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Development of Anti-SSC OCTG and Collapse Resistant OCTG

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Synopsis :
An increasing energy demand has stimulated a considerable development of high strength oil country tubular goods (OCTG) with superior resistance to sulfide stress corrosion cracking (SSC) and/or collapse failure in hostile environments. The experimental trials of modified Cr-Mo steel casing have proved that addition of Mo up to 1.0%, Nb and B to 0.2-0.3% C steels, product 90 ksi(63.3kgf/mm2) yield strength pipe with superior SSC resistance. Multiple regression analysis has been conducted to estimate the effects of various factors concerning the collapse of casing pipe and it has been demonstrated that residual stress of finished pipe is one of the most significant factors. This report summarizes some metallurgical aspects in the manufacturing process of these special grades of OCTG.

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An increasing energy demand has stimulated a considerable development of high strength oil country tubular goods (OCTG) with superior resistance to sulfide stress corrosion cracking (SSC) and/or collapse failure in hostile environments.

The experimental trials of modified Cr-Mo steel casing have proved that additions of Mo up to 1.0%, Nb and B to 0.2–0.3% C steels, produce 90 ksi (63.3 kgf/mm²) yield strength pipe with superior SSC resistance.

Multiple regression analysis has been conducted to estimate the effects of various factors concerning the collapse of casing pipe and it has been demonstrated that residual stress of finished pipe is one of the most significant factors. This report summarizes some metallurgical aspects in the manufacturing process of these special grades of OCTG.

1 Introduction

The recent tight demand and supply position in oil and natural gas throughout the world has promoted prospecting for oil and gas fields in severe excavational environments, and thus increased demand for high strength oil field steel pipe having good resistance to hydrogen sulfide stress corrosion cracking and to collapse.

Kawasaki Steel Corporation has established the manufacturing system of API standard casings for oil wells (C-75, N-80, and P-110, etc. of API standards) which are of the yield strength class of 52.7 to 77.3 kgf/mm² (75 to 110 ksi). Small and medium diameter seamless pipes produced by induction type heat treating equipment (the maximum capacity of 25 t/h)¹⁾ have such characteristics as the fine, quench-hardened structure by rapid heating and the absence of residual stress because of minimum strains and of no need for cold straightening.

This paper highlights necessary metallurgical factors in manufacturing anti-sulfide stress corrosion cracking casings (Kawasaki Steel standard KO-90SS) of the yield strength class of 63.3 kgf/mm² (90 ksi) and collapse resistant casings (Kawasaki Steel standard KO-95T, etc.) of the yield strength class of 66.8 kgf/mm² (95 ksi), both types of which have been developed as OCTG for special applications.

2 Development of OCTG using Cr-Mo-Nb Steel with Excellent SSC Resistance

It is generally known that strengthening of steel materials results in reduced SSC resistance, and in the case of modified low-alloyed steels, OCTG of the yield strength class of 63.3 kgf/mm² (90 ksi) to 70.3 kgf/mm² (100 ksi) are the most advantageous for economical and metallurgical reasons in the design of oil wells. From this viewpoint, API is examining the standardization of 5AC C-90 with chemical composition of AISI 4 130 (0.3%C-1%Cr-0.2%Mo). For improving the SSC resistance of Cr-Mo alloy steels, modified steels with additional Nb, Ti, and V, etc., have been announced²⁻⁴⁾. In this study, a prospective increase in the SSC resistance of Cr-Mo alloy steels was examined in terms of quench hardenability, tempering parameters, and crystalline microstructure which have the most important influence on the SSC phenomenon of steels.

2.1 Quench Hardenability

Fig. 1 shows the relationship between the quench hardenability and SSC resistance of 0.2 to 0.3%C

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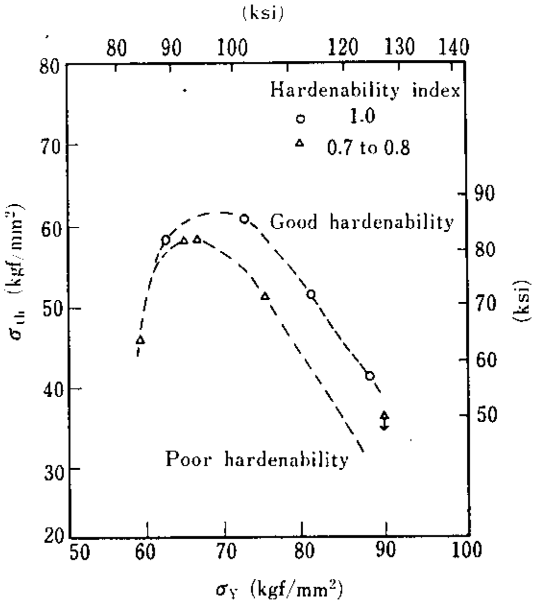

Fig. 1 Relation between SSC threshold stress σ_{th} and yield strength σ_Y of 0.2 to 0.3 %C steel

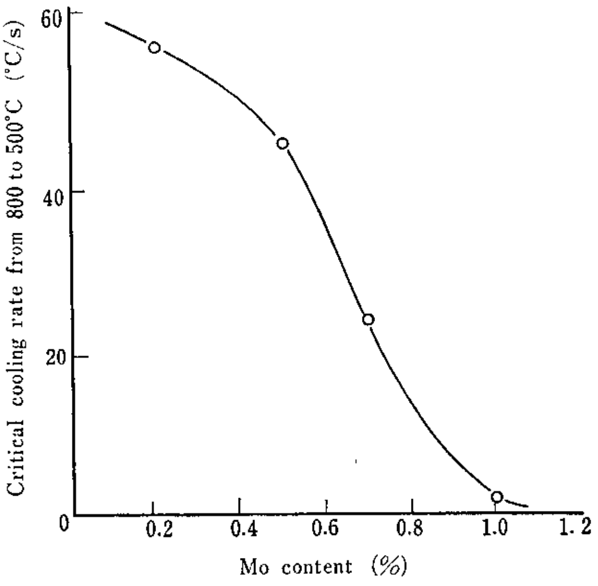

Fig. 2 Relation between critical cooling rate for martensite formation obtained by the CCT diagrams and Mo content of 0.2%C-1%Cr-Mo steels

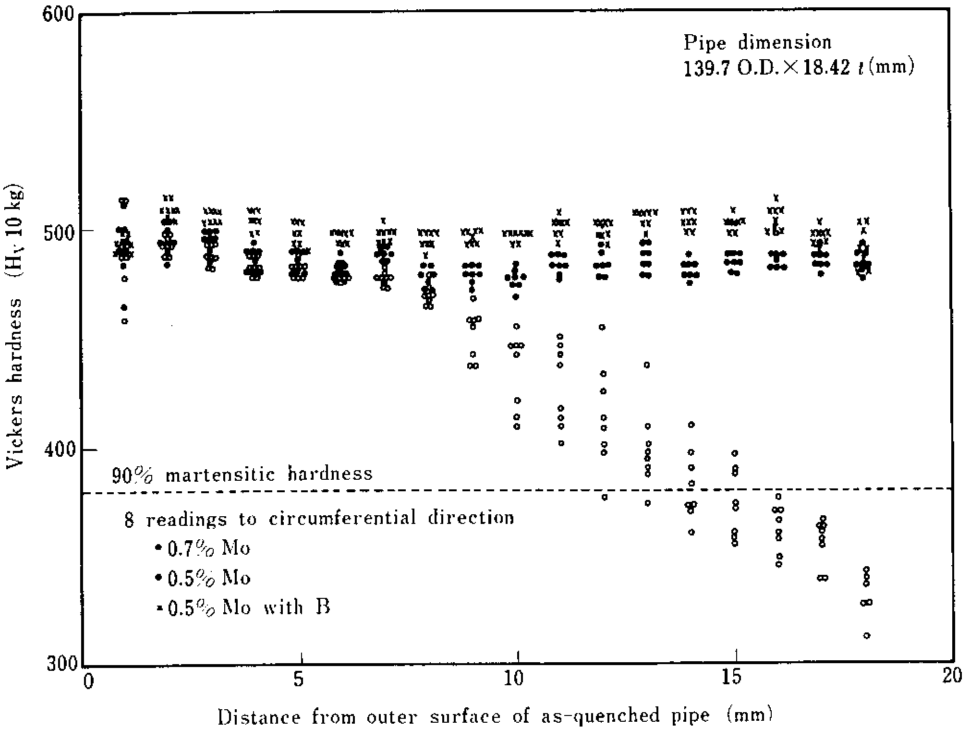

Fig. 3 Through-wall Vickers hardness distribution of as-quenched 0.2%C-Cr-Mo steel pipes

steels. SSC tests were carried out according to the constant load tension testing method prescribed in NACE standard⁵⁾, and the maximum stress which was withstood by the test piece for 720 hr. without breaking was taken as the SSC threshold stress (σ_{th}).

If the ratio of the quench hardness of a test piece to the 100% martensite hardness is taken as the quench hardenability index, the figure indicates that the SSC resistance of a material of poor quench hardening decreases quickly when the yield strength exceeds 66.8 kgf/mm² (95 ksi). Therefore, the selection of a proper quench hardenability index depending upon the dimensions and heat treatment method of steel materials can be regarded as important in increasing the rate of martensite in the steel and improving SSC resistance. **Fig. 2** shows the relationship between the Mo content of 0.2%C-1%Cr-Mo alloy steels and the critical cooling rate for producing martensitic structure obtained from continuous cooling transformation diagrams.

Fig. 3 illustrates the hardness distribution through the wall cross section of heavy wall Cr-Mo steel casings when they are subjected to outside quenching. These figures indicate that an increase in Mo content and the addition of B will produce a martensite rate of over 90% throughout the whole thickness in the quench hardening of heavy wall pipe, and will fulfil the fundamental conditions for increasing the SSC resistance.

2.2 Tempering Characteristics

The addition of alloying elements of precipitation hardening type retards softening during tempering. **Fig. 4** shows the relationship between the addition of Mo and Nb, and tempered hardness in 0.2%C-1.4%Cr-Mo alloy steels, and **Fig. 5** shows the relationship between the contents of Mo and Nb, and the ratio of SSC threshold stress to yield strength (σ_{th}/σ_Y). From these results, it is clear that secondary hardening during tempering permits high temperature tempering, and increases SSC resistance.

2.3 SSC Tests

Fig. 6 summarizes the results of SSC tests of Cr-Mo and Cr-Mo-Nb small and middle diameter seamless steel pipes, in connection with yield strength and SSC threshold stress. Tested steel pipe samples were of 139.7 to 177.8 mm (5½ to 7 in.) outside diameter, 10.54 to 30.48 mm (0.415 to 1.200 in.) thick, and quenched at 950°C, having a martensite ratio of over 90%. The tempering conditions were 615 to 702°C, 30 to 195 min. depending upon chemical compositions and yield strengths; cold straightening following tempering or SR was not needed.

Fig. 6 indicates that the SSC threshold stress of Cr-Mo low alloy steels becomes a maximum near the yield strength of 70.3 kgf/mm² (100 ksi), and the addition of Nb results in an increase in the ratio of SSC threshold stress to yield strength.

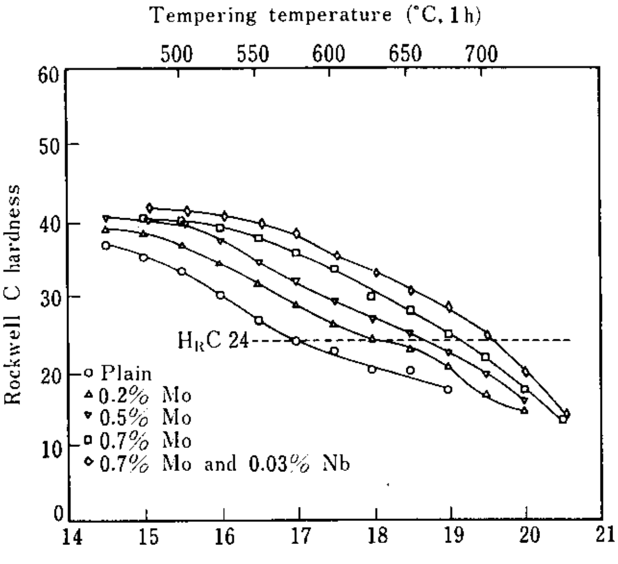

Fig. 4 Effects of Mo and Nb on the tempering resistance of 0.2%C-1.4%Cr-Mo steels

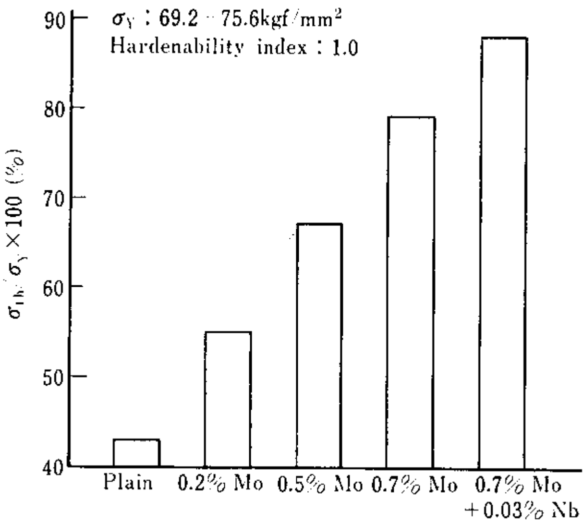

Fig. 5 Relation between Mo and Nb contents and the ratio of SSC threshold stress σ_{th} to yield strength σ_Y

2.4 Actual Results

Table 1 shows the typical chemical composition and mechanical properties of SSC-resistant casings. As the result of induction heating quench, the addition of Mo, B, and Nb in proper quantity, respectively, and

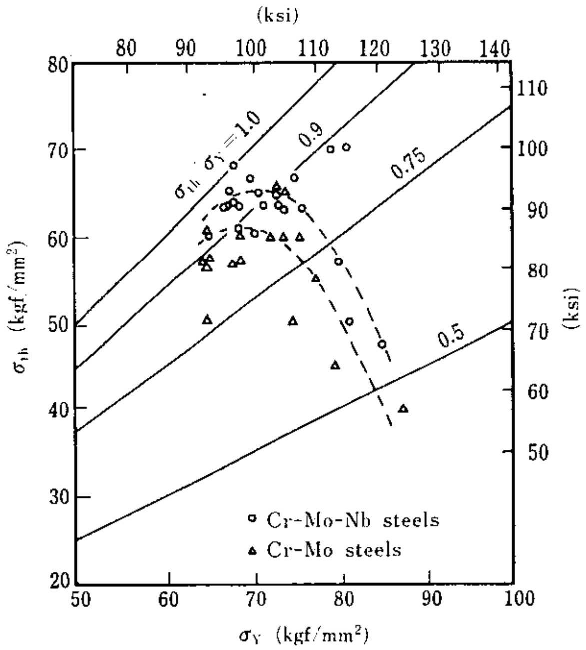

Fig. 6 Relation between SSC threshold stress σ_{th} and yield strength σ_Y of Cr-Mo and Cr-Mo-Nb steels with 0.19–0.31C, 0.50–0.85Mn, 0.93–1.48Cr, 0.20–1.00Mo, 0.003–0.035Nb, 0–0.002 7B, 0.027–0.081Al and 0.004 0–0.005 9N (%)

high temperature tempering, the uniform distribution of hardness, refined austenitic grains, and good SSC resistance have been obtained.

3 Development of OCTG with High Collapse Resistance

The resistance of steel pipe to external pressures, that is, collapse resistance, is one of the important characteristics of OCTG. Therefore, there is a great demand for OCTG of excellent collapse resistance, and API is also examining the establishment of a new standard. It has been already made clear theoretically or experimentally that the collapse resistance of steel pipes depends upon such factors as the ratio of outside diameter to wall thickness, yield strength, ovality, eccentricity, and residual stress due to the cold straightening of pipes after heat treatment[6–8].

In the development of OCTG of high collapse resistance, an accurate tester for collapse resistance was devised first, and then the relationship between the aforementioned factors and collapse resistance has been formulated by means of multiple regression analyses.

Table 1 Chemical compositon and mechanical properties of SSC-resistant Cr-Mo steel pipe

	Pipe dimension (mm)	Chemical composition (%)							
		C	Si	Mn	P	S	Cu	Ni	Cr
KO-90 SS specification		0.15/0.35	≦0.35	≦1.00	≦0.030	≦0.015	≦0.30	≦0.10	0.80/1.60
	139.7 O.D. ×18.42 t	0.20	0.27	0.84	0.010	0.005	0.02	0.02	1.47

						Heat treatment			
	Mo	Nb	B	Al	N		Yield strength psi(kgf/mm²)	Tensile strength psi(kgf/mm²)	Elongation (%)
KO-90 SS specification	0.15/1.10	≦0.050	≦0.004 0			Tempering temp. ≧649°C	90 000/105 000 (63.3/73.8)	100 000/115 000 (70.3/80.8)	Same as required by API spec.
	0.71	0.031	0.000 7	0.069	0.005 9	Quenched at 950°C Tempered at 700°C	97 700 (68.7)	106 700 (75.0)	37.9

	Hardness(HRC)testing			Prior austenitic grain size	SSC(NACE)testing
	Max.	Max. variation	Ave.	Min.	Threshold/Specified min. yield strength(%)
KO-90 SS specification	24.0	4.0		5.0	≧75
	20.5	1.7	19.8	10.5	95

3.1 Collapse Tester

Fig. 7 shows the cross section of the collapse tester. The specimen is 1 143 mm (45 in.) long, and both its ends are furnished with clearances to allow sealing without a longitudinal load being applied. When pressurized, the inside of the pipe and the space between the pipe and vessel are filled with water, and the change in volume inside the pipe following the deformation can be measured with an outside gage.

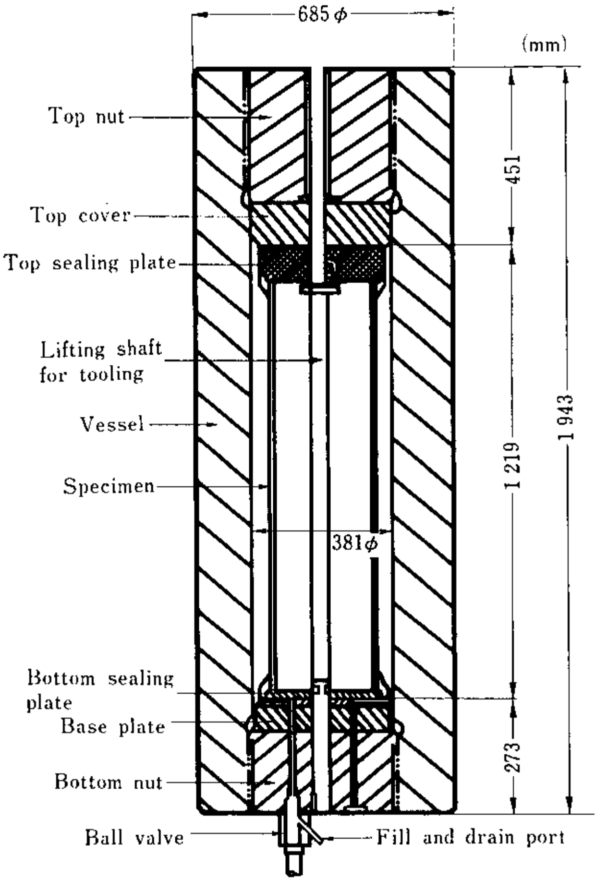

Fig. 7 Collapse tester

3.2 Multiple Regression Analysis

The seamless steel pipes for the investigation were quenched and tempered in the induction heating equipment, and for the purpose of facilitating the analysis, the factors of ovality, etc., were varied by a larger extent than would be necessary for practical use. The outside diameter (D) and wall thickness (t) were measured at four points and eight points, respectively, around the circumference at the pipe end, and then the ovality (u) and eccentricity (ε) were calculated. The effect that the outside diameter and wall thickness have on the collapse resistance is evaluated by D/t, and in the region where values of D/t are small, initial yielding in the inside of a heavy wall tube results in yield collapse. This, however, does not apply to OCTG of API standard. With a large value of D/t, the yielding condition formula of a light wall tube is applied, resulting in plastic collapse, and with a further increase in the value of D/t, the transition to elastic collapse occurs, thus the collapse pressure turning independent on the strength of the steel pipe. Therefore, the plastic collapse phenomenon pertains to small diameter OCTG, and the plastic collapse and the elastic collapse to medium diameter OCTG.

The D/t value of the steel pipe samples tested in this study ranges between 14 and 20, belonging to the region of plastic collapse. As for yield strength (σ_Y), it is appropriate to use a compression stress in a circumferential direction, but our heat treating equipment is so designed as to minimize the strain in steel pipe induced by heat treatment, thereby eliminating the work for reducing the diameter with the sizer. Therefore, for σ_Y, the tension yield strength in the longitudinal direction was used, neglecting the directionality in strength.

For measuring residual strength (σ_R), a slit method was applied.

Figs. 8 and 9 show collapse resistances used for analyses of the casings of API standard 5A N-80 and 5AX P-110. The figures indicate that in particular, σ_R contributes to the fructuation of collapse resistance. For the multiple regression analysis of collapse resistance (p), the following six models were assumed, and the regression coefficient, reliability of the coefficient, confidence interval, and multiple correlation coefficient were obtained.

$$p = a_1 + a_2(D/t)^{-1} + a_3u + a_4\varepsilon + a_5\sigma_Y + a_6\sigma_R \quad \cdots\cdots(1)$$

$$p = b_1 + b_2(D/t)^{-1.5} + b_3u + b_4\varepsilon + b_5\sigma_Y + b_6\sigma_R \quad \cdots\cdots(2)$$

$$p = c_1 + (D/t)^{-1}(c_2 + c_3u + c_4\varepsilon + c_5\sigma_Y + c_6\sigma_R) \quad \cdots\cdots(3)$$

$$p = d_1 + (D/t)^{-1.5}(d_2 + d_3u + d_4\varepsilon + d_5\sigma_Y + d_6\sigma_R) \quad \cdots\cdots(4)$$

$$p = e_1(D/t)^{(e_2+e_3u+e_4\varepsilon+e_5\sigma_Y+e_6\sigma_R)} \quad \cdots\cdots(5)$$

$$p = f_1(D/t)^{f_2}(1 + u/100)^{f_3}(1 + \varepsilon/100)^{f_4} \sigma_Y^{f_5}(1 + |\sigma_R|)^{f_6} \quad \cdots\cdots(6)$$

As a result, it was found that multiple correlation coefficients in above equations do not differ very much from each other.

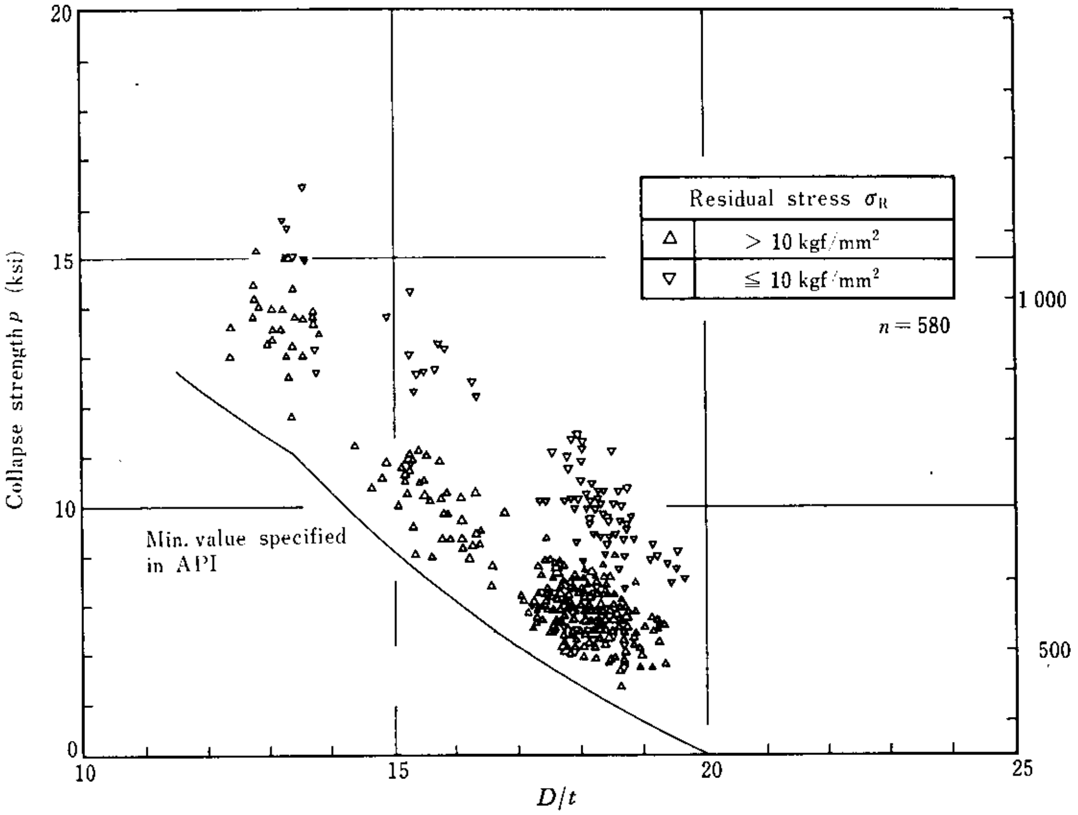

Fig. 8 Relation between collapse strength of N-80 casing and the ratio of pipe dia. D to wall thickness t

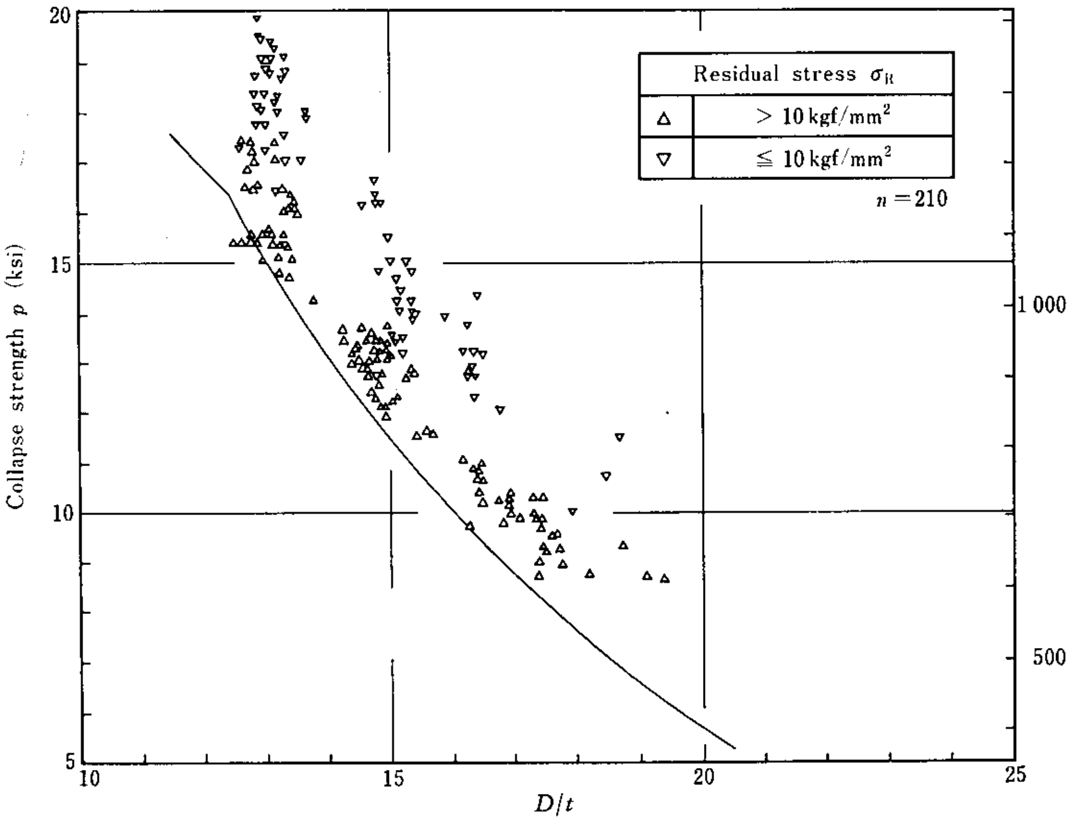

Fig. 9 Relation between collapse strength of P-110 casing and D/t

Table 2 shows an example of the regression formula, and **Fig. 10**, the relationship between the regression formula and measured values. The table indicates that, of the factors of collapse resistance, D/t, σ_Y, and σ_R have large effects, and u and ε have relatively small effects.

3.3 Actual Results

The result of multiple regression analysis gives an important hint to the manufactures of high collapse OCTG. In particular, residual stress due to cold working following heat treatment of the pipe markedly reduces the collapse resistance; therefore the uniformity in heating and cooling, the method for conveying pipe, and deformation preventive measures have been improved in the induction heating equipment. In Kawasaki Steel standards of high collapse casings, there are KO-95T, and KO-105T which guarantee collapse resistance of an even greater extent. **Table 3** shows a typical example of chemical composition and mechanical properties, and **Fig. 11**, the collapse resistance.

Table 2 Multiple regression analysis of collapse strength

Equation (1) : $p=a_1+a_2\ (D/t)^{-1}+a_3u+a_4\varepsilon+a_5\sigma_Y+a_6\sigma_R$

p : Collapse strength (psi)

u (Ovality) $=2(D_{max}-D_{min})/(D_{max}+D_{min})$

ϵ (Eccentricity) $=2(t_{max}-t_{min})/(t_{max}-t_{min})$

σ_Y : Yield strengh (kgf/mm^2)

σ_R : Residual stress (kgf/mm^2) measured by slit method

Regression coefficient		95% confidence interval	Judgement	Multiple correlation coefficient
a_1	−1405	± 508	* *	0.979
a_2	292 670	±6 995	* *	
a_3	− 450	± 288	* *	
a_4	− 22	± 20	*	
a_5	110	± 7	* *	
a_6	− 77	± 6	* *	

* * Significant at 1% level
* Significant at 5% level

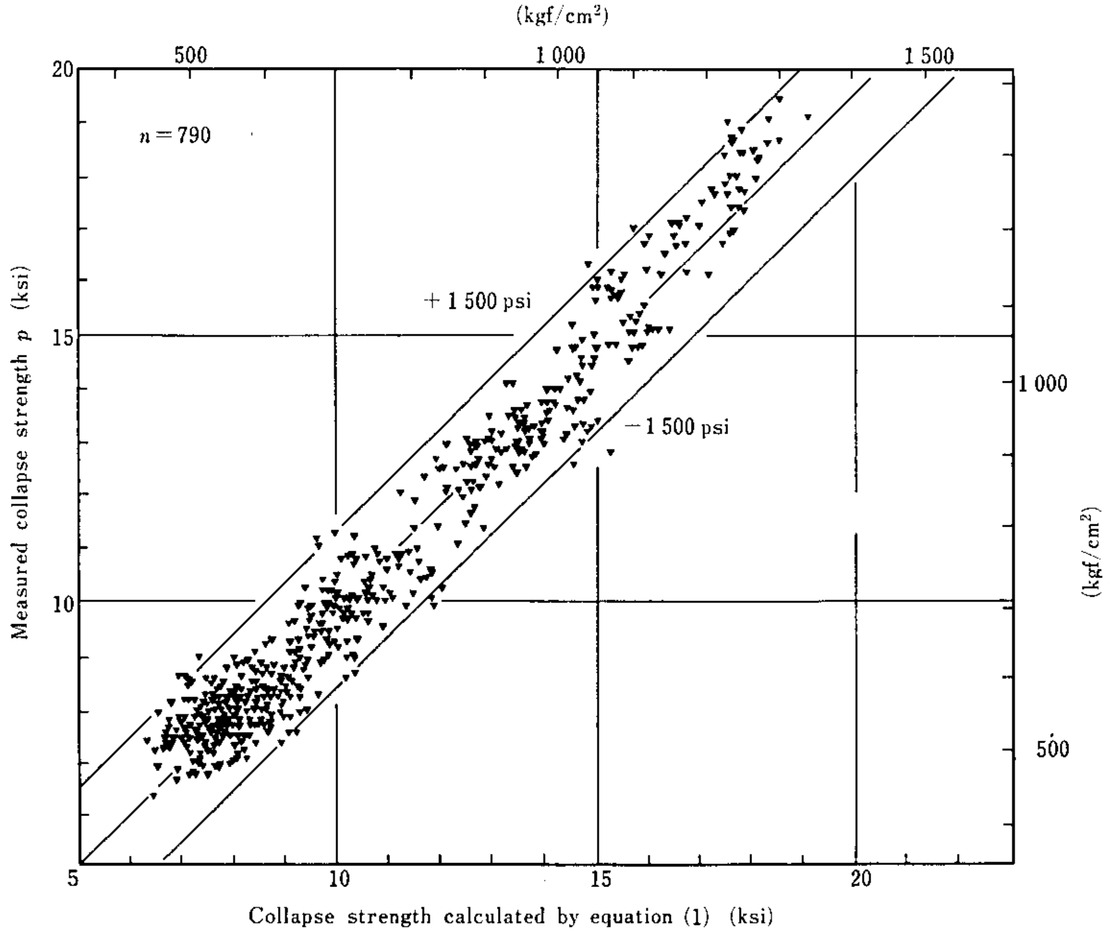

Fig. 10 Comparison of regression analysis results with measured values in collapse resistance of pipes

Table 3 Chemical composition and mechanical properties of high collapse resistant steel pipe

	Pipe dimension (mm)	Chemical composition (%)						Tension testing	
		C	Mn	P	P	S	Al	Yield strength psi(kgf/mm^2)	Tensile strength psi(kgf/mm^2)
Specification of KO-95T and KO-105T		≦0.35	≦0.35	≦1.60	≦0.030	≦0.030	≦0.10	95 000/125 000 (66.8/87.9)	≥110 000 (≧77.3)
	244.5 O.D. ×13.8 *t*	0.26	0.24	1.39	0.017	0.004	0.039	116 550 (81.9)	125 300 (88.1)

Elongation (%)	Residual stress psi(kgf/mm^2)	Collapse resistance (psi)	
		Min.	Max.
Same as required by API spec.			
30.9	0	KO-95T 8 850	13 260
		KO-105T 9 350	

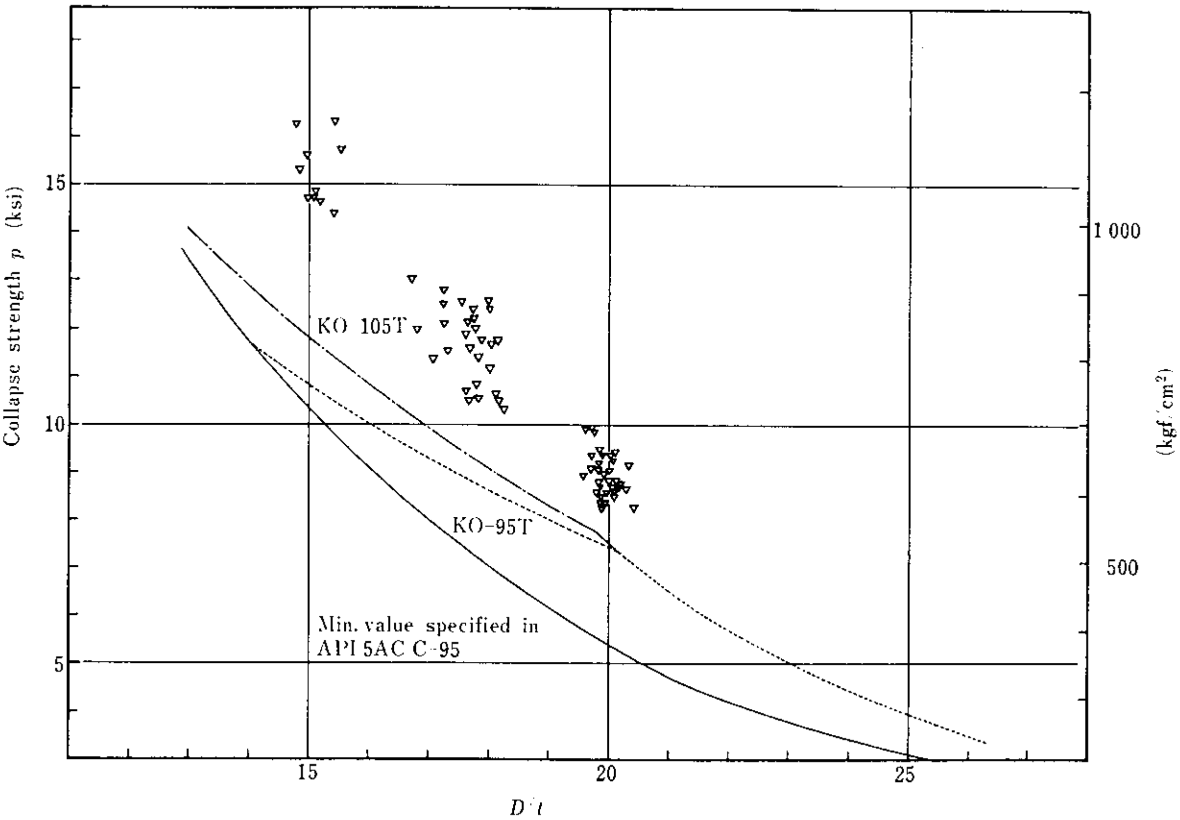

Fig. 11 Relation between collapse strength and D/t of high collapse casings KO-95T and KO-105T

4 Conclusion

In developing OCTG for special use having excellent SSC resistance, an investigation was made on their metallurgical factors, and it has been found that Cr-Mo-Nb-B steel is the most suitable in terms of chemical composition to ensure quench hardenability and tempered hardness. It is also important to minimize residual stress following heat treatment in manufacturing OCTG of high collapse resistance.

In response to the demand for high quality OCTG sufficient to withstand excavating and operating conditions of even greater severity, further research and development are under way.

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