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Steam Distribution Line Pipe and Fittings for Oil Sands Development

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Synopsis :
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Steam Distribution Line Pipe and Fittings for Oil Sands Development*

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Strengths of the pipe and fittings satisfied the specifications at room temperature and 350°C. Tensile strength of the girth welded joint is almost as high as that of the parent metal, at both room temperature and 350°C.

The steel has good weldability and can be field-welded with cellulosic type electrode.

The value of 67% of the 10^5hr. creep rupture strength at 350°C is sufficiently higher than 1/3 of the tensile strength; so the allowable stress is determined simply by the tensile strength.

1 Introduction

The crude oil situation of the world has recently become much worse than predicted and the need of developing a substitute energy is stressed. There are various kinds of other energy, among which oil sands (tar sands) are one of the most promising that can take the place of conventional crude oil.

Most oil sands reserves are said to be in the State of Alberta, Canada, and in the basin of the River Orinoco, Venezuela. But there are few deposits that allow surface mining and a large number of them must depend on insitu recovery techniques[1]. In Canada, various projects have recently been developed more actively in order to establish such recovery techniques and full-scale commercial productions are close at hand[2]. For example, Esso Resources Canada, Ltd. has already completed a steam injection method without electric preheating, and is now planning to construct a commercial-scale plant of is 120–145 thousand bbl. per day in Cold Lake area[3]. And the company offers a proposal, against the recent rise in crude oil price, that the development should be promoted by means of its technique also in Athabasca area where there is more reserve[4].

The steam injection method is the one in which steam of high temperature and pressure is injected through wells to reduce the viscosity of the heavy oil so that bitumen may be obtained. The same method seems to have been adopted in the project of Shell Canada, Ltd. recently made public[5].

In order to practice such steam injection method, it is necessary to distribute the high-pressure steam from a steam plant to thousands of wells. Then there arises a question of what material should be used as the steam distribution line pipe. Steam temperature, in this case, does not require consideration of the creep effect in the steel. But if such a carbon steel pipe as ordinary A106B is used, such a heavy wall thickness steel pipe as that of 35 mm thickness would be necessary in case, for example, of 16 in. outside diameter. The use of such material would not only increase the weight of the pipe but also pose some problems in view of field weldability.

Therefore, the following matters have been comprehensively taken into account as requirements for the material.

(1) The design temperature is moderate and the creep effect can be almost negligible.
(2) Good field weldability is required as well as high strength at moderate temperature below creep range.
(3) Cheap pipes are needed in order to keep economic efficiency of oil sands.

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As a result, quenched and tempered seamless steel pipe KSC-X65M (tentatively named) for moderate temperature service has been developed as the most suitable material for the steam distribution pipeline.

This pipe, regardless of its low P_{cm} value, realizes a high strength by making active use of quench and temper treatment which has not hitherto been applied to the making of steel pipes used at elevated temperature, and, at the same time, maintains the high strength up to moderate temperature, insuring strength at 350°C. Though KSC-X65M still has something temporary in part for specification, this report intends to outline a series of experiments so far conducted for its development.

2 Specifications

2.1 Composition

Composition of KSC-X65M is specified in **Table 1.** The material is required to contain the amount of C, most harmful to weldability, as low as about 0.10%, and is an Al-killed steel with a little amount of Mo and V added.

2.2 Heat Treatment

Heat treatment is the same as usual quenching and tempering. Heating temperature before quenching is required to be maintained at about 920°C, and tempering temperature, higher than 600°C depending on wall thickness.

2.3 Strength

Specification of strengths at room temperature and at 350°C is shown in **Table 2.** This pipe insures the tensile strength higher than 80 ksi at 350°C as well as at room temperature.

3 Experimental Procedures

Before establishing the specifications, the following experiments were conducted.

First of all, 207 mmϕ billets were produced from a vacuum induction-melted 5 t ingot having the composition in **Table 3**, and these were rolled into seamless steel pipes of $6\frac{5}{8}''\phi \times 0.562''t$ (168.3 mmϕ × 14.27 mm$t$) according to an ordinary rolling schedule. The pipes were quenched and tempered as described above in order to be tested in various ways.

Steam pipeline system needs not only ordinary straight pipes but also fittings suitable for them. Therefore, the following three kinds of fittings were manufactured from some of the above $6\frac{5}{8}'' \times 0.562''$ seamless steel pipes in cooperation with a fitting manufacturer.

Table 1 Specification of chemical composition for steam distrisbution line pipe

(wt%)

C	Si	Mn	P	S	Mo	V	Al	P_{cm}
Max. 0.14	Max. 0.50	Max. 1.50	Max. 0.025	Max. 0.015	Max. 0.30	Max. 0.060	Max. 0.060	Max. 0.23

$P_{cm} = C + Si/30 + (Mn + Cu + Cr)/20 + Mo/15 + Ni/60 + V/10 + 5B(\%)$

Table 2 Specification of tensile properties

Temperature	Yield strength, min.		Tensile strength, min.		Elongation, min. in 2 in.
°C	ksi	kgf/mm²	ksi	kgf/mm²	%
R.T.	65	45.7	80	56.2	$625\,000\frac{A^{0.2}}{U^{0.9}}$
350	56	39.4	80	56.2	

A : Cross sectional area of the specimen (in²)
U : Specified tensile strength (psi)

Table 3 Chemical composition of the steel investigated

(wt%)

C	Si	Mn	P	S	Mo	V	Al	N
0.12	0.31	1.35	0.013	0.004	0.09	0.033	0.022	0.0037

Elbow ......8″B × Sch. 80
Tee ....4″B × Sch. 80
Reducer......6″B × 4″B × Sch. 120

After giving the fittings the same quenching and tempering as were given to the pipes, their properties were investigated.

The tempering condition both for the pipe and for the fittings is about 17 500 calculated in terms of tempering parameter, $T(20 + \log t)$.

In case of quenched and tempered steel, one of the characteristics is the local softening of weld heat affected zone. Using the above-sized pipe after the heat treatment, girth-welded joints were made and the properties of the weld zone were investigated.

Fig. 1 shows specimens used for tensile tests in order to determine the strength of these pipes, fittings and girth welds. For the pipe, Type 1 specimens were taken parallel to pipe axis. Type 2 specimens were used for tensile tests of the girth weld. Since fittings had complicated shapes, their strengths were examined with Type 3 round specimens.

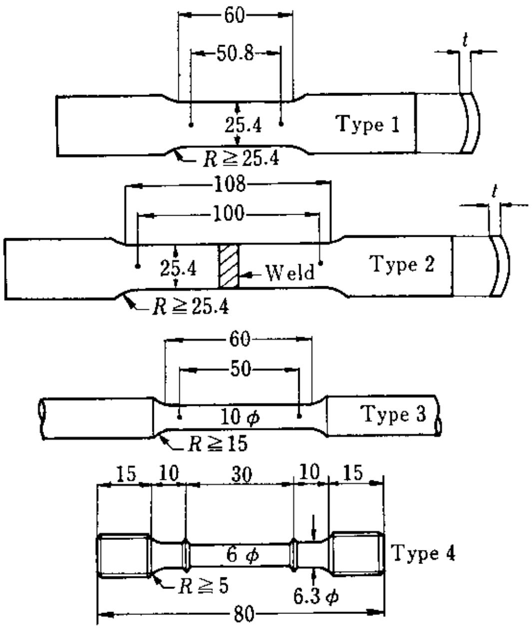


Fig. 1 Specimens used for tensile tests at room temperature and elevated temperatures

In addition to the tests of the above three types at room temperature, elevated temperature tensile tests were given to each of the pipe, fittings and girth weld, using Type 4 specimens within the range between room temperature and 550°C. Strain rate was about 0.25%/min in the vicinity of 0.2% proof stress, and about 7.5%/min in the vicinity of maximum load.

As for the fittings having complicated shapes, tensile test specimens were taken after flattening and subjected to a 600°C × 20 min SR in order to remove the influence of work hardening. Charpy impact specimens 10 mm × 10 mm size were taken without flattening for each of the pipe, fittings and girth weld. **Fig. 2** shows the positions in the fittings where tensile or Charpy specimens were taken.

As these pipes and fittings are to be used at elevated temperature, softening characteristic for reheating seems to be important. Therefore, the pipe after QT was reheated at various temperatures and Type 4 specimens were taken from it, in order to investigate how much the strengths at room temperature and at 350°C decrease due to reheating.

To examine the weldability of the pipe, Battelle type underbead cracking tests and maximum hardness tests were conducted with various heat inputs.

For the underbead cracking test, a bead of 1.5 in. length was placed on the inside wall of the pipe in circumferential direction, using cellulosic type electrode (HYP) or low hydrogen type electrode (KS86), and its

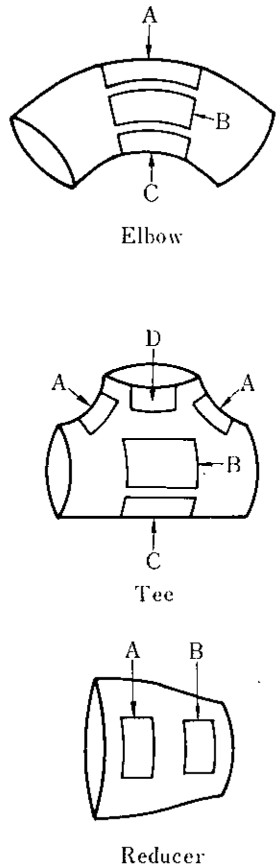


Fig. 2 Specimens positions in the fittings

section was observed under a microscope of 100 magnification. In case of the maximum hardness test, a bead along the axial direction was placed on the outside wall of the pipe with various heat inputs and Vickers hardness was measured immediately under the bead.

Creep tests and creep rupture tests with a specimen of outside diameter 6 mm and gage length 30 mm are not completed as yet. Therefore, this paper reports on only rupture strengths obtained hitherto.

4 Test Results

4.1 Pipe Strength at Room Temperature

Table 4 shows the pipe strength at room temperature.

Table 4 Tensile properties of the pipe at room temperature

Y.S.		T.S.		El.
ksi	kgf/mm²	ksi	kgf/mm²	%
82.9	58.3	94.7	66.6	37.3

Specimen : Type 1

ture tested with Type 1 specimens. The result shows the average value of four specimens, and all individual values satisfied the specification of **Table 2** with sufficient allowance.

4.2 Charpy Impact Properties of Pipe

Fig. 3 shows the Charpy impact test results of the pipe. Each plot is the average value of three specimens. Probably because of the precipitation hardening $_{v}Trs$ in C-direction (transverse to the pipe axis) is a little high compared with usual quenched and tempered steel. But, owing to the low sulfur content, absorbed energy values are rather high down to a low temperature range even in the C-direction. The temperature is supposed to fall to about −30°C during construction, but the steel has sufficient toughness and is suitable for the use in a cold district.

4.3 Elevated Temperature Tensile Properties of Pipe

Type 4 specimens were taken along the pipe axis (L-direction) and elevated temperature tensile tests were conducted within the range between room temperature and 550°C. The results are shown in **Fig. 4**.

Generally when such a specimen having a small section is taken from the center of the wall thickness, the strength tends to be lower than that of the full thickness specimen of Type 1. But even in this case, the strength measured sufficiently meets the specification in **Table 2**. As shown in **Fig. 4**, yield strength and tensile strength at 350°C sufficiently exceed their specified minimum value 56 ksi (39.4 kgf/mm^2) and 80 ksi (56.2 kgf/mm^2), respectively.

In the case of ordinary carbon steel, the peak of tensile strength is usually in the vicinity of 250°C, but this steel has it in the vicinity of 300°C. The difference may be due to the addition of the small quantity of Mo and V. And because this steel contains such elements as Al and V which fix free nitrogen, the peak strength is not extremely high.

On the other hand, the decrease of yield strength in the range from room temperature to moderate temperature is less than that of normalized steel, and this may be one of the characteristics of quenched and tempered steel.

4.4 Strength of Fittings at Room Temperature

Table 5 shows the strengths of fittings obtained with round specimens of Type 3. Each value is the average of two specimens. Compared with pipe strength of **Table 4**, each of the elbow, tee and reducer is found to have almost the same strength as that of the pipe, regardless of the directions or positions where specimens were taken.

4.5 Charpy Impact Properties of Fittings

Figs. 5–7 show results of Charpy impact tests of the fittings. Each plot is the average value of two or three specimens. The directions L and C show those of specimens in the original pipe before formed into fittings.

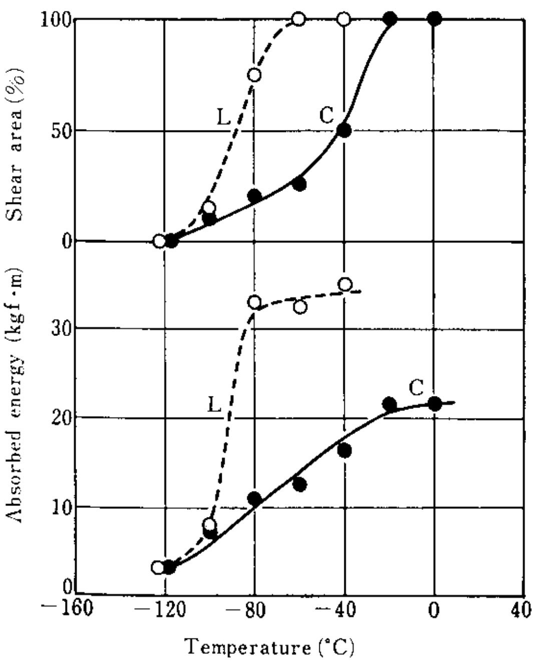


Fig. 3 Charpy impact properties of the pipe

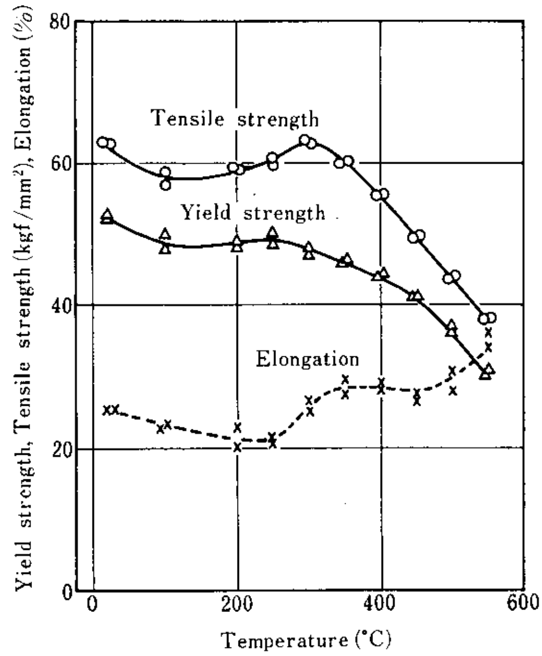


Fig. 4 Tensile properties of the pipe at elevated temperatures

Table 5 Tensile properties of the fittings at room temperature

Type of fitting	Position	Direction	Y.S. (kgf/mm²)	T.S. (kgf/mm²)	El. (%)
Elbow	A	L	58.1	67.4	20.5
		C	55.8	64.9	21.1
	B	L	58.4	67.0	19.5
		C	56.5	65.6	20.5
	C	L	53.8	63.8	20.7
		C	58.0	67.3	20.8
Tee	A	C	58.1	64.9	19.8
	B	L	56.2	65.5	21.4
	C	L	56.5	65.2	23.9
		C	57.3	64.6	21.3
Reducer	A	C	54.5	62.7	21.0
	B	C	55.6	63.5	22.5

Specimen : Type 3

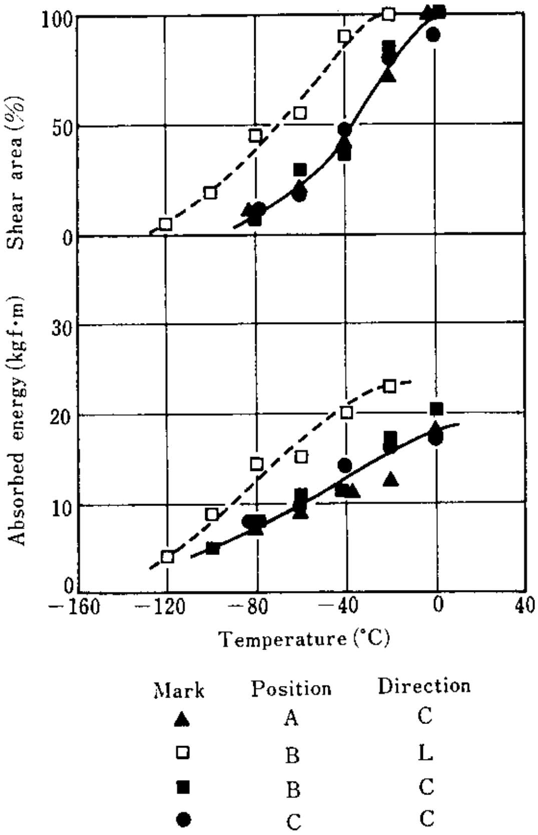


Fig. 5 Charpy impact properties of the elbow

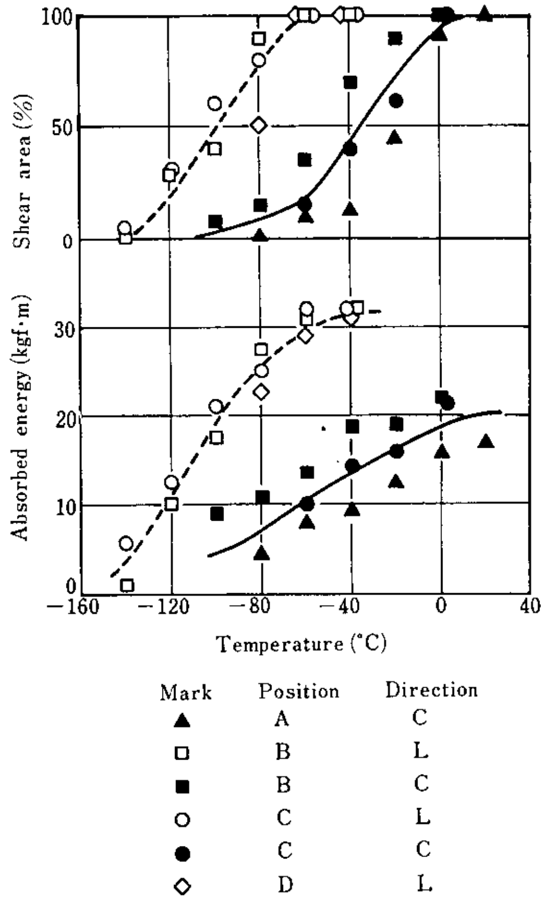


Fig. 6 Charpy impact properties of the tee

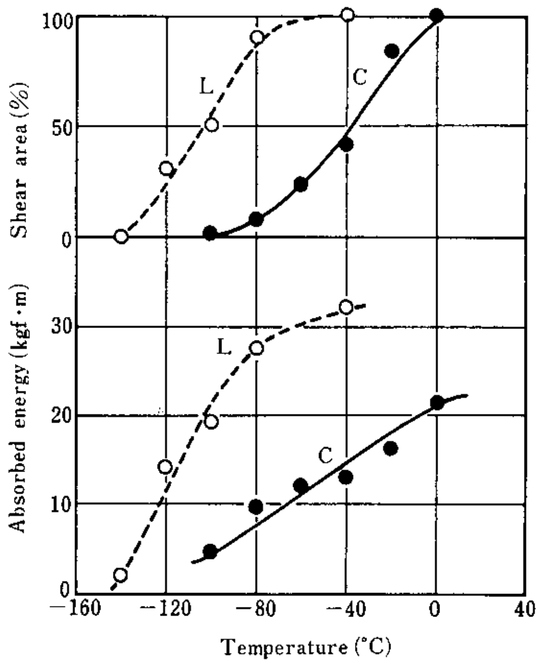


Fig. 7 Charpy impact properties of the reducer

There is some variation in the results depending on the positions where specimens were taken. But, the test results are more largely influenced by the direction of specimens in the original pipe than by the positions. In the C-direction of the tee, the toughness is slightly poor at the throat (A part) where the given working is considered the severest.

On the whole, the results show sufficient toughness at 0°–-40°C for the use in a cold district.

4.6 Elevated Temperature Tensile Properties of Fittings

Figs. 8–10 show the results of tensile tests of the fittings within the range between room temperature and 550°C by using Type 4 specimens.

Sampling position of specimens were as follows: for the elbow from crotch side, for the tee from run pipe, and for the reducer from small diameter side; all in L-direction.

From these Figures, it can be seen that the strengths of the fittings at room temperature and at 350°C meet the specification, and the entire shape of the curve between room temperature and 550°C is almost similar to that of the pipe.

These test results show that, though there is some difference between pipe and fittings concerning quenching method, there is not large difference between them concerning their strength, and therefore fittings can be manufactured with almost the same composition as that of the pipe.

When the diameter of the pipe increases, the fittings that match to it become extremely thick locally. The test is now being conducted for confirmation, but even for the larger diameter, it seems possible to manufacture such fittings by increasing some chemical contents only slightly.

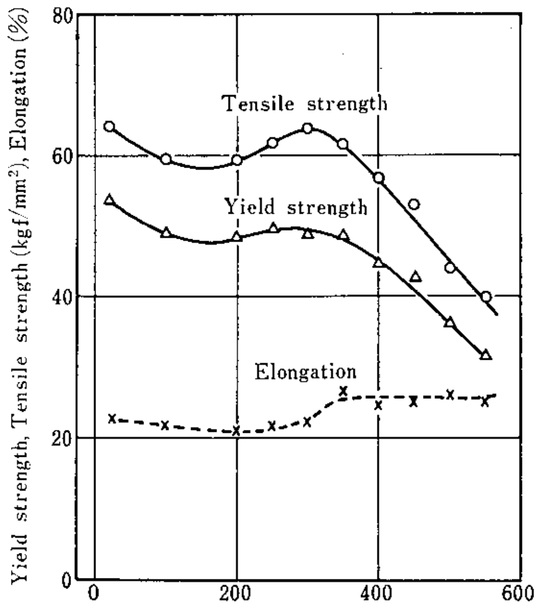


Fig. 8 Tensile properties of the elbow at elevated temperatures

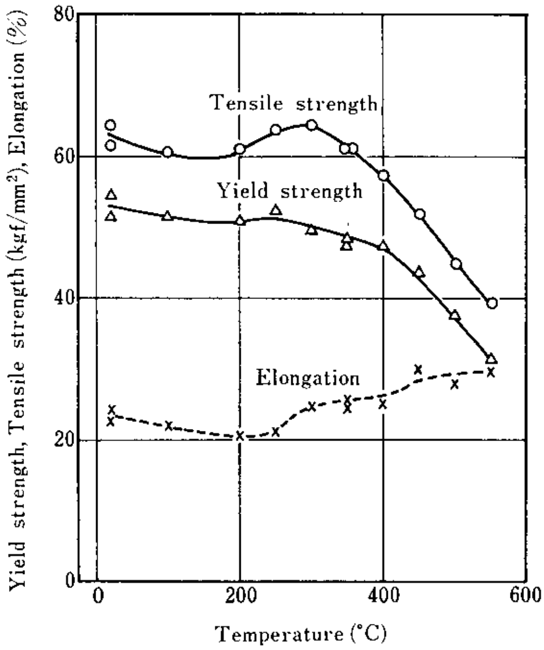


Fig. 9 Tensile properties of the tee at elevated temperatures

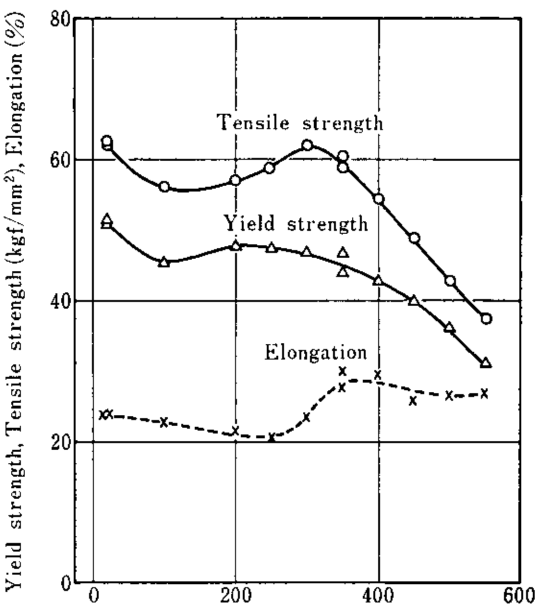


Fig. 10 Tensile properties of the reducer at elevated temperatures

4.7 Strength of Girth Weld at Room Temperature

Girth-welded joints were made under the condition of **Table 6** without preheating and post-heating by using low hydrogen type electrodes KS 86 H (equivalent to E9 016-G). Pipe edges were prepared according to API specification. **Fig. 11** shows hardness distribution traversing the girth weld zone and microstructures around that.

Type 2 specimens were used for weld tensile tests and the results are given in **Table 7** in comparison with the strength of the parent metal.

The tensile strength of the girth weld is almost the same as that of the parent metal, and local softening in HAZ as shown in **Fig. 11** has almost no influence upon the tensile strength of this specimen.

Cellulosic type electrodes are more likely to be used for actual field welding, but their lower heat input per pass than that of the low hydrogen type electrode seems to make surer of avoiding any strength decline of HAZ.

4.8 Charpy Impact Properties of Girth Weld

Fig. 12 shows Charpy impact test results of the girth weld with the notch at each position of (b)-(d) in **Fig. 11**.

This shows that the bond has the worst toughness but, since the absorbed energy is pretty high within the range of 0–40°C, no problem will be brought about even in cold districts.

Table 6 Girth welding condition

Pass	Electrode diameter (mm)	Welding current (A)	Arc voltage (V)	Welding speed (cm/min)	Heat input (J/cm)
1	3.2	112	23	9.4	16 400
2	4.0	170	25	17.4	14 700
3	4.0	140	23	9.5	20 300
4	4.0	140	23	9.5	20 300
5	4.0	140	23	7.2	26 800

Table 7 Tensile properties of the girth weld zone

Yield strength (kgf/mm^2)		Tensile strength (kgf/mm^2)		Elongation in 100 mm (%)	
Each	Av.	Each	Av.	Each	Av.
52.4	50.5 (58.3)	66.0	66.1 (66.6)	22.5	19.3
49.8		66.1		18.3	
49.3		66.1		18.7	
50.4		66.1		17.8	

Figures in parentheses show the strength of parent metal

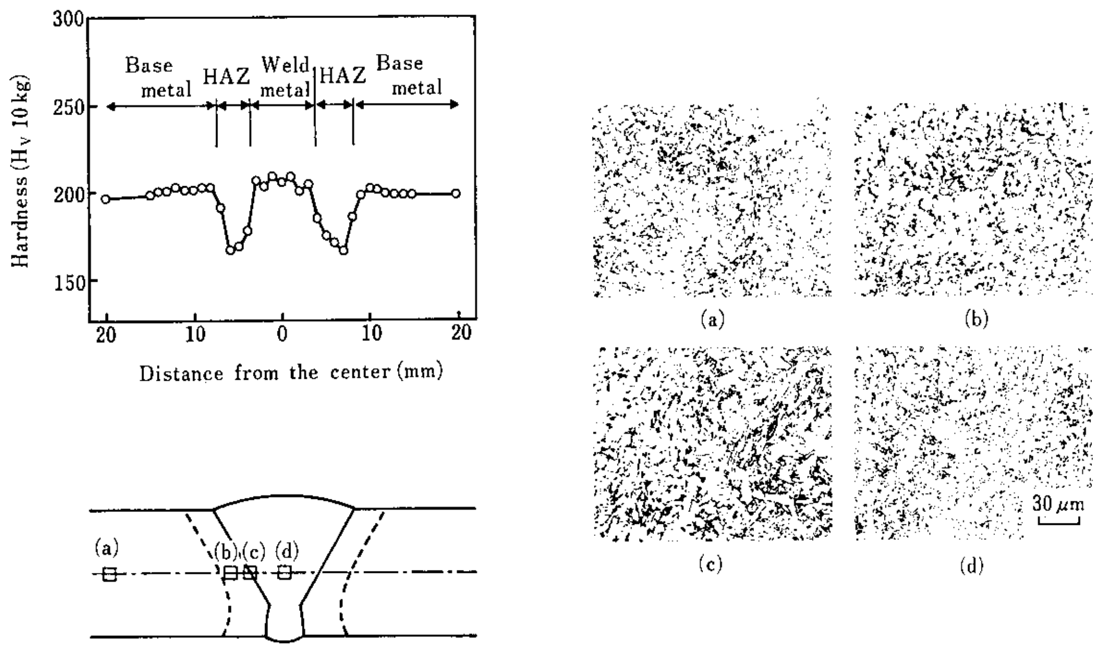


Fig. 11 Hardness distribution, and microstructures of the girth weld zone

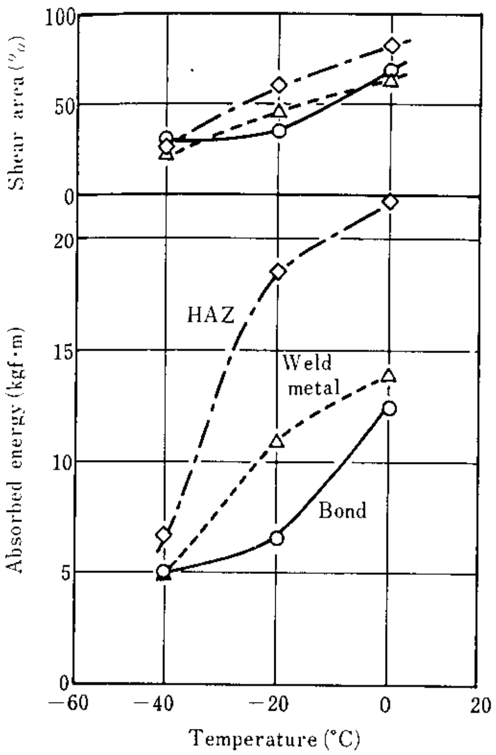


Fig. 12 Charpy impact properties of the girth weld zone

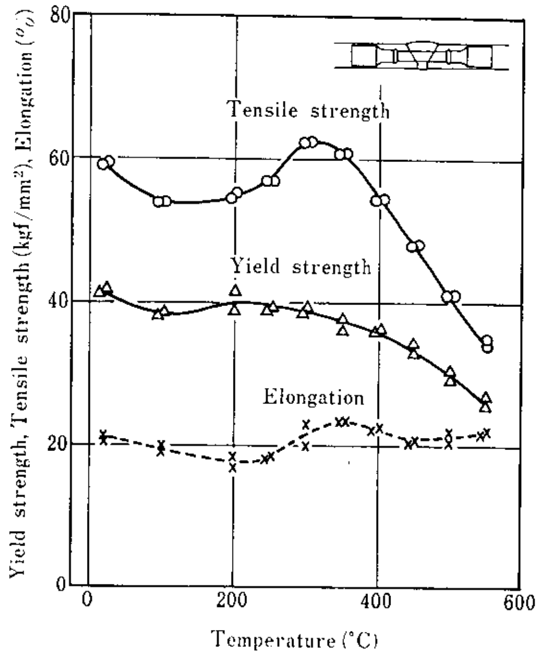


Fig. 13 Tensile properties of the girth weld zone at elevated temperatures

4.9 Elevated Temperature Tensile Properties of Girth Weld

Type 4 specimens were taken from the center of the wall thickness traversing the weld zone and tested at elevated temperatures. The results are shown in **Fig. 13**.

Generally, in the case of tensile test including soft HAZ, the smaller the size of specimen the larger the influence of soft HAZ[6,7]. In terms of tensile strength, however, the girth weld (**Fig. 13**) is only slightly inferior to the parent metal (**Fig. 4**) in the lower temperature region from room temperature to 250°C, and there is no difference between them at 300–350°C.

Although the girth weld specimens ruptured at HAZ the tensile strengths at room temperature and at 350°C satisfied the same specified minimum value as that of the parent metal.

4.10 Strength after Reheating

It is possible that reheated QT steel decreases its strength when the tempering parameter as a condition of reheating becomes so large as to exceed the original tempering parameter. Therefore, samples were taken from the pipe after QT and reheated at various temperatures. After that, their strengths at room temperature and at 350°C were investigated using Type 4 specimens. Reheating conditions were 400–700°C × 1 hr. and 680°C × 20 hr.

Figs. 14 and **15** show the strength at room temperature and at 350°C, respectively, after reheating. From these results, it can be seen that a large decrease in strength by reheating begins around the point where tempering parameter of reheating exceeds about 18 500. Though tempering parameter of the original heat treatment is about 17 500, no significant decrease in strength occurs over this value up to 18 500. One reason may be that the addition of a small quantity of Mo and V increases the resistance of the steel to temper softening. Therefore, in case that a stress relief treatment is required, heating of about 620°C × 30 min. equivalent to the original tempering condition will maintain sufficient strength.

Large decrease in strength above 18 500 corresponds to the recrystallization of quenched and tempered microstructure, which can be clearly observed even under an optical microscope. But, even when the service condition is supposed to be 350°C × 10^5hr., this condition is simply converted into the tempering parameter of 15 600, which indicates that there will be no change in microstructure during that period.

But even if no change in microstructure is supposed at the temperature, it should be confirmed by creep and creep rupture tests that the steel can be used for long hours under the stress.

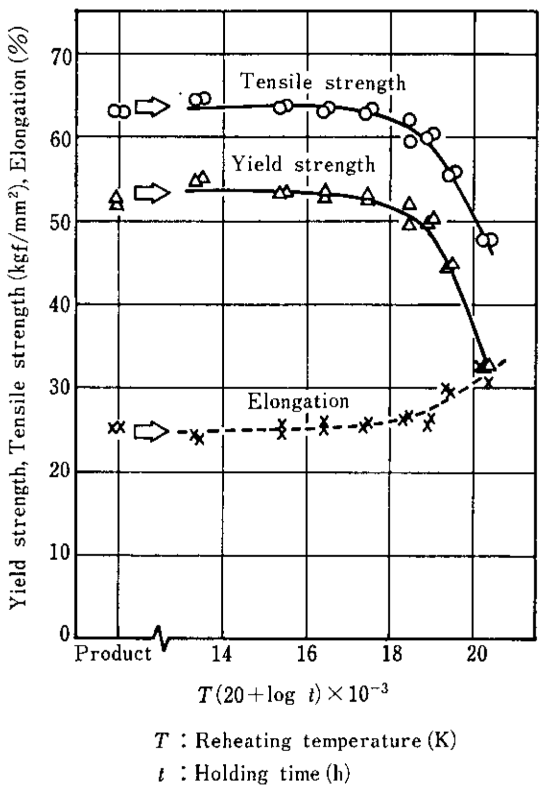


Fig. 14 Tensile properties of the pipe at room temperature after reheating under various condition

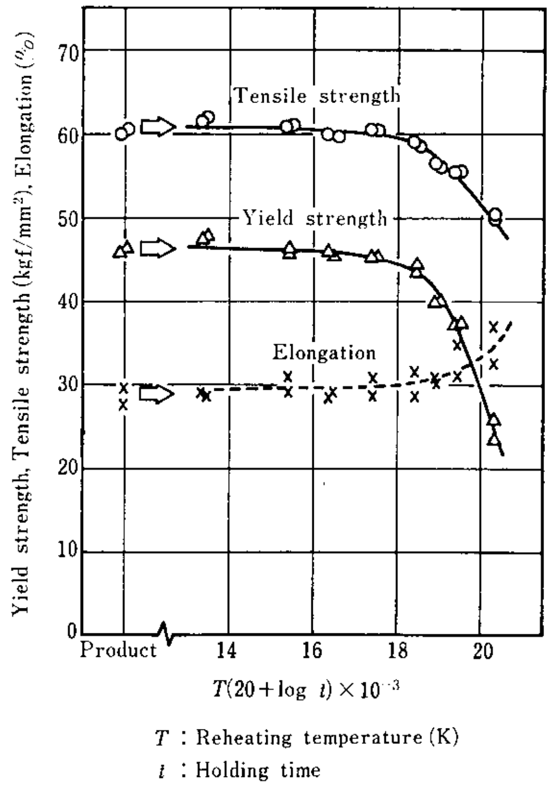


Fig. 15 Tensile properties of the pipe at 350°C after reheating under various conditions

Table 8 Welding condition for underbead cracking tests

Electrode	Current (A)	Voltage (V)	Velocity (cm/min)	Heat input (J/cm)
HYP 3.2φ KS86 3.2φ	100	23	25	5 520

Table 9 Results of underbead cracking tests

Electrode	% Cracking					
	1	2	3	4	5	Av.
HYP	0	0	0	0	0	0
KS 86	0	0	0	0	0	0

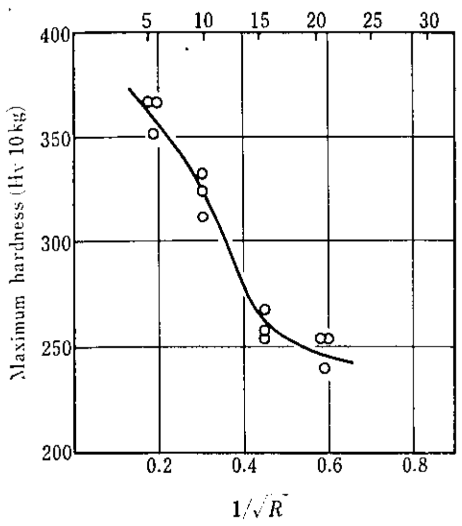
4.11 Weldability

Underbead cracking tests were conducted using cellulosic type electrode (HYP) and low hydrogen type electrode (KS86), 1.5 in. beads in the circumferential direction were placed on the inside wall of the pipe under the condition in **Table 8**. The results in **Table 9** show no crack even for cellulosic type electrode that generates much hydrogen.

Fig. 16 shows the results of maximum hardness tests at various heat inputs given in **Table 10**. Here, cooling rate R at 300°C was calculated using the formula by Cottrell et al.[8]

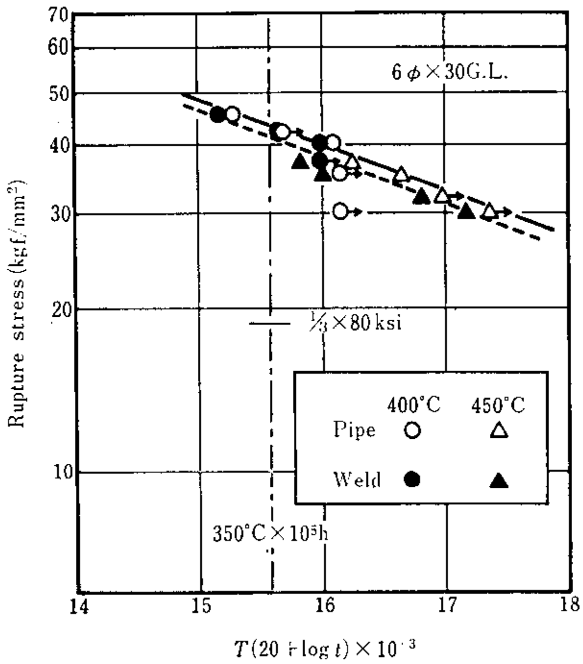
In the case that cellulosic type electrode is used, there is no danger of hydrogen cracking, according to Coe[9], if maximum hardness of HAZ is below 350 Hv.

As shown in **Fig. 16**, cooling rate when HAZ maximum hardness becomes 350 Hv is given in terms of $1/\sqrt{R_{350}} = 0.22$. When the thickness is 0.562″ (14.3 mm), the heat input corresponding to this cooling rate is also known to be about 7 kJ/cm from the same figure. Therefore, if the heat input of the root pass is over 7 kJ/cm, preheating higher than room temperature does not seem necessary for the thickness lower than or equal to 14.3 mm.



$1/\sqrt{R}=(E+1\,000N)/\{54T(1+T/1\,000)(N+0.5)\}$
R : Cooling velocity at 300°C
E : Heat input (J/in)
T : $300-T_0$(°C)
T_0 : Preheating temperature (20°C)
N : TSN (8 × inch thickness)

Fig. 16 Maximum hardness change with various heat inputs shown in Table 10



T : Test temperature (K)
t : Time to rupture (h)

Fig. 17 Results of creep rupture tests

Table 10 Welding conditions for maximum hardness tests

Condition	Current (A)	Voltage (V)	Velocity (cm/min)	Heat input (J/cm)	$1/\sqrt{R}$	Electrode
1	100	23	25	5 520	0.19	HYP 3.2φ
2	170	29	30	9 860	0.31	HYP 4.0φ
3	180	27	20	14 580	0.43	HYP 4.0φ
4	200	26	15	20 800	0.59	HYP 4.0φ

4.12 Creep Rupture Strength

Since creep and creep rupture tests are still continued, only rupture stresses obtained hitherto are shown in **Fig. 17**, after arranging with Larson Miller parameter, $T(20+\log t)$.

Suppose the service condition is 350°C × 10^5 hr. equivalent to 15 600 of Larson Miller parameter, then 10^5 hr. rupture stress of the parent metal is determined to be about 43 kg/mm², according to **Fig. 17**.

For reference, **Fig. 17** also shows the rupture stress of the girth weld obtained with specimens traversing the weld zone. The value is only slightly lower than that of the parent metal.

5 Discussion

As described above, quenched and tempered, seamless pipe and fittings (KSC-X65M), for moderate temperature service were produced on trial as the most suitable material for Steam Distribution Pipeline, and investigated on their properties.

As for the allowable stress of this steel pipe, the minimum value of the following will be adopted if, for example, 302.3.2 of ANSI B 31.3 is applied.

(1) 1/3 of the specified minimum tensile strength at room temperature
(2) 1/3 of the "tensile strength at temperature"
(3) 2/3 of the specified minimum yield strength at room temperature
(4) 2/3 of the "yield strength at temperature"
(5) 100% of the average stress for a creep rate of 0.01% per 1 000 hr.
(6) 67% of the average stress for rupture at the end of 100 000 hr.
(7) 80% of the minimum stress for rupture at the end of 100 000 hr.

Suppose the service temperature is 350°C, the 10^5 hr. rupture strength is determined at about 43 kgf/mm² according to **Fig. 17**, the 67% of which is far higher than 1/3 of the specified minimum tensile strength at room temperature and 350°C. Further, 2/3 of the yield strength is always larger than 1/3 of the tensile strength; therefore, after all, allowable stress can be decided at 1/3 of the specified minimum tensile strength.

The higher the tensile strength, the larger the allowable stress can be. However, if the pipe is welded in the same way as a usual line pipe with cellulosic type electrodes, the value of about 80 ksi seems adequate as the tensile strength.

To date, there were examples in the fields of boiler tubes and pressure vessels that high strength steels of normalized type or normalized and tempered type for moderate temperature service were developed[10,11]. But such steels are not satisfactory in weldability and economical efficiency as a line pipe to be used in a cold district. The Steam Distribution Line Pipe can be considered to be a case where the service temperature is rather low for high temperature piping, or also a case where the service temperature is rather high for an ordinary line pipe. If emphasis is placed on weldability and economic efficiency, it seems most proper to apply quench and temper treatment positively in the same way as in the usual line pipe, and ensure the strength at the service temperature.

One of the problems for the quenched and tempered steel might be the softening of the weld heat affected zone. But fortunately, there is no weld zone along the pipe axis in the case of seamless pipe; therefore, the heat influence will be limited only to what accompanies girth welding. Even concerning this girth weld, the tensile strengths at room temperature and at 350°C stand comparison with that of the parent metal as shown in the test results. And, though the yield strength becomes lower than that of the parent metal, 2/3 of the yield strength is always higher than 1/3 of the tensile strength. Originally, the direction of pipe axis is not the one in which main stress works. And if the system is so designed that the longitudinal deformation accompanying thermal expansion and shrinkage can be sufficiently absorbed, the existence of heat affected zone owing to the girth welding will not be any problem at all from the practical point of view.

6 Summary

Quenched and tempered seamless line pipe and fittings (KSC-X65M) for moderate temperature service were developed with low C-Mo-V steel, and investigated on their suitability for steam distribution pipelines in oil-sand projects. The test results are summarized below.

(1) The strengths of pipe and fittings all satisfied the target values at room temperature and at 350°C.
(2) The tensile strength of girth weld stood comparison with that of the parent metal at room temperature and at 350°C.
(3) The Charpy impact properties of pipe, fittings and girth weld showed sufficient absorbed energy within the range between 0 and −40°C, to be used in a cold district.
(4) As for the softening characteristic of the steel due to reheating after QT, there is no significant decrease in strength up to about 18 500 of tempering parameter.
(5) The weldability of the steel is satisfactory, and for the thickness below 14.3 mm, if the heat input of the root pass is more than 7 kJ/cm for cellulosic type electrodes, there is no need of preheating higher than room temperature.
(6) 67% of the 10^5hr. rupture strength of the steel at 350°C is sufficiently higher than 1/3 of 80 ksi; therefore allowable stress can be determined at 1/3 of the specified minimum tensile strength.

The above test results have already been offered to some of the customers in Canada and have been given a favorable reception. Energy is a big problem now all over the world, and the authors are very happy if the above findings somehow contribute to the development of substitute energy.

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