygonal Ferrite + M/A,, Grain Size ASTM 12-13 Scanning Microscopy.

According to the definition in Europe and North America, the Grade X70 pipe is controlled rolled with stop rolling below Ar_3 temperature with low Pearlite-Ferrite–Bainite microstructure and the Grade X80 pipe steel is stop rolling just above Ar_3 producing Acicular ferrite / Bainite microstructure (Fig. 41)[20,28, 59,61].

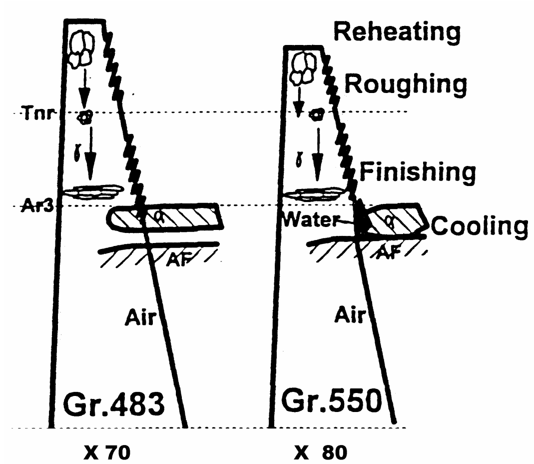

Figure 41 The TMCP schedule for X 70 and X 80 grade pipe steels at IPSCO steel plant Canada [59].

In the pipeline industry, one of the apprehensions concerning more widely applying Grade X80 steel pipe is the benefit. By comparison of the strength and price balance, one finds that the benefits of applying Grade X80 pipe is very limited after taking out the higher price (Table16).

Another is the raising of the longitudinal strength of the pipe body causes difficulty during infield girth welding. For high pressure gas pipelines the strength of the girth weld is generally required to be higher than that of the parent pipe to avoid stress concentration at the girth welding joint (Figure 42)[76,77]. In fact, the strength of Grade X70 pipe has already been up to the safe margin of over matching girth weld using conventional girth welding materials and techniques. (Figure 43)[78],

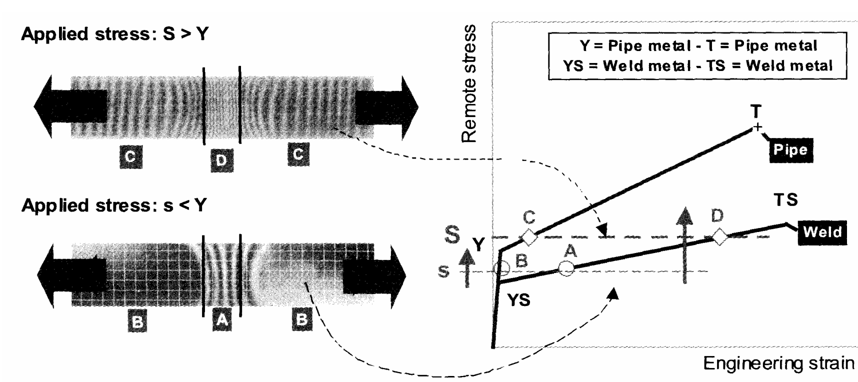

Figure 42. Photo elastic sensitivity patterns of the line pipe when it is loaded by land movement. The upper case is over match. The lower case is under match [76].

Because the strength of "Grade X70" pipe steel in China essentially corresponds to Grade X80 overseas, the girth weld of so called Grade X70 steel pipe in **WEGP** can only get equal-match in most cases as well as the distribution of girth welding joints in overseas (Figure 44).

Furthermore according to recent girth welding experiment results for the Grade X80 steel pipe in China, it is difficult to avoid under matching girth weld in Grade X80 pipelines.

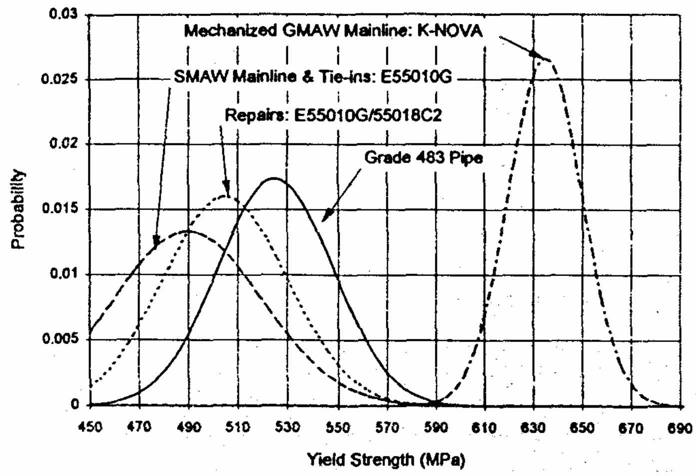

Figure 43. Schematic curves of yield strength distributions for Grade X70 (483) pipe steels and girth welding joints [60].

Fortunately, up to now, the design of long distance gas transmission pipe line in China is still based on the stress design or loading design, which do not therefore require overmatching girth welds.

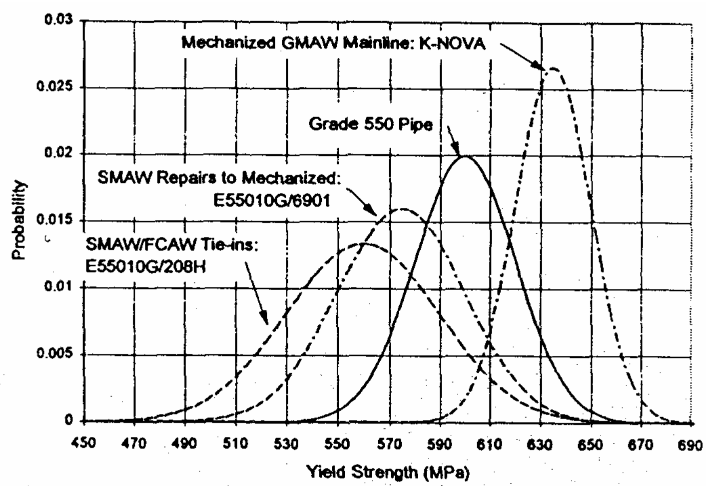

Figure 44. Schematic curves of yield strength distributions for Grade X80 (550) pipe steels and girth welds [60].

This is the chief reason why Grade X80 line pipe steel was widely applying during the past twenty years [78]. Obviously, according to the strain based design principle for pipeline design in special region [75 – 78], overmatching girth weld joints is a predetermined condition before widely applying Grade X80 pipe steels, especially in the special geological regions that **WEGP** experienced (Figure 17 – 21) [7].

Inspiring Innovations Overseas

As to the objective for the next phase of high performance line pipe steel development, a review of the inspiring innovations overseas is meaningful. Amongst which first should be noticed is the concept of "effective grain size" based on the micro-orientation of the lath packets. This indicates neither the size of prior Austenite grain nor the cellular substructure separated by low angle boundaries in the niobium containing TMCP steel is a decisive factor controlling toughness. The toughness of the niobium containing steel after TMCP depends on the domain or packet size, which is separated by the high angle (≥10° or 12°) boundaries (Figure 45) [51 – 54].

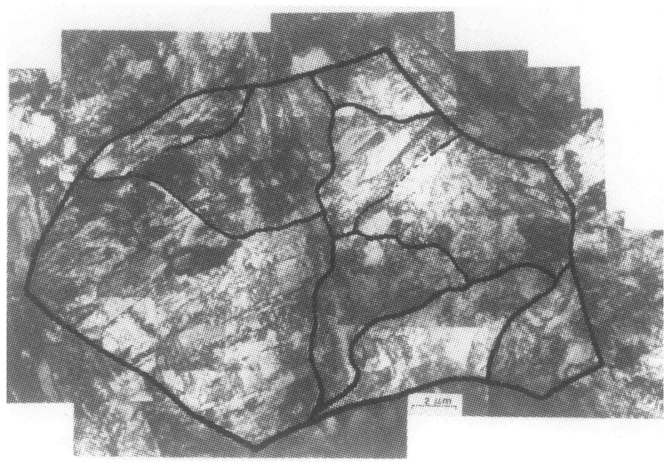

Figure 45. Domains or packets, separated by high angle (≥10°) boundaries in Nb containing and TMCP steels, typical size 2-4μm [61].

The recent research by ExxonMobil and BP concerning pipeline costs reduction in order to develop remote gas resources, which are currently considered non-commercial gives us new inspiration [62 – 68]. However, we are aware that the direct replacement of conventional grade linepipe with higher strength grades pipe only can offer modest cost saving and that significant reduction gas transmission cost can only be realized by fully capturing the benefits of a total components approach to gas transmission using ultra-high pressure pipe line [62,64,65]. This completely separates the present independent approach between steel itself and selection of welding technique. This represents a new field for developing high strength line pipe steels and simultaneously welding technique.

The advantages of using X100-Grade X120 high strength steels in such projects are material reduction (thinner pipe wall), less weight and volume of pipe for transport, faster welding, less pipeline coating, and reduction in the number of compressor stations, etc. The expected cost reductions are not merely 5 – 15 percent on capital cost but also 5 – 15 percent on the life cycle cost of this pipeline [62].

The application of Grade X100-X120 high strength pipe steel supports the idea of integrated project saving, i.e., by increasing the operational pressure of the pipeline the gas and the heavier hydrocarbon natural gas liquids (NGLs) can be combined to form a single – phase dense fluid for transportation. This single – phase dense fluid pipeline eliminates the need for liquid pipeline construction and enables moving the facilities to separate and stabilize NGLs from the remote gas production field to the end user location. These are particularly meaningful for exploitation and commercialization of the natural gas reservoirs in remote Western plateau of China [62].

Of course, there are a series of material developments that must be done before using the high strength line pipes [61, 63, 64, 66 – 68]. Obviously the microstructure of Grade X100 and X120 high strength pipe steels are finer that those of X 70 and X80 product (Figure 46 – 48). In order to get such fine microstructure, more strictly controlled rolling, the addition of boron and inline accelerate cooling are needed. The research on X 100 and X 120 should it also probe deeply into the relationship between the orientation of the low and high angle grain boundaries of the matrix, the parameters and the toughness of the steel (Figure 45 – 48).

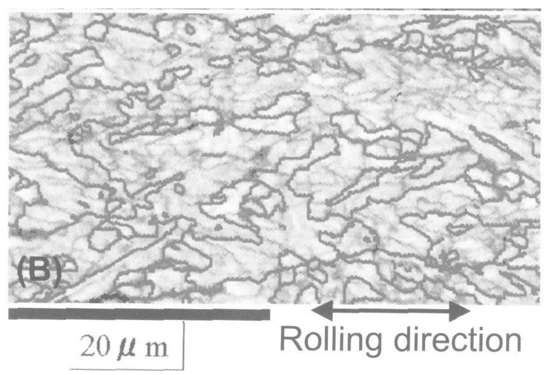

Figure 46. Grain Orientation (domains) Map of X-100 grade pipe steel with Upper Bainite microstructure by EBSD in scanning Microscopy [63,64].

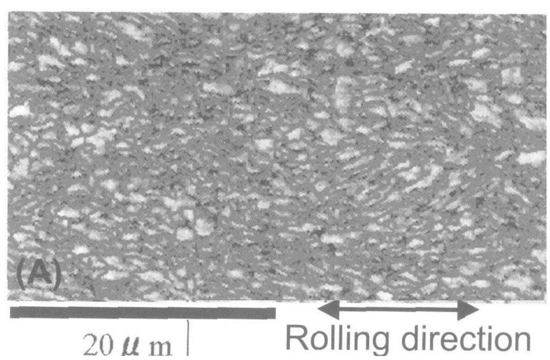

Figure 47. Grain Orientation (domains) Map of X-120 grade pipe steel with Lower Bainite microstructure By EBSD in scanning Microscopy [63,64].

Techniques such as grain orientation maps using electron back scattering diffraction (EBSD) during scanning microscopy show the steels produced by the TMCP technique possess domain based microstructure. The domains with ≥10°boundaries in Grade X100 pipe steel of Upper Bainite microstructure (Figure 46) are quite a lot larger than those in Grade X120 pipe steel having lower Bainite microstructure (Figure 47).

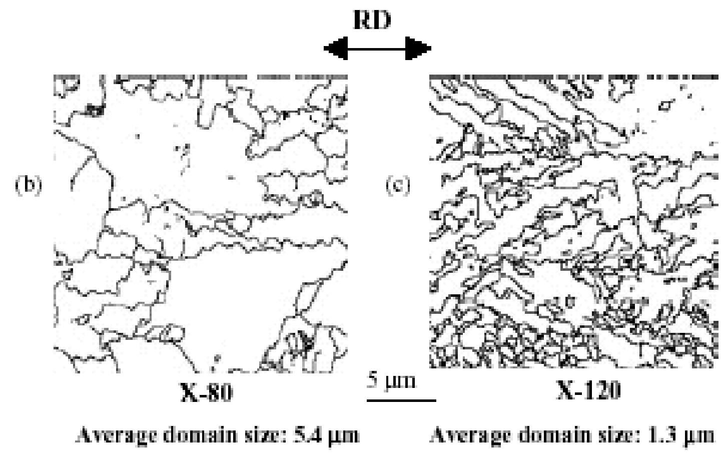

Figure 48. Comparison of domain size according to the grain orientation maps between X80 and X 120 grade pipe steel by EBSD in scanning Microscopy [64]

A comparison of the EBSD grain orientation maps shows the average size of the domains with $\geq$10° boundaries in Grade X80 steels is about 5.4 µm and in Grade X120 pipe steels is just 1.3 µm (Figure 47), i.e., much smaller than those in the Grade X 80 pipe steels.

In order to put this Lower Bainite pipe steel into routine production, some preparations are necessary in advance, such as how to correctly add the boron into the melted steel, enforce the cooling device, strengthen the plate leveling device, reconstruct the U press of the pipe forming device, etc. In a word a period of reconstruction of the relevant facilities in the plate rolling and pipe mill is needed beforehand [63,66-68].

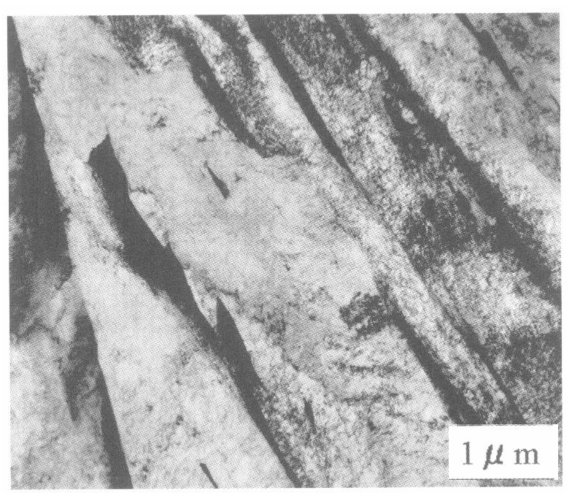

Figure 49. Typical microstructure of HAZ in X100 grade pipe steel. by TEM [63,64].

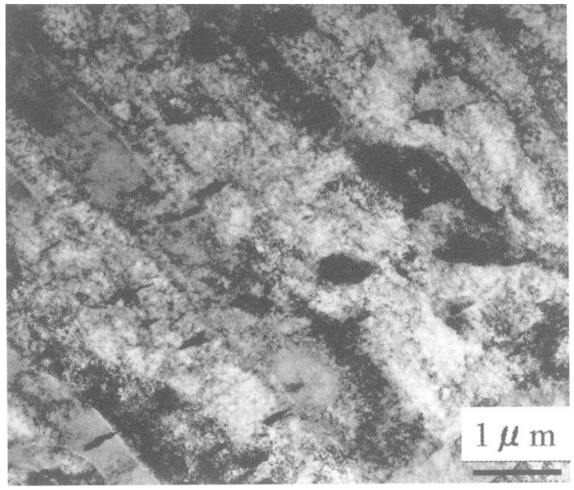

Figure 50 Typical microstructure of HAZ in X120 grade pipe steel. by TEM [63,64].

One of the merits of these high strength pipe steels is their good microstructure in the weld heat affected zone. This possesses both sufficient strength and good toughness to avoid softening phenomena occurring in high strength steels during welding. Of course, development of welding technique is necessary. (Figure 51□53).

The innovations in Grade X120 high strength pipe steels are not confined to steel plate, also new type welding metals and welding techniques (Figure 50) [63,64] are involved. Weld metals are made up of two distinct constituents, a soft phase of acicular ferrite (AF) and a hard phase of lath martensite (LM) and degenerate upper Bainite (DUB). This microstructure is named acicular interspersed in martensite (AFIM). The AF divides the prior austenite grains into smaller sub-units by introducing many high angle (≥10°) interfaces which improve the toughness (Fig. 52, 53).

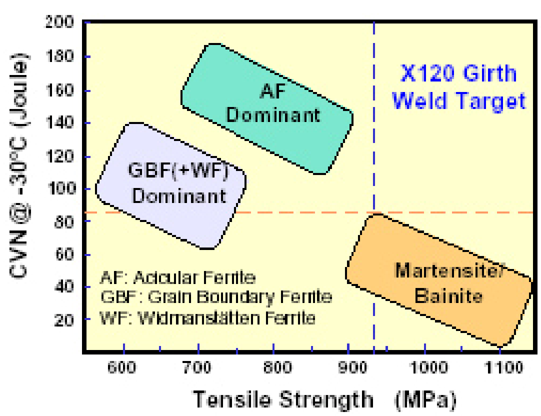

Figure 51. Strength vs. toughness for the newly developing welding metals for X120 pipe girth welding [63,64].

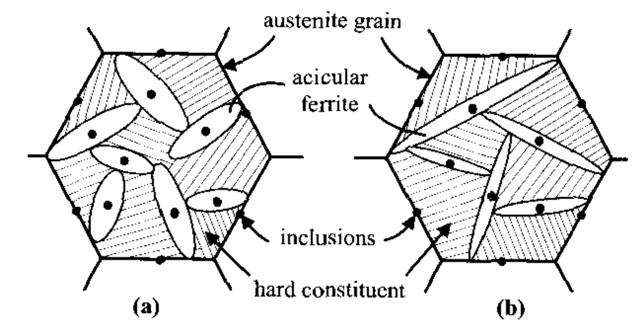

Figure 52. Innovation on the girth welding technique and metals for the X120 grade pipe steel. Schematic of the AFIM microstructure of the AFIM microstructure, (a) lower Pcm morphology , (b) higher Pcm morphology [63,64].

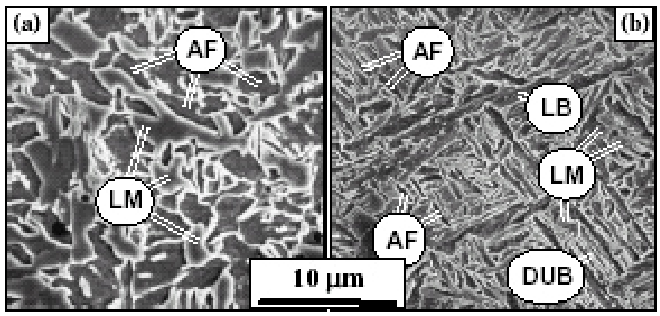

Figure 53. SEM of acicular interspersed in martensite (AFIM). (a) lower Pcm morphology 36 % AF, (b) higher Pcm morphology; 14 % AF [63,64].

Besides, there are other new developments in pipe steels which are worthy. These include oxide metallurgy, i.e., the steel containing TiO to dramatically improve the toughness of its (HAZ) heat affected zone (Fig. 54) [69].

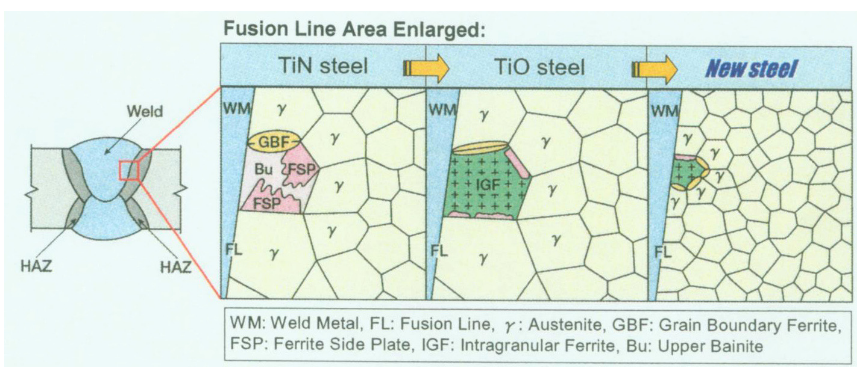

Figure 54. Schematic of the TiO containing and advanced TiO contained steel to dramatically improve its HAZ toughness [69].

Additionally special pipe steels with higher deformability than that of the conventional pipe steels are now available (Figure 54). These are especially suitable for line pipe laid in seismic regions where the pipe needs to have higher resistance to bucking under large strains induced by earthquakes. A new microstructure controlling process was developed to give the steels dual phase microstructure which contain harder second phase. Steels such as Grade X100 pipe steels possess Bainitic microstructure with dispersed Martensite – Austenite hard phases in the matrix. Their η values ($\sigma=A\varepsilon^{\eta}$) are raised from the conventional pipe steel ≤ 0.09 to values higher than 0.016 [70 – 72].

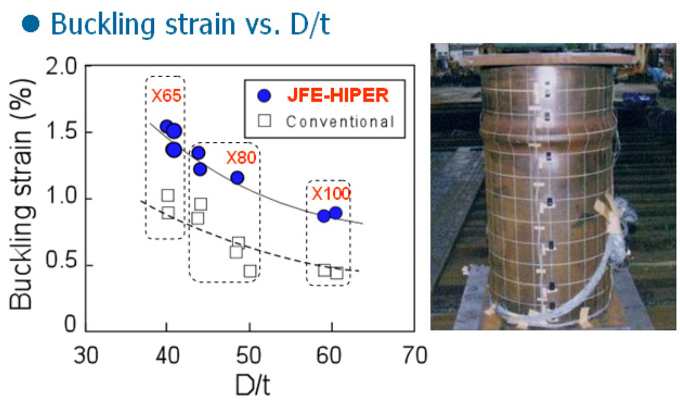

Figure 55. The JFE hiper pipe steel series with high deformability than the conventional pipe steel series. [70,71]

Research on resistance to the mechanical damage show that Grade X100 grade has higher resistance to mechanical damage than the lower grades of pipe steel, e.g., Grade X65 grade pipe steel. is a meaningful result concerning pipeline integrity [74].

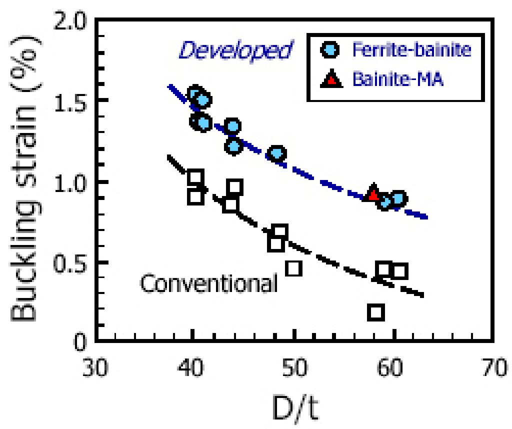

Figure 56. Relation between buckling strain and diameter to thickness ratio in full scale bucking test [72].

In order to completely assure the integrity of gas transmission pipe lines layed through the geological unstable regions in the coming decade, these pipelines must be designed according the strain principle, relevant research [75 – 77], and the development of special steel pipe series with higher deformability should be arranged.

Research to prevent the ductile fracture in the high strength pipe line and the development of composite crack arresters overseas should be taken into consideration [29-36, 62,65, 74].

4. Keeping pace with progress in the pipeline industry.

One of the major experiences from the **WEGP** practice is maintaining contact with the oversea pipeline industry to study the advanced concepts and to recognize achievements in a timely way. This is not only beneficial for the Chinese pipeline industry but also an incessant stimulus for developing high performance steels in China.

Figure 57. Attendees of International conference of pipe line steel, August 2003, Langfang China

Figure 58. International Seminar Forum for X100 / X120 Grade High Performance Pipe Steels, 28-29, June 2005, BEIJING China.

Since 2000 there have been four International conferences concerning microalloying steel for the Oil and Gas Industry arranged by the China Petroleum Storage and Transportation Society, i.e. “International Seminar on Ductile Fracture and Prevention in High Pressure Gas Transmission Pipeline”, Oct.25-27, 2000, BEIJING China, “International Conference on Line Pipe Steel”, August 2003, Langfand China, ““International Seminar on Construction Storage”, 1-2 June, 2004 Beijing China and “International Seminar Forum of Grade X100 / X120 high performance pipe steels”, 28-29 , June 2005, BEIJING China..

Figure 59. International Seminar Forum concerning X100 / X120 Grade High Performance Pipe Steels, 28-29, June 2005, BEIJING China.

Summary

1. As a consequence of the energy supply bottlenecks and environment pollution becoming problems in Chinese development, economically delivering natural gas through pipeline from remote Western desert or neighboring countries to the Eastern economical region has become an urgent problem to be solved.

2. Since 2000, the progress in high performance linepipe steel has been aided by the rapid development in the pipeline industry. High strength linepipe steel called Acicular Ferrite / Bainite Steel was successfully developed and widely applied in high pressure trunk gas line in China.

3. The Acicular Ferrite / Bainite exhibits a special morphology of low carbon upper bainite, present in microalloyed TMCP steel. The so called acicular ferrite steel consists of aciaular ferrite/bainite, polygonal or granular ferrite and retained auatenite / martenite which is consistent with the research by Korean scientists and similar to those of so called residual – austenite (RA) steel in the family of multiphase steels for automobile manufacture..

4. In acicular ferrite steel, neither the size of prior austenite grain nor the cellular substructure separated by low angle boundaries in the steel matrix is the decisive factor for toughness. The toughness of acicular ferrite chiefly depends on the domain or packet size in the matrix which is separated by the high angle (≥10° or 12°) boundaries. Additionally, the retained austenite / martensite film existing between the lath boundary and the dispersed precipitations of microalloy element's carbonitrides of niobium, titanium and vanadium, play import roles in the strengthening and toughening of steel.

5. The Acicular Ferrite / Bainite high strength pipe steel with yield strength YS≥530-630 MPa and good field welding behavior used for the present West – East gas transmission pipeline construction, is essentially corresponds to Grade X80 steel both in its strength level and microstructural characteristics. The project adopted the steel as a 490 MPa, (X70) strength grade, for purpose of design yield strength in view of the yield strength lost due to Bauschinger

effects during spiral pipe forming and specimen preparation.

6. Now, the actual strength of the acicular ferrite pipe steels used in China, either YS≥530-630 MPa as X70 or higher as X80 have been limited due to getting overmatched girth weld using the conventional girth welding materials and techniques. In view of the complicated geology of this country, methods to achieve over matching girth weld joint should be a prerequisite for widely applying the acicular ferrite steel above the present strength levels.

7. The expense to delivery large values of natural gas from the West remote reservoirs to the Eastern, Southeastern and Northeast China by pipeline using present grades of pipe steel, X70 or X80, is not competitive with delivering the gas from offshore and import LNG by barging.

8. Recent researches by ExxonMobil and BP concerning reduction in pipeline costs are inspiring. These companies took comprehensive measures, redesigned the pipelines to higher pressure and higher strength steels. They researched the steel matrix and welding technique which are disengaged in previous technical studies. Their results are particularly meaningful for exploitation of the natural gas reservoirs in remote western plateau China.

9. There are a series of material developments which must be done before applying higher strength linepipe, these include research and reconstruction of the relevant facilities in China steel and pipe plants. Contemporary pipe steels have a domain base microstructure. Research on pipe steels should go more deeply into the relationship between the domain properties and TMCP techniques.

10 In order of completely assure integrity of future high pressure gas transmission pipe lines, research to prevent ductile fracture in the high strength pipeline including the developing of composite crack arrester should be taken into consideration.

11. In view of the complicated geology in China, the pipelines crossing the geologically unstable regions must be designed according to strain based principles and applying steels having higher deformability.

12. An important experience from having rapidly developed high performance line pipe steel in China is the ability to keep pace with the frontal advance of pipeline industry in the world.

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Tables

Table 1 Forecast of Crud and Gas Demand in China

Year	**Crude Oil** **Million Tons / year**		**Natural Gas** **0.1 Billion** **Cub Meters/year**	
	Demand	**Import**	**Demand**	**Import**
2000	**2.1**	**0.696**	**200**	
2010	**3.8**	**1.87**	**1000**	**200**
2020	**4.9**	**2.95**	**2000**	**400**

Table 2. Chemical Composition of X70 Acicular Ferrite Steels

Steel Plant (Alloy system)	C	Mn	Si	P	S	Ni	Cr	Mo	Nb	V	Ti	Cu	Ceq	Pcm
Domestic plant A coil (Cu-Ni-Mo-Nb-V-Ti)	0.06	1.39	0.26	0.015	0.004	0.14	N.R.	0.18	0.07	N.R.	N.R.	N.R.	0.36	0.16
Domestic PlantB Coil (Cu-Ni-Mo-Nb-V-Ti)	0.04	1.50	0.21	0.01	0.002	0.20	N.R.	0.23	0.05	N.R.	N.R.	N.R.	0.37	0.16
Domestic Plant C Coil (Cu-Ni-Mo-Nb-V-Ti)	0.06	1.48	0,.2	0.008	0..00 2	N.R.	N.R.	N.R.	0.06	N.R.	N.R.	N.R.	0.36	0.16
Domestic plant C Plate (Cu-Ni-Mo-Nb-V-Ti)	0.07	1.48	0.25	0.015	0.003	N.R.	N.R.	N.R.	0.06	N.R.	N.R.	N.R.	0.36	0.16
Domestic plant D Plate (Cu-Ni-Nb-V-Ti)	0.06	1.54	0.34	0.01	0.004	N.R.	N.R.		N.R.	N.R.	N.R.	N.R.	0.39	0.18
Posco* Coil (Cu-Ni-Mo-Nb-V-Ti)	0.05	1.47	0.21	0.10	0.002	0.20	N.R.	N.R.	0.06	N.R.	N.R.	N.R.	0.38	0.15
WE Gas Project Spec.	≤ 0.09	≤ 1.65	≤ 0.35	≤ 0.020	≤ 0.005	≤ 0.30	≤ 0.25	≤ 0.30	≤ 0.08	≤ 0.06	≤ 0.025	≤ 0.30	≤ 0.42	≤ 0.21
Alliance Spec.	≤ 0.05	≤ 1.85	≤ 0.40	≤ 0.015	≤ 0.005			≤ 0.30	≤ 0.05	≤ 0.07	≤ 0.02		≤ 0.43	≤ 0.20
SE Asia Pacific Submarin Spec. (Cu-Ni-Nb-V-Ti)	≤ 0.07	≤ 1.6	≤ 0.40	≤ 0.02	≤ 0.006	≤ 0.25		≤ 0.01	≤ 0.05	≤ 0.07	≤ 0.02	≤ 0.03	≤ 0.41	≤ 0.23

* $V + Nb + Ti \leq 0.15$ $Ni + Cr + Cu \leq 0.50$. $N \leq 80$ ppm , $Ceq = C + Mn/6 + (Cr + Mo + V)/5 + (Cu + Ni)/15$

$Pcm = C + Si/30 + (Mn + Cu + Cr)/20 + Ni/30 + Mo/15 + V/10 + 5B$, N.R. – Not Reported

* Posco is from South Korea

Table 3. The strength of TMCP AF pipe steels from steel plants used for West-East Gas Project.

Steel Plant	YS(Mpa)	TS (Mpa)	YS/TS	EL %
Domestic Plant A 14.7mm Coil	532- 601 / (562)	626-698/ (654)	0.79- 0.91 / (0.86)	36-46/(42)
Domestic Plant B 14.7mmCoil	535-580	590-640	0.89- 0.91	41-43
Domestic Plant C 14.7mm Coil	520-600	625-695	0.81-0.91	37-44
Domestic Plant D 17–27mm Plate	545-605	625-675	0.81-0.9	33-42
Domestic PlantD 17–27mm Plate	540-625/(570)	650-705/(664)	0.83- 0.9 / (0.86)	29-38
Posco* 14.7mmCoil	585	665	0.87	44
W-E Gas Project Spec.	530-630	≥ 570	≤ 0.90	≥ 22
API5L for X80 Steel	552-690	621-827	≤0.93	≥21

The coil steel strip is sampled along the 30ºaxial angle with the rolling direction, The steel plate is sampled along the transverse direction , * Posco is from South Korea

Table 4. Transverse toughness of TMCP X70 AF pipe steels from steel plants used for the West-East Gas Project.

Steel Plant	Akv (Joule) – 20 ºC		Shear (%)	
	Range	Average	Range	Average
Domestic Plant A 14.7mm Coil	197 - 400	317	92 - 100	99
Domestic Plant B 14.7mm Coil	288 - 294	292	100 - 100	100
Domestic Plant C 14.7mm Coil	230 - 250		100 - 100	100
Domestic Plant C 17–27mm Plate	240 - 390		100 - 100	100
Domestic Plant D 17–27mm Plate	250 - 300	296	98 -100	99
Posco(Korea) 14.7mm Coil	283 - 312	294	83 – 100	95
W-E Gas Project Spec. at - 20 ºC	≥ 135	≥ 180	≥ 90	≥80

Table 5. Strength of Φ1016 × 14.6 mm X 70 Spiral Welded Pipe (Baoji Pipe Mill)

Steel Strip Resource	Sampling Position	YS MPa	TS MPa	EL%	YS/TS
Domestic Plant A Strip Coil	Pipe Body Transverse	555, 530, 555	700,700,710	41,39,48	0.79,0.80, 0.78
	Pipe Body Longitudinal	535,525	715,715	40,39	0.75, 0.73
	Welding Seam		750, 750 (Breaking in Pipe body)		
West-East Spec.		530□630	≥ 570	≥22	≤0.90

Tab.6. Charpy V-notch Toughness at -40°C Demanded by Specifications for the West – East Gas Transmission Project

Sampling Position	Shear Area Percent %	
	Single Specimen	Average Value
Pipe Body Transverse	≥ 80	≥ 90
Welding Seam & HAZ	≥ 30	≥ 40
Sampling Position	Charpy Impact Energy (10 mm × 10mm × 55mm)	
	Single Specimen	*Average Value
Pipe Body Transverse	≥ 140 J	≥ 190J
Welding Seam & HAZ	≥ 30 J	≥ 90J

- At least for three testing data

Table 7 Chemical Composition of the fatigue tested Steels.

Material	C	Mn	Si	Mo	Ti	Nb	V	P	S	O	N
X60	0.076	1.33	0.24	–	0.10	–	–	0.014	0.0032	0.0048	0.0035
X70	0.037	1.58	0.24	0.19	0.018	0.052	0.03	0.007	0.0005	0.0034	0.0040
2#	0.025	1.56	0.24	0.32	–	0.039	0.019	0.002	0.0006	0.0043	0.0062
3#	0.077	1.28	0.25	–	0.027	0.045	0.053	0.001	0.0006	0.0011	0.0018

Table 8 Mechanical Properties of Fatigue Tested Steels

Steel	σb (MPa)	σs (MPa)	δ (%)	CVN * (J) –40°C
X60	519	454	29	64
X70	660	560	25	94
2#-1	679	578	22	112
3#-1	660	587	24	80
2#-2	650	588	24	148
3#-2	639	576	26	136

Sub size specimen (5×10×55mm)

Table 9 Low Frequency Fatigue Life Results

Steel	Loading (MPa)	Fatigue Life (cycles)
X60	372	26,482
X70	410	37,310
2#-1	416	27,758
3#-1	422	29,434
2#-2	423	44,983
3#-2	415	44,626

Table 10. TMCP Parameter for obtaining the AF (No. A) and Ultra fine (No. B) microstructures

	Schedule I—No. A					Schedule II—No. B				
Interpass reduction distribution, mm	60-44	44-32	32-22	22-12	12-8	40-26	26-15	15-7.5	7.5-3.8	3.8-1.9
Rolling temperature, °C	1100	1080	950	930	820	1000	900	820	820	820

Table 11. The Mechanical Properties of the AF steel and ultra-fine ferrite steel

Microstructure	Yield strength YS, MPa	Tensile strength UTS, MPa	YS/UTS ratio	Elongation EL, %	Reduction of area RA, %	Transverse toughness a_{kv}[a], J/cm^2
No. A—acicular ferrite	529	595	0.89	27.7	85.3	398
No. B—ultrafine ferrite	477	625	0.76	27	72.6	–

[a] Tested temperature being −60 °C.

Table 12. Anti-sour behavior testing (SSC) and Scr value of pipe steels with different microstructure.

Pseudo-stress, MPa	Acicular ferrite		Ultrafine ferrite		Ferritic–perlitic microstructure	
	Number of specimen	Number of cracking specimen	Number of specimen	Number of cracking specimen	Number of specimen	Number of cracking specimen
90% YS	2	0	2	0	2	0
630	2	0			3	0
700			2	0		
770	2	0			3	0
840			2	0		
910	2	0			5	0
1000			2	0		
1050	2	0	2	0	4	3
1120	3	0	3	0	3	3
1260	3	0	2	2	2	2
S_c, MPa	more than 1260		1190		1008	

Table 13. Chemical composition of X80 steel spiral pipe and UOE pipe (%)

Specimen	C	Si	Mn	P	S	Cu+Cr+Mo+Ni	V+Nb+Ti	Ceq	Pcm
Spiral Pipe	0.065	0.24	1.85	0.011	0.0028	≤ 0.8	≤ 0.1	0.47	0.20
Weld Metal Of Spiral Pipe	0.066	0.31	1.62	0.013	0.0036	≤ 0.7	≤ 0.1	0.43	0.20
UOE pipe	0.040	0.31	1.75	0.011	0.001	≤ 0.7	≤ 0.1	0.41	0.17

$$Ceq = C + Mn/6 + (Cr + Mo + V)/5 + (Cu + Ni)/15$$
$$Pcm = C + Si/30 + (Mn + Cu + Cr)/20 + Ni/30 + Mo/15 + V/10 + 5B$$

Table 14. Mechanical Properties of X80 spiral and UOE pipe (Transverse)

Sample From	YS (MPa)	TS (MPa)	EL (%)	YR (%)	Impact Energy (Joule) –20°C	DWTT ≥ 85%	Weld TS(MPa)
APL 5L for X80	552-690	621-827	≥ 21	≤ 93			620-870
Spiral Pipe	572	755	30	75	280 J Pipe Body 150 J Weld Meta 280 J HAZ Zone	≤ 20°C	829 at BM
UOE Pipe	623-629	707-709	37-38	88 89	418 J Pipe Body 163 J Weld Metal 231 J HAZ Zone	≤ 20°C	735-745 at BM

Table 15 Mechanical properties of X70 AF steel coil from Domestic Steel Plant A

Item	YS MPa	TS MPa	EL %	YS/TS	CVN(J) -20°C	Hv_{10}	DWTT SA% -15°C
Average	562	654	42	0.860	317	218	99.7
Maximum	601	698	46	0.919	400	255	100
Minimum	532	626	36	0.795	197	205	92
Spec. Of WEGB	530-630	≥570	≥22	≤0.92	≥190	≤260	≥85
API 5L For X80	552-690	621-827	≥21	≤0.93			

Table 16 The Price and Strength Balance of X 70 - X 120 Pipe Steels

Steel Grade	Price Ratio (X70 as 100 %)	Strength Ratio (X70 as 100 %)
X 70	100 %	100 %
X 80	105 - 110 %	114 %
X100	115 - 120 %	143 %
X120	130 - 145 %	171 %