CRACK ARRESTABILITY OF HIGH-PRESSURE GAS PIPELINES BY X100 OR X120

Authors

Izumi TAKEUCHI
Hiroyuki MAKINO
Shuji OKAGUCHI
Nobuaki TAKAHASHI
Akio YAMAMOTO

Sumitomo Metal Industries Lt., Japan
ABSTRACT

The demand of natural gas has been increasing. To meet the growing demand of natural gas, new gas fields must be developed. The transportation cost of gas to market is an important factor for the development of new gas fields, which are located in remote area. High-pressure gas pipelines by high strength steel pipes have been focused to find the solution of it. API grade X100 and X120 line pipes for high-pressure gas pipeline have been successfully developed and the application technologies have been studied to construct safe and economical pipelines.

High quality steel and TMCP (Thermo-Mechanical Control Process) technology in plate rolling made it possible to achieve high strength and high toughness of X100 or X120 grade large diameter line pipes. Optimum steel chemistry for high strength and high toughness has been selected to maintain good weldability. Lower cooling finishing temperature has been applied to get higher strength. Pipes produced by UOE process were proved to meet X100 or X120 grade high strength line pipes for high-pressure operation.

One of the key issues for the application of these high strength line pipes is the arrestability of propagating ductile fracture in high-pressure gas pipelines. A series of full scale burst tests were conducted to evaluate the arrest energy for high strength line pipes. It was reported that the prediction of arrest energy based on the previous experiments with conventional grade pipes was not suitable to apply in X100 or X120 line pipes and intrinsic arrest of propagating ductile fracture in high pressure pipelines was hard to achieve. The discussion was started on the necessity of crack arrestors in high-pressure gas pipelines. However the arrest energy depends on pipe arrangement in the burst test and the possibility of intrinsic arrest of X100 or X120 pipes is revealed by the HLP (High-strength Line Pipe committee in ISIJ) simulation method.
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7. SUMMARY
1. INTRODUCTION

One of the barriers to increase natural gas supply to market is the transportation cost. High-pressure gas pipelines are expected to give a solution to it. High strength steel pipes have an advantage to transport gas in high-pressure, as high strength steel pipes result in less steel consumption and less construction cost comparing to ordinal API grade line pipes, whose highest grade is X80.

The development of X100 and X120 grade line pipes for high-pressure gas pipelines has been conducted as the common interest of steel manufactures and major oil companies\textsuperscript{1-3}. The steels for higher strength line pipes are state-of-the-art products of pipe manufactures. Lean chemistry is selected from the viewpoint of weldability and alloy cost. The accelerated cooling technology has been investigated to achieve strength and toughness, which are essential requirements to line pipes. The properties of pipes produced by UOE process are carefully investigated for safe operation under high pressure\textsuperscript{4,5}.

One of the critical issues in high-pressure gas pipelines is the arrest of propagating ductile fracture. Propagating ductile fracture is the unique fracture mode in high-pressure gas pipelines. To estimate the arrest energy against propagating ductile fracture in high-pressure gas pipelines, series of burst test conducted in conventional manner of test procedure by X100 or X120 are reviewed. The possibility of intrinsic arrest of X100 or X120 in realistic pipelines will be presented.

2. DEVELOPMENT OF X100 AND X120 STEEL FOR LINE PIPES

The target tensile properties of X100 and X120 were selected to be 690 MPa (SMYS) and 760 MPa (SMTS) for X100 and 827 MPa (SMYS) and 931 MPa (SMTS) for X120, as there is no specification for X100 or X120 in current API 5L.

Traditionally quench and tempered process was employed to get high strength of X100 or X120 grade. However the capacity of heat treatment process is not sufficient to adopt for line pipe steel production, as large amount of high quality steel is required in short delivery period. Firstly high strength steels, which are suitable for TMCP (Thermo-Mechanical Control Process), have to be developed. The microstructure of X70 grade steel consists of ferrite and pearlite/bainite. Lower transformation microstructure such as martensite and lower bainite is required to increase strength and fine low carbon martensite and lower bainite dominant microstructure is essential to achieve adequate fracture toughness at the strength level over 900 MPa. In order to maximize austenite hardenability while keeping the Pcm low for enhanced weldability, low carbon Mo-Nb bearing and boron free steel and low carbon Mo-Nb bearing steel with a minute amount of boron were designed for X100 and X120, respectively.

Figure 1 illustrates the continuous cooling transformation diagrams after hot deformation of 0.06\%C-Mn-Cu-Ni-Mo-Nb-Ti steel (Pcm = 0.20 \%) and 0.05\%C-Mn-Cu-Ni-Mo-Nb-V-Ti-B steel (B = 10 ppm, Pcm = 0.20 \%). The figure shows that addition of 10 ppm of B suppressed the ferrite formation entirely, and
lowered the bainite transformation temperature. After accelerated cooling (> 20 K/s), bainitic ferrite with martensite and lower bainite composed the microstructure of the boron free steel, and martensite and lower bainite dominate microstructure of boron bearing steel. According to hardness test, Hv 280 for boron free steel and Hv 320 for boron steel were observed, so they are suitable for X100 and X120 tensile strength, respectively.

Figure 2 shows the effect of the cooling finishing temperature (CFT) in TMCP on tensile strength and ductile to brittle transition temperature (vT5) of Charpy test of 16 mm thick plate. Tensile strength and vT5 are improved by lowering the CFT from 500 °C to below 300 °C. The low CFT below 300 °C is stable range for production in terms of strength and toughness. 0.06%C-Mn boron free steel can meet X100 and 0.05%C-Mn-boron steel can meet X120 grade. In order to achieve optimum properties, the precise control of rolling conditions such as re-heating temperature, reduction rate in austenite and cooling start temperature are required in addition to CFT.

Heat affected zone (HAZ) toughness is an important property of steel for welded large diameter pipes. Steel chemistry must be optimized for SAW welding in UOE process. The carbon and silicon contents were controlled in low level to minimize the amount of MA (Martensite-austenite) constituent. Microalloys (Nb, V and Ti) were carefully selected to help control of MA, restrict grain growth and adverse precipitation effects. Nitrogen, phosphorus and sulfur contents were reduced to gain cleanliness, and the hardenability was controlled to ensure fine lath base microstructure in HAZ during weld thermal cycle.

3. PROPERTIES OF X100 AND X120 LINE PIPES

Prototype X100 and X120 line pipes were produced in Sumitomo Metal's Kashima Steel Works. The converter of 250 tones was used to melt the steels and vacuum degassing was employed. Slabs for plate were made by the continuous caster. The steel for X100 is 0.07%C-1.83%Mn-(Cu-Ni-Cr-Mo-Nb-Ti) and the steel for X120 is 0.05%C-1.56%Mn-(Cu-Ni-Cr-Mo-Nb-V-Ti-B). The Pcm for the steel are 0.21 % for X100 and 0.20 % for X120, respectively. TMCP was applied in plate rolling with strict control of rolling and cooling conditions to achieve optimum microstructure for each grade. The pipes were produced by UOE process with double submerged-arc welding (SAW). The pipe sizes are 914 mm OD (Outer diameter) X 19 mm thick of X100 and 914 mm OD X 16 mm thick of X120.

Table 1 summarizes the tensile properties in transverse direction as average value of over 20 joints. The hoop tensile properties of line pipes were measured by flattened strip specimen and un-flattened round bar specimen. The YS and TS measured by both specimens meet the target properties of X100 or X120. The flattened strip specimen has been employed for line pipes according to API 5L specification. However in case of X100 or X120 the yield strength measured by un-flattened round bar specimen is around 110 MPa higher than by flattened strip specimen. It is reported that the Bauschinger effect is not ignored in case of X100 or X120. The yield strength by round bar specimen is more reasonable value to evaluate the pipe strength. It is proved that the strength of pipes can meet X100 or X120 grade, though the Y/T ratio exceeds 0.93, which is current requirement in API 5L for line pipes. Hydrostatic burst test was conducted to confirm the burst stress of X100 and X120 high strength line pipe. Burst stress in hydrostatic burst test is also shown in the same table. The burst stress reasonably coincides with tensile stress of base metal.
Table 2 shows the Charpy impact test and DWTT result. Transition temperature is low enough to keep share area of DWTT at $-10\,^\circ\text{C}$ more than 85%. Absorbed energy in base metal at $-10\,^\circ\text{C}$ or $-30\,^\circ\text{C}$ is over 250 J in both grades. The absorbed energy is the key factor to estimate arrestability of propagating ductile fracture in high-pressure gas pipelines. The absorbed energy increases depending on sulfur content in X100 as the same manner of conventional grades. Low C and low sulfur steel is essential for high strength line pipe. The Charpy absorbed energy in HAZ and weld metal are enough high for low temperature service.

4. REVIEW OF FULL-SCALE BURST TESTS USING X100 OR X120 LINE PIPES

4.1 ECSC Program on X100\(^7,8\)\)

A research program on behalf of ECSC (European Coal and Steel Community) had been carried out by a joint co-operation among CSM, SNAM and Europipe. This research program included two full-scale fracture propagation tests on X100 pipes. The two tests were undertaken in 1998 and in 2000 at the CSM Perdasdefogu test site in Italy. The pressurizing medium was air. Each test results are shown in Figure 3(a) and 3(b), respectively.

In the 1\(^{\text{st}}\) ECSC test, 56" diameter 19.1 mm wall thickness pipes pressurized to 12.6 MPa corresponding to 68 % SMYS, the crack on the west side propagated through the initiation pipe but split in two different cracks at the girth weld with the adjacent pipe. The two separate cracks, after running about 200 mm along the weld joint, went back in the base metal till they joined causing the severance of the test line and the ejection of the pipe No.6129 out of the trench. The premature severance invalidated the result from the west side. On the east side, the crack propagated through the initiation pipe and entered in pipe No.6058 where propagated and in pipe No.6157 where it arrested at the end of the pipe.

In the 2\(^{\text{nd}}\) ECSC test, 36" diameter 16.0 mm wall thickness pipes pressurized to 18.1 MPa corresponding to 75 % SMYS, the crack on the west side propagated with a maximum speed of about 310 m/s and arrested in the last pipe No.9447. The crack on the east side propagated with a maximum speed of about 300 m/s and entered in the following pipe No.9456 where it arrested after about 5 meters progress.

4.2 ExxonMobil X120 Test\(^9\)\)

In 2000, a full-scale fracture propagation test using X120 pipes was carried out by CSM on behalf of ExxonMobil. The pressurizing medium was lean natural gas containing approximately 98 % methane. Test results are shown in Figure 3(c). In this test, 36" diameter 16.0 mm wall thickness pipes pressurized to 20.85 MPa corresponding to 72 % SMYS, a loose sleeve crack arrestor (X65, length 2.0 m, thickness 19 mm, clearance 9.5 mm) was placed in pipe 3E. The initiated crack propagated to both ends of the test section indicating insufficient toughness in pipe for intrinsic arrestability at the test conditions and the ineffectiveness of the loose sleeve crack arrestor. The measured crack speed ranged between 350 and 280 m/sec.

4.3 Advantica’s JIP on X100\(^{10}\)\)


A Joint Industry Project had been undertaken by Advantica, sponsored by Alliance Pipeline, BG, BP and TransCanada Pipelines. This project included two full-scale fracture propagation tests on X100 pipes. The two tests were undertaken in 2001 at Advantica’s Spadeadam test site in UK. Both tests used lean natural gas containing approximately 96% methane as the pressurizing medium. Each test results are shown in Figure 4(a) and 4(b), respectively.

In the Advantica’s JIP No.1 test, 36” diameter 13.0 mm wall thickness pipes pressurized to 13.6 MPa corresponding to 69% SMYS, the initiated crack propagated through two pipes and arrested in the third pipe on either side. Finally, the severance at weld joint between 4E and reservoir pipe was occurred and the section containing 4E and part of 3E pipe was left the trench.

In the Advantica’s JIP No.2 test, 36” diameter 15.0 mm wall thickness pipes pressurized 18.0 MPa corresponding to 80% SMYS, the crack on the west side propagated through the 1W pipe but bifurcated at the weld joint and arrested as a “ring-off”. The ring-off lifted the section of pipes containing the initiation pipe. Finally, the severance at weld joint between 2W and 3W pipe was occurred and the 2W pipe was left the trench. The premature ring-off invalidated the result from the west side. On the east side, the crack propagated through the 1E and arrested in the 2E pipe. Finally, the severance in the 3E pipe was occurred and the section of pipes containing the initiation pipe was left the trench.

4.4 DemoPipe Project on X100

The DemoPipe Project, a new ECSC program with additional sponsorship from EPRG, commenced in 2001 and the experimental activities concluded in 2003. This project included two full-scale fracture propagation tests on X100 pipes. The two tests were undertaken in 2002 and in 2003 at the CSM Perdasdefogu test site. Both tests were performed using lean natural gas containing approximately 98% methane as the pressurizing medium. Each test results are shown in Figure 4(c) and 4(d), respectively.

In the 1st DemoPipe test, 36” diameter 16.0 mm wall thickness pipes pressurized to 19.3 MPa corresponding to 80% SMYS, the initiated crack propagated to both ends of the test section indicating insufficient toughness in pipe for intrinsic arrestability at the test conditions.

In the 2nd DemoPipe test, 36” diameter 20.0 mm wall thickness pipes pressurized to 22.64 MPa corresponding to 75% SMYS, a composite crack arrestor was positioned after the last pipe in the east side (length 2.0 m, fiberglass, thickness 40 mm). The crack on the east side propagated quickly in the first pipe No.8835 after the initiation pipe, and then decreased to 120-130 m/s on the last three pipes until finally stopping at the beginning of the crack arrestor. On the west side, after the initiation pipe, the crack speed decreased to 110 m/s in the first pipe No.8831 and arrested in the middle of the second pipe No.8834.

4.5 Bp X100 Test

In 2003, a full-scale fracture propagation test using X100 pipes was carried out by Advantica on behalf of Bp. This test was executed under extreme severe conditions, since the high usage factor, rich natural gas and low temperature were acting simultaneously. In this test, composite reinforced arrestor and grouted sleeve arrestor were tested. Details of this test remain confidential to Bp at this stage. However, it may be stated that the crack propagated through the test section and stopped at the crack arrestors.
indicating insufficient toughness in pipe for intrinsic arrestability at the test conditions and the effectiveness of the composite reinforced arrestor and the grouted sleeve arrestor (X80, thickness 20.6 mm, clearance was filled with epoxy grouting).

5. SIMULATION OF PROPAGATING DUCTILE FRACTURE IN GAS PIPELINES

The propagating ductile fracture is an interactive phenomenon between gas decompression and crack propagation. Once a crack initiates, inner gas escapes from the ruptured portion of the pipeline and decompression wave proceeds in the pipeline. The crack chases after the decompression wave, so that a fast crack produces high pressure and a slow crack produces low pressure at the crack front, and the interaction determines extent or distance of the propagating ductile fracture.

Traditionally, pipelines are designed such that the toughness in pipe body is sufficient to intrinsically arrest a propagating crack. Therefore, determination of the required toughness for the arrest of propagating ductile fracture has been the focus of much research over the past thirty years. Many models and formulae have been developed for the determination of the required toughness. Among these models, the Battelle Two Curve method\textsuperscript{13} is the most popular predictive method.

In order to predict the toughness requirement, the Battelle Two Curve method takes the comparison of curves expressing the variation of crack velocity and of gas decompression velocity with pressure. If no intersection exists between the crack and the gas decompression velocity curves, gas decompression velocity exceed crack velocity for all pressure levels, the pressure at the crack front will decreases and the crack will arrests. On the other hand, if an intersection exists between the crack and the gas decompression velocity curves, the pressure level where crack and gas decompression run together at the same velocity exists, no further decrease of the pressure at the crack front is possible and crack will continue to propagate. Thus, the tangent condition between the two curves represents the boundary between arrest and propagation, and the corresponding toughness level is referred to as the arrest toughness by this Battelle Two Curve method.

The Battelle Two Curve method successfully accounted for a considerable quantity of full-scale experimental results on lower grade pipe materials (X70 and lower). However, as the strength of materials increases, direct application of this model no longer correctly predicts the required toughness. In order to extend its applicability, correction factors have been implemented to align the predicted toughness with results from full-scale experimental tests on higher grade pipe materials.

On the other hand, the HLP Committee (High-strength Line Pipe Committee in ISIJ) developed\textsuperscript{14} a simulation model for the propagating ductile fracture in pipelines from a series of seven full-scale burst tests. This HLP method is a dynamic variant of the Battelle Two Curve method and be able to calculate instantaneous crack velocity and propagating distance\textsuperscript{15}. Another feature of this method is that the constant and exponent in the original Battelle's crack velocity equation were recalibrated to accommodate pre-cracked DWTT energy per unit area directly to the index of material resistance, instead of Charpy energy per unit area. Pre-cracked DWTT energy can be converted to Charpy energy by the relationship developed by HLP Committee for the convenience of Charpy test.
Examples of simulated results of the propagating ductile fracture by HLP method are shown in Figure 5. In this figure, pipelines with even toughness arrangement are supposed and simulated fracture arrest distances (crack propagation distances) are plotted against Charpy energy of pipes used. As the Charpy energy of pipes increases, the fracture arrest distance decreases drastically showing that the fracture arrest distance is very sensitive to the toughness of pipes used. Figure 5(a) shows the effect of pipe grade and figure 5(b) shows the effect of design factor on crack propagation. Both the increase in pipe grade and the increase in design factor offer higher operating pressure but invite higher required toughness. It is notable that transporting gas composition also changes the required toughness widely, as shown in figure 5(c). The gas compositions used for these simulations are shown in Table 3.

6. INTRINSIC ARRESTABILITY OF X100 OR X120 IN REAL PIPELINES

Based on the full-scale burst tests, it becomes a common view that intrinsic arrest of X100 or X120 in pipeline is hard to achieve and in this case the use of crack arrestors may be required. However, when we estimate the intrinsic arrestability of real pipelines on the basis of the full-scale burst test results, we have to take careful considerations on the difference between real pipelines and the full-scale fracture propagation tests.

Traditionally, increasing toughness arrangement is used in the full-scale fracture propagation test. And not so much attention seems to be paid to the effect of the toughness arrangement. However, since the propagating ductile fracture is the interactive phenomenon between the gas decompression and the crack propagation, the fracture arrest toughness in test depends on the pipe toughness arrangement, in other words the crack propagation history. In particular, the toughness of the initiation pipe controls the maximum crack velocity and has a strong effect on total crack propagation length.

Figure 6 shows the effect of the increasing toughness arrangement on crack propagation. In this figure, four cases of the simulated crack propagation for different pipe toughness arrangement are compared. As shown in this figure, as the gradient of the increasing toughness arrangement becomes steeper, crack will propagate longer and the arrest toughness in test tends to increase. This tendency always exists in this kind of traditional style test. This increasing toughness arrangement used to have an effective aspect that only one test can determine approximately the required toughness for the interested operating condition of a pipeline. This effective aspect works well so far as the required toughness lies in the middle between toughness ranges available. However, in case of X100 or X120 pipes, the required toughness may lie on the upper borderline and in this case the harmful aspect of the increasing toughness arrangement comes out.

The unrealistic higher crack velocity produced from the unrealistic lower toughness initiation pipe is harmful to assess the crack arrestability of a pipeline. This effect mislead into underestimating the crack arrestability of a real pipeline with even toughness arrangement. In case of X100 or X120 pipes, this misleading may imply the misjudgment concerning the necessity of crack arrestors. Therefore, for the full-scale crack propagation test on such high grade pipes, since their arrest toughness may lie on the upper borderline, the even toughness arrangement as same as a real pipeline instead of the increasing toughness arrangement and the judgment on the basis of the total propagation length is recommended. Based on the
simulated crack propagation for even toughness arrangement, as shown in figure 6, HLP method suggest the possibility of intrinsic arrest of X100 or X120 pipes in real pipelines.

7. SUMMARY

API grade X100 and X120 grade UOE pipes for use in gas transmission pipelines have been successfully developed. The steels are low carbon, low Pcm, and contains the following alloys: Mn-Cu-Ni-Cr-Mo-Nb-Ti for X100, Mn-Cu-Ni-Cr-Mo-Nb-V-B-Ti for X120. The microstructures are fine bainitic ferrite with finer martensite/lower bainite for X100 and fine ausformed martensite and bainite for X120. The developed pipes have excellent combinations of strength and toughness in both base metal and heat affect zone of the longitudinal seam weld. The results of mechanical tests conducted on prototype pipes were satisfactory according to the target properties for X100 and X120 pipe. The burst stress of these pipes reasonably coincides with tensile stress of base metal.

To estimate the arrest energy against propagating ductile fracture in X100 or X120 gas pipelines, full-scale fracture propagation tests using X100 or X120 pipes are reviewed and analyzed. Traditionally, increasing toughness arrangement is used in the full-scale fracture propagation test. However, since the propagating ductile fracture is the interactive phenomenon between the gas decompression and the crack propagation, the fracture arrest toughness in test depends on the pipe toughness arrangement. Based on the simulated crack propagation length for different pipe toughness arrangement, HLP method reveals the possibility of intrinsic arrest of developed X100 or X120 pipes in real pipelines with even toughness arrangement.
REFERENCES

Fig. 1: CCT diagram after hot deformation of low C-Mn-Cu-Ni-Cr-Mo-Nb-Ti boron free steel and boron bearing steel (Reheating temp.: 1100 °C, Deformation: 900 °C 50% compression)

Fig. 2: Effect of cooling finishing temperature on tensile strength and Charpy impact properties of low C-Cu-Ni-Cr-Mo-Nb-V-T-B steel plates (laboratory scale test: 16mm thickness)

Fig. 3: Results of full-scale burst tests using X100 or X120 pipes -1

Fig. 4: Results of full-scale burst tests using X100 or X120 pipes -2

Fig. 5: Simulated results of the propagating ductile fracture by HLP method (pipelines with even toughness arrangement are supposed)

Fig. 6: Simulated results for the effect of pipe toughness arrangement on crack propagation

Table 1: Tensile properties (Base metal: Transverse direction) and burst stress of the X100 and X120 linepipe

Table 2: Toughness of the X100 and X120 linepipe (Transverse direction)

Table 3: Gas compositions for analysis (mol%)
FIGURES

Fig. 1: CCT diagram after hot deformation of low C-Mn-Cu-Ni-Cr-Mo-Nb-Ti boron free steel and boron bearing steel (Reheating temp.: 1100 °C, Deformation: 900 °C 50 % compression)

Fig. 2: Effect of cooling finishing temperature on tensile strength and Charpy impact properties of low C-Cu-Ni-Cr-Mo-Nb-V-T-B steel plates (laboratory scale test: 16mm thickness)
(a) 1st ECSC Test results
 Pipe Charpy V(J) 6020 6083 6129 6113 6058 6157 6061
 (ejected)
 propagation distance: 25m

(b) 2nd ECSC Test results
 Pipe Charpy V(J) 9447 9458 9460 9461 9456 9457 9446
 propagation distance: 26m 8m

(c) ExxonMobil X120 Test results
 Pipe Charpy V(J) 270 278 276 225 223 216 215 226
 propagation distance: Over55m Over35m

(a) Advantica's JIP No.1 Test results
 Pipe Charpy V(J) 264 250 184 117 126 179 254 256
 (ejected)
 propagation distance: 35m 34m

(b) Advantica's JIP No.2 Test results
 Pipe Charpy V(J) 290 256 198 174 168 185 214 294
 (ejected)
 propagation distance: 16m 25m

(c) 1st DemoPipe Test results
 Pipe Charpy V(J) 8808 8795 8797 8786 8781 8783 8780 8799
 propagation distance: over45m over45m

(d) 2nd DemoPipe Test results
 Pipe Charpy V(J) 8824 8826 8834 8831 8837 8835 8839 8836
 (Composite Crack Arrestor)
 propagation distance: abt.18.5m Over44m

Fig.3: Results of full-scale burst tests using X100 or X120 pipes -1

Fig.4: Results of full-scale burst tests using X100 or X120 pipes -2
Fig. 5: Simulated results of the propagating ductile fracture by HLP method (pipelines with even toughness arrangement are supposed)

(a) Effect of pipe grade on crack propagation

(b) Effect of design factor on crack propagation

(c) Effect of gas composition on crack propagation

Full-size Charpy energy of pipes used; $C_v$ (J)

(a) Test result (Advantice' JIP No.2 Test)

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(c) Pipe toughness arrangement (CharpyV(J))

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(d) Simulated results by HLP method

Fig. 6: Simulated results for the effect of pipe toughness arrangement on crack propagation
### TABLES

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<th>Grade</th>
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<td>Round bar speci.</td>
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<td>API strip speci.</td>
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<td>Burst stress</td>
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Table 1: Tensile properties (Base metal: Transverse direction) and burst stress of the X100 and X120 linepipe

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Table 2: Toughness of the X100 and X120 linepipe (Transverse direction)

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<td>0.02</td>
<td>0.03</td>
<td>-----</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>----</td>
<td>-----</td>
</tr>
<tr>
<td>“S gas”</td>
<td>92.00</td>
<td>4.00</td>
<td>2.00</td>
<td>0.30</td>
<td>0.50</td>
<td>0.100</td>
<td>0.050</td>
<td>0.050</td>
<td>------</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>“C gas”</td>
<td>89.57</td>
<td>4.70</td>
<td>3.47</td>
<td>0.24</td>
<td>0.56</td>
<td>0.106</td>
<td>0.075</td>
<td>0.033</td>
<td>0.026</td>
<td>0.50</td>
<td>0.72</td>
</tr>
</tbody>
</table>

Table 3: Gas compositions for analysis (mol%)