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1 Introduction

The wildcats and production wells for petroleum and natural gas require three kinds of oil country tubular-goods: casing, tubing and drill pipe. Kawasaki Steel Corporation has expanded the manufacturing capacity of casings and tubings through the construction and reinforcement of small- and medium-diameter seamless pipe mills and finishing lines including various heat treatment facilities. Moreover, research and development efforts were promoted in the area of technology of manufacturing drill pipe for oil well drilling, and the commercial production was started in August 1982.

While the proportion of drill pipe in the total world production of oil country tubular goods is as small as about 5% according to the 1981 API shipping statistics, drill pipe is characterized by requirements for high strength, severe upsetting and high fatigue resistance. The specifications for the strengths of drill pipes in API standards 5A and 5AX are shown in **Table 1**, and the production of drill pipes[1] in the world for different grades and outer diameters in **Table 2**. As noticeable trends in terms of grade and size, pipe of 5A E and 5AX G105 grades and of 4½" and 5" in outside diameter are used in the greatest amount. In the ordinary rotary drilling arrangement, as schematically shown in **Fig. 1**, the tool joint with pin-thread is friction-welded to the one end of the drill pipe and the tool joint with box-thread to another end of the drill pipe so as to form a drill string with threaded connections. At the lowest end of the drill pipe, drill collars are coupled so as to provide necessary weight, and the drill pipe is used in such a way as to rotate the bit at the tip.

Subjected to welding and rotation, quite contrary to

Table 1 API Specifications for drill pipes

API Standard	Grade	YS		TS	El.	Chemical composition	Process
		kgf/mm² (ksi)			%		
		Min	Max	Min	Min		
5A	E	52.7 (75)	73.8 (105)	70.3 (100)	$e=625\,000\frac{A^{0.2}}{U^{0.9}}$ (*1)	P≤0.040% S≤0.060%	Heat treated
5AX	X95	66.8 (95)	87.9 (125)	73.8 (105)			QT or NT
	G105	73.8 (105)	94.9 (135)	80.8 (115)			
	S135	94.9 (135)	116.0 (165)	101.9 (145)			

*1 e : Elongation for 2 inches GL. (%)
A : Cross section area of tensile specimens (in²)
U : Specified minimum tensile strength (psi)

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Table 2 Amount of drill pipes produced in the world

(Met. tons)

Outer dia. (in)	Grades						Total
	D	E	X95	G105	S135	Others	
2⅜	326	262	89	371	30	313	1 391
2⅞	635	2 889	238	1 893	605	868	7 128
3½	1 208	15 247	5 203	5 807	3 054	2 506	33 025
4	–	12 582	622	983	648	2 592	17 427
4½	2 438	151 010	12 000	16 798	4 928	16 140	203 314
5	1 863	16 094	3 344	40 635	10 519	7 477	79 932
5½	352	1 366	147	2 495	376	–	4 736
6⅝	–	–	–	–	–	–	–
Total	6 822	199 450	21 643	68 982	20 160	29 896	346 953

(API Annual report, 1981)

casing and tubing, drill pipe requires appropriate quality design and manufacture control according to operating conditions. The present report describes manufacturing and properties of drill pipe for weld-on tool joint application.

2 Manufacture of Drill Pipe

2.1 Quality Design

In the quality design of drill pipe, the following items are emphatically pursued in consideration of strength requirements and operating conditions in service.

2.1.1 Strength and Toughness

The specified yield stress of widely used drill pipe ranges from 52.7 kgf/mm^2 (grade E) to as high as 94.9 kgf/mm^2 (grade S135). Moreover, it is also desired to have high toughness since impact load is applied during the operation. It is necessary, therefore, to select such chemical composition and heat treatment that ensure high strength and toughness at steady level.

2.1.2 Hardenability in welded area

Since the heavy wall upset portion of drill pipe is friction-welded to the tool joint and subjected to local quenching and tempering, it is necessary to select the chemical composition ensuring the excellent hardenability so as to secure sufficient strength at the upset area.

2.1.3 Fatigue resistance

The drill pipe which is rotated in drilling is subjected to repetitive rotary bending stress owing to the dogleg of the drill hole, often resulting in fatigue failure. High fatigue strength is, therefore, one of the important properties required for drill pipes.

In order to achieve high fatigue resistance, nonmetallic inclusions which deteriorate the fatigue strength must be reduced in the steel-making process and chemical composition must be selected so as to minimize the occurrence of harmful precipitates. Furthermore, it is necessary to pay particular attention to the profile of upset as will be described in the next paragraph.

2.1.4 Profile of upset

The upset portion develops geometrical discontinuities at the transition from the pipe body, which cause stress concentration, and initiate fatigue failure.

In order to reduce the stress concentration, it is most effective to smoothen the shape at the upset–pipe body transition as much as possible by selecting an optimum upsetting condition.

With these points taken into consideration, the following basic concepts were adopted for the material design of Grades E, G, X and S drill pipe.

(1) Quench and temper (Q-T) treatment is applied to every grade of pipe so as to realize high strength and toughness.
(2) High C-Mn-Mo steel is adopted as the basic composition, with Cr and/or V addition depending on required strength.
(3) The content of impurity elements is controlled below 0.010% for S, and 0.020% for P, so as to provide clean steel.
(4) The geometrical smoothness at the upset–pipe body transition region is ensured by selecting an optimum upsetting condition.

2.2 Manufacturing Process

An outline of the manufacturing process for drill pipe is shown in **Fig. 2**, and the principal steps are briefly described below.

2.2.1 Pipe rolling

Drill pipe with required outside diameter and wall thickness is manufactured by the mandrel mill and the hot stretch reducer in the small diameter seamless pipe plant and cut to specified length.

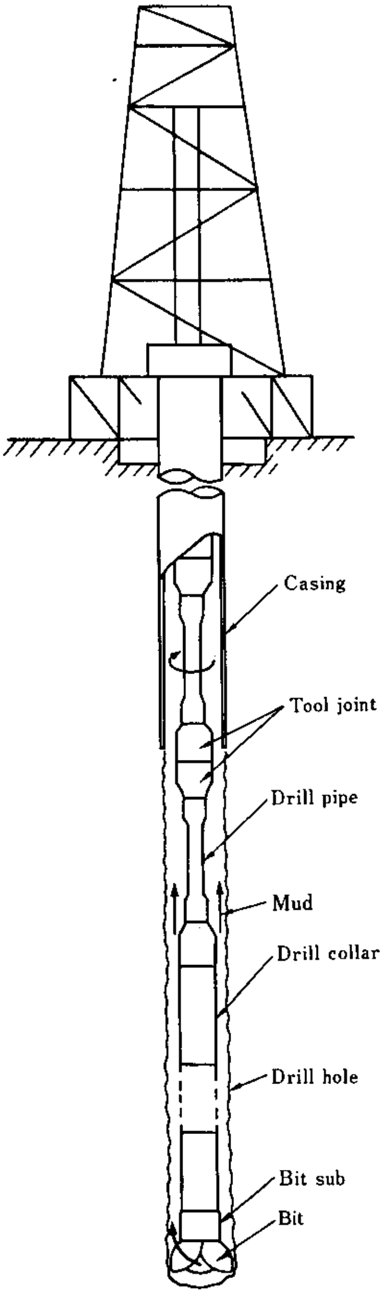

Fig. 1 Schematic illustration for rotary drilling

2.2.2 Upsetting

For upsetting, a 4½″ or 7″ upsetter is used. As to the shape of upset portion, three types are specified in the API standards: internal upset end (IUE), external upset end (EUE) and internal/external upset end (IEUE). In some cases, upset may be so severe that the upset ratio exceeds 100%. It is essential, therefore, not only to satisfy the specified dimensional accuracy, but also to prevent occurrence of crinkling and to ensure smooth curvature on both internal and external faces in consideration of high fatigue resistance. In order to establish an optimum upsetting condition, experiments covering a wide range of parameters were conducted[2]. As an example, the relationship of maximum crinkling depth λ (maximum crinkling depth/upset thickness) to upset ratio in the external upsetting is shown in **Fig. 3**. Since the smaller the t/D ratio (wall thickness/outer diameter) is, the deeper the crinkling tends to be; thus, there exists a critical upset ratio for particular t/D to keep the crinkling depth below a certain level. The critical upset ratio for two-shots upsetting is given by Eqs. (1) and (2):

$$\alpha_{1cr} = f(t/D) \quad \cdots\cdots \textbf{(1)}$$

$$\alpha_{2cr} = (1 + \alpha_{1cr})\{1 + f[(1 + \alpha_{1cr})t/D]\} - 1 \quad \cdots\cdots \textbf{(2)}$$

where α_{1cr} and α_{2cr} are critical upset ratios for the 1st and 2nd shot, respectively.

The partition of upset ratios for the 1st and 2nd shots is also important and can be given by Eq. (3),

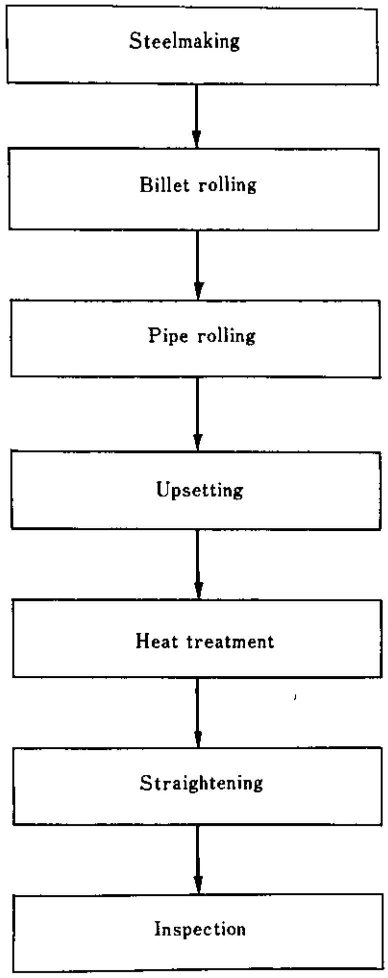

Fig. 2 Manufacturing process of drill pipes

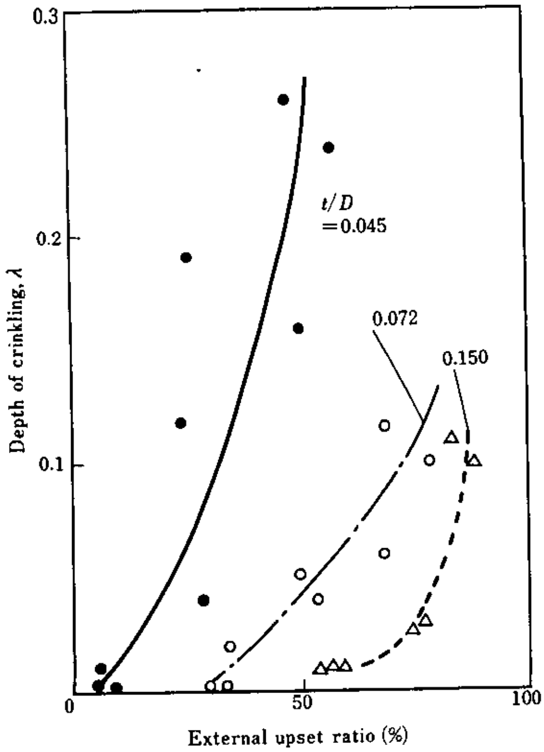

Fig. 3 Effect of external upset ratio on depth of crinkling[2)]

$$\alpha_1 = \alpha_2 \times \frac{\alpha_{1cr}}{\alpha_{2cr}} \cdots\cdots (3)$$

$$\alpha_{1cr} < \alpha_2 < \alpha_{2cr}$$

where α_1 and α_2 are upset ratios for the 1st and 2nd shots, respectively.

The same applies to the internal upsetting. The relationship of critical upset ratio to t/D ratio in the internal and external upset is shown in **Fig. 4**.

Moreover, the geometry of upset curvature is affected by upset ratio per shot and heating conditions. Upset of good profile can, thus, be realized by setting appropriate upset conditions on the basis of these findings.

2.2.3 Heat treatment

For the quench and temper treatment, the heat treatment facility for tubing is used[3)]. The quenching facility is of an internal and external immersion quenching type for high pressure internal water jet and agitated external flow, to ensure homogeneous quenching through the entire thickness and over the whole length of the pipe. Besides, quenching and tempering furnaces are each equipped with a rapid heating device for upset portion, so as to assure uniform mechanical properties by reducing the difference in heating time between heavy walled upset and body.

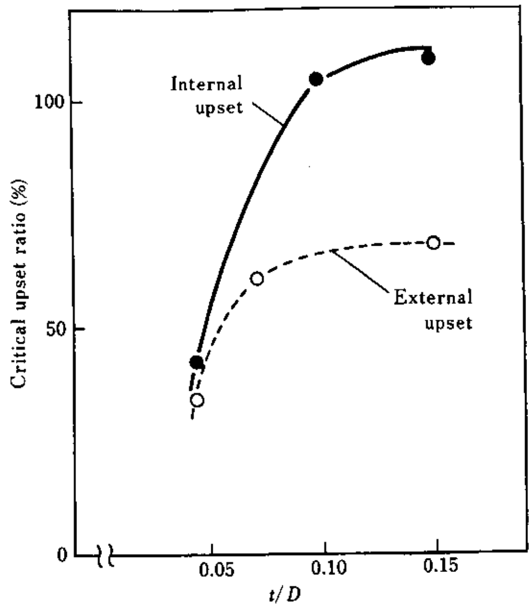

Fig. 4 Effect of t/D on critical upset ratio[2)]

3 Properties of Drill Pipe

Through the trial manufacture and testing on the basis of fundamental concepts described in the preceding section, the chemical compositions and manufacturing conditions of drill pipe have been determined and the manufacturing technology has been established. The present section describes the properties of drill pipe of Grades E, X95, G105 and S135.

3.1 Metallurgical Properties

3.1.1 Hardenability

A CCT diagram of Grade S135 drill pipe is shown in **Fig. 5**. The martensitic structure is obtained in a wide range of cooling rate. In order to evaluate the hardenability of upset portion after the friction weld, a hardenability test was conducted through the end-quenching method.

The distribution of hardness was measured on a small size specimen of 6.35 mmϕ, specified under ASTM A25, which was one-end-quenched after holding at 925°C for 30 min and was tempered at 565°C for 1 h. The result is shown in **Fig. 6**. At a point 20 mm away from the quenched end, the hardness was higher than 30 HRC, suggesting that adequate hardness would be obtained at the upset after the friction welding and the subsequent heat treatment.

3.1.2 Microstructure

The microstructures of pipe body and upset portion in drill pipes of Grades E, X, G and S after the heat treat-

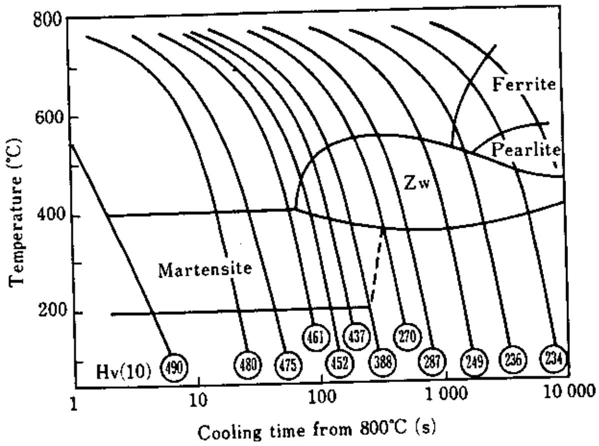

Fig. 5 CCT diagram of steel for S135 drill pipe

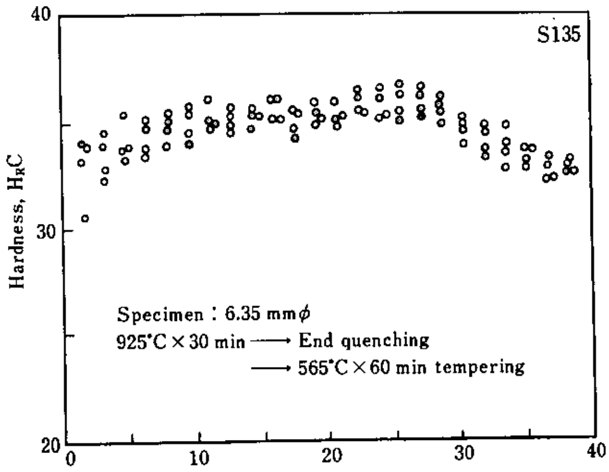

Fig. 6 Hardness distribution in Jominny specimen after end-quenching and tempering (S135 drill pipe)

ment are shown in **Photo 1**. These structures consist of tempered martensite, and the formation of ferrite is not recognized even at the upset portion.

3.1.3 Cleanliness

The cleanliness of drill pipe of various grades is shown in **Table 3**. As the content of non-metallic inclusion is less than 0.03%, it becomes evident that drill pipe of every grade is clean enough.

3.2 Mechanical Properties

3.2.1 Tensile properties

The results of tensile tests (with API specimens) are shown in **Table 4**. The tensile strength satisfies the specified values adequately, and there is little difference whithin the whole length of pipe.

3.2.2 Hardness

The results of measuring hardness distribution in the longitudinal and radial direction of pipe including upset portions are shown in **Fig. 7**. The difference in hardness between upset and body is so small that the pipe can be regarded as uniform with respect to strength.

3.2.3 Impact properties

The results of Charpy impact test at the middle of pipe body are shown in **Table 5**, and an example of transition curve in **Fig. 8**. The $_vT_{rs}$ in the L direction is below -50°C for every grade, indicating excellent impact properties.

3.2.4 Collapse properties

The collapse test was conducted with samples taken from the top, middle and bottom of pipe, to determine the collapse strength. The results are shown in **Table 6**.

Table 3 Cleanliness of drill pipes

Grade	Cleanliness			
	dA	dB	dC	Total
E	0.016	0	0.008	0.024
X95	0.021	0	0.004	0.025
G105	0.017	0	0.000	0.017
S135	0.008	0	0.008	0.016

Table 4 Tensile properties of drill pipes

Grade	Size		Upset	Position								
				Top			Middle			Bottom		
	OD×Weight	Thickness		YS	TS	El.	YS	TS	El.	YS	TS	El.
	in ×lbs/ft	mm		kgf/mm²		%	kgf/mm²		%	kgf/mm²		%
E	5×19.5	9.19	IEUE	71.1	79.9	28	68.8	78.3	28	68.6	78.3	29
X95	4½×16.6	8.56	IEUE	74.3	85.6	26	73.5	84.2	26	74.0	84.5	27
G105	4½×16.6	8.56	IEUE	88.0	96.1	22	87.7	96.8	22	87.7	95.4	22
S135	4½×16.6	8.56	IEUE	99.1	107.9	21	99.5	108.2	21	99.0	108.5	21

IEUE : Internal external upset end

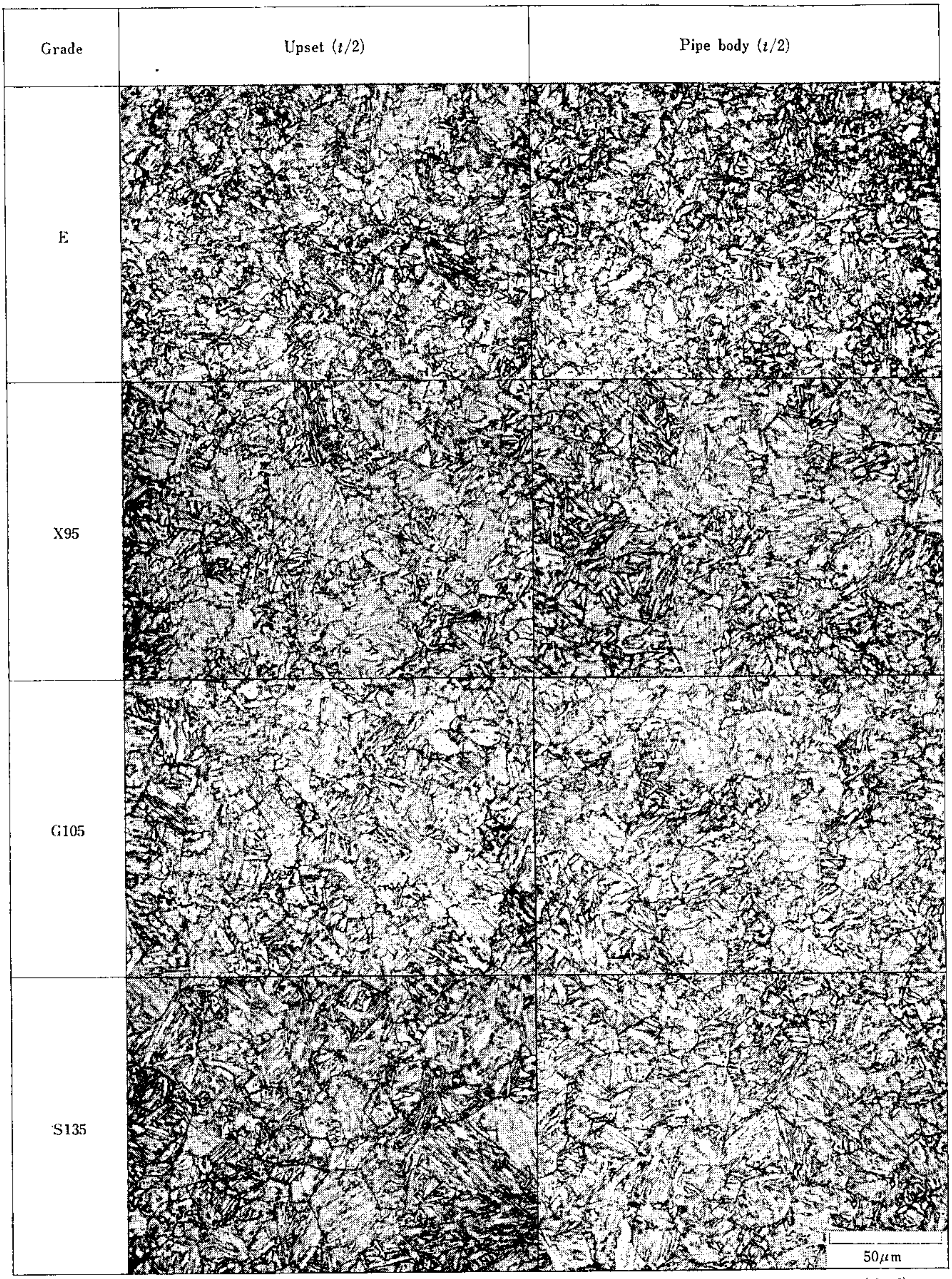

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Photo 1 Microstructures of pipe body and upset portion in drill pipes

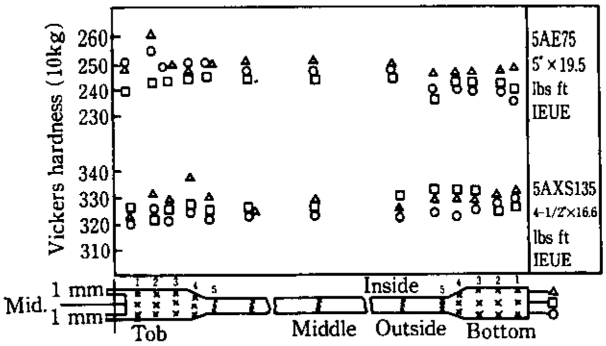


Fig. 7 Hardness distribution in E75 and S135 drill pipes

Table 5 V-notched impact test results

Grade	Direction	Specimen size mm	v*Trs* °C	vE_{-40} kgf·m
E	L	10×7.5	−128	16.0
	C	10×5.0	−85	5.5
X95	L	10×5.0	−145	9.8
	C	10×5.0	−100	4.3
G105	L	10×5.0	−130	7.9
	C	10×5.0	−95	4.0
S135	L	10×5.0	−57	3.1
	C	10×5.0	−35	1.5

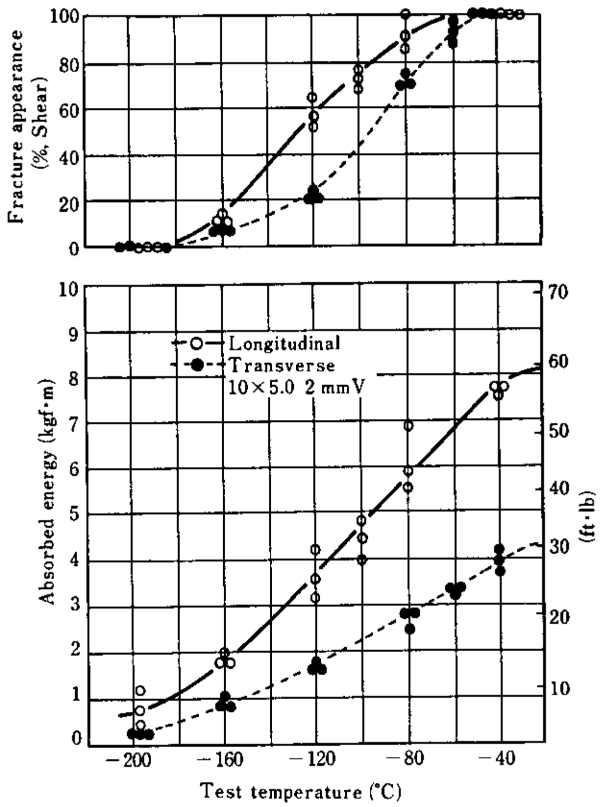


Fig. 8 Transition curves in Charpy impact test of G105 drill pipe

The collapse strength of drill pipe of every grade is 10~40% higher than that specified in the API BUL 5C2. Though the collapse strength of a pipe depends upon yield strength and t/D ratio, it is known that residual tensile stress reduces the collapse strength to some extent.[4] The residual stress was 5 kgf/mm^2 and under in Grade E and 10 kgf/mm^2 and under in S135, which were not so high as to deteriorate the collapse strength.

3.2.5 Fatigue properties

The results of rotating bending fatigue test with 8 mmϕ round bar specimens sampled from the bodies of Grade E, G and S drill pipes are shown in **Fig. 9.** While the fatigue strength obtained from a full-sized pipe speci-

Table 6 Collapse strength of drill pipes

Grade	Size (in.×lbs/ft)	Collapse strength kgf/cm^2 (psi): API specification	Top	Middle	Bottom	Actual/API
E	5×19.5	703 (10 000)	951 (13 530)	979 (13 920)	911 (12 960)	1.30 ~ 1.39
X95	4½×16.6	896 (12 750)	1 116 (15 870)	1 171 (16 650)	1 196 (17 010)	1.24 ~ 1.33
G105	4½×16.6	972 (13 820)	1 181 (16 800)	1 225 (17 430)	1 244 (17 700)	1.22 ~ 1.28
S135	4½×16.6	1 181 (16 800)	1 327 (18 870)	1 324 (18 840)	1 394 (19 830)	1.12 ~ 1.18

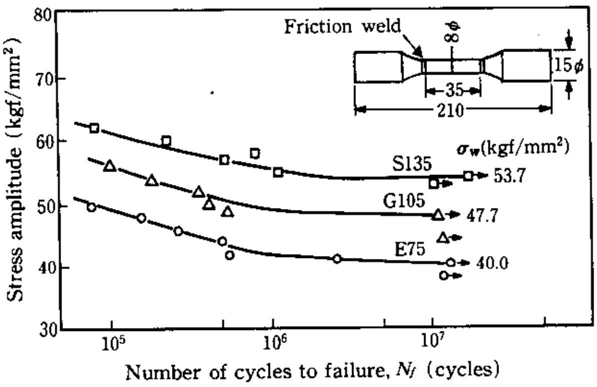


Fig. 9 S-N curves in rotating bending fatigue of grade E, G and S drill pipe bodies

Specimen	Stress range (kgf/mm²)	Number of cycles to failure	Upsetting condition
G1	65	1.21×10^5	Bad
G2	65	2.30×10^5	Good

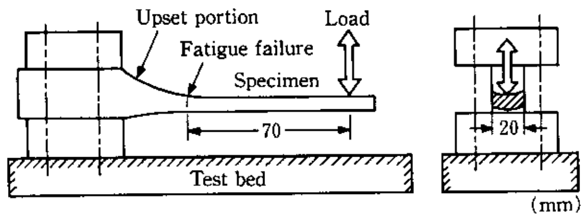


Fig. 10 Schematic illustration for fatigue test of upset portion of G105 and test result

men is known to be considerably lower than that shown in Fig. 9 due to the effect of mill scale and the stress concentration at the upset portion[5,6], the result shows that the base material has satisfactory fatigue strength corresponding to each strength level.

3.3 Profile of Upset Portion

An example of metal flow for the upset portion of Grade G105 drill pipe is shown in **Photo 2**, where the result of optimum upset condition (G2) is compared with that of an artificially worsened upset condition (G1). It is evident that, while under the optimum upset condition no disturbance occurs in the metal flow and the profile varies smoothly from the heavily upset internal upset portion to the body, under the improper upset condition the profile changes abruptly causing marked stress concentration.

The influence of upset geometry on the fatigue properties was examined in the experiment with small size specimens. The experimental arrangement and the results are shown in **Fig. 10**. Arc-shaped specimens of 20 mm width were sampled along the longitudinal direction of pipe from the upset portions, as shown in Photo 2, prepared under different upset conditions, and subjected to the cantilever-beam-type fatigue test, as illustrated in Fig. 10. The fatigue failure occurred at the curved area of upset portion where the stress concentration was high. The fatigue life of upset portion prepared under the optimum condition was twice as long as that of upset portion worked under the improper condition. It may be concluded, therefore, that the smooth profile at the upset portion of drill pipe effectively improves its

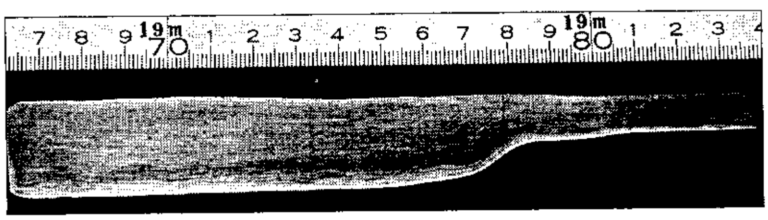
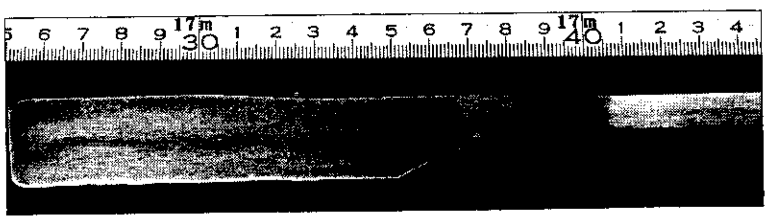
No.	Upset		Metal flow and profile
	Condition	Shape	
G 1	Bad	Bad	
G 2	Good	Good	

Photo 2 Effect of upsetting condition on the profile and metal flow of the upset portion (G105)

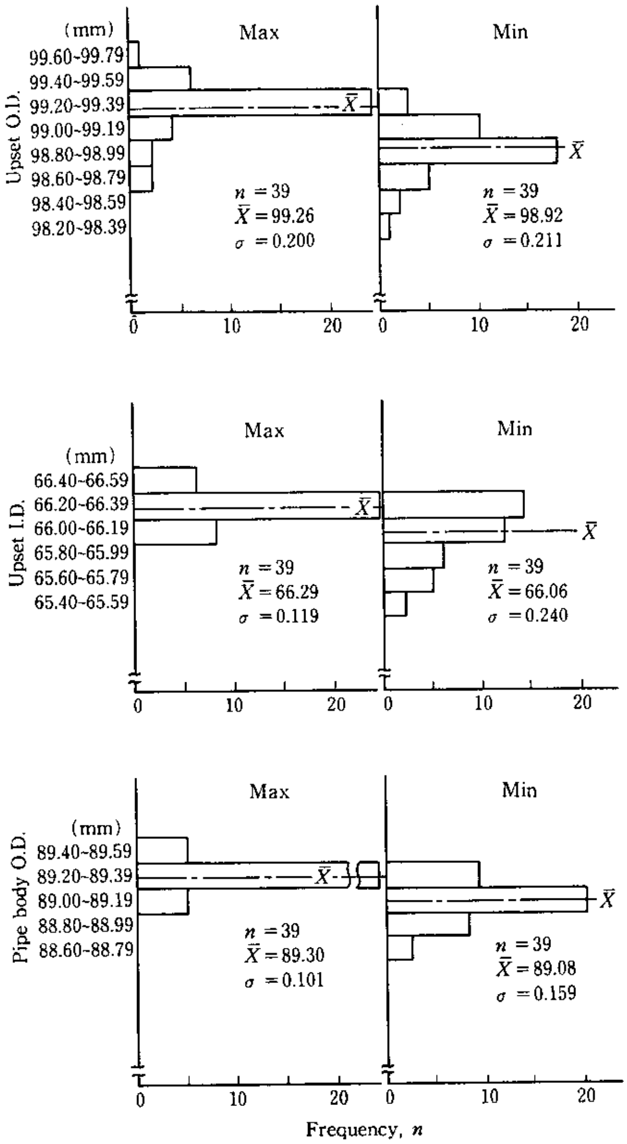


Fig. 11 An example of diameter histograms in grade E drill pipes (3½″ × 13.3 lbs/ft × R-2, EUE)

fatigue properties, and the upset condition to realize such a profile has, therefore, been adopted in the production process.

4 Production of Drill Pipe

Before starting the commercial production of drill pipe, sample pipe of various grades were sent to principal tool joint manufacturers overseas and were approved through various kinds of tests. The commercial production has been in practice since August 1982. Histograms of produced pipe diameters are shown in **Fig. 11.**

5 Conclusions

Technology for manufacturing grades E, X, G and S drill pipes of the API specification has been established to start the commercial production.

In manufacturing the drill pipe, the chemical composition was designed on the basis of C-Mn-Mo steel for the sake of securing adequate strength and toughness, and the contents of S and P were controlled to 0.010% or less and 0.020% or less, respectively, for the purpose of improving the fatigue resistance. Moreover, the upsetting condition to ensure smooth profile of upset portion was established.

The drill pipe manufactured in this way not only satisfy the specified strength with sufficient margin, but also are so homogeneous that little difference in strength exists whithin the whole length of pipe. There are also little difference in hardness between the upset portion and the body. As for the impact property, ${}_{v}T_{rs}$ in the L direction is below −50°C for every grade. The collapse strength satisfies the specification adequately.

While it is expected that the operating conditions become more and more severe, greater efforts will be made to attain further improvements in the quality of drill pipes so as to meet the prospective needs.

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