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Synopsis :

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Production of Hot Rolled Steel Sheet for High Strength Steel Pipes with Good Cold Formability*[1]

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Characteristics of the newly developed steel sheet and steel pipe are as follows:

(1) The steel is a low C and Ti bearing steel.

(2) Hardening due to electrical resistance welding of pipe is little because of low C content, and the pipe shows good machinability and excellent formability without heat treatment for softening.

(3) Mechanical strength and fatigue properties of the pipe are also better than those of STKS 1C (Cr-Mo steel seamless pipe).

(4) The pipe is less expensive than conventional high strength pipe, because heat treatment is not necessary and alloy content is low. This leads to higher productivity at the users of this pipe.

1 Introduction

High strength steel sheets have been widely used in recent years to decrease the weight of automobiles and improve mileage. The weight of high strength steel sheets used in some types of passenger cars exceeds 10% of the total weight, and the application of high strength steel sheets has expanded from the "white" body to the underside such as chassis and wheels.[1,2)]

With automobile parts consisting largely of pipes and shafts, one of challenging tasks is a reduction in weight and cost that would be attainable by the strengthening of steel pipes and the replacing of steel bars, castings, and forgings with steel pipes.[3,4)]

Motorcycle frames and other parts also use many steel pipes, mainly machine-structural carbon steel pipes (JIS G3445 STKM) and structural alloy steel pipes (JIS G3441 STKS—currently SCM). Since these conventional high strength steel pipes are produced from steels of high carbon equivalent design containing a large amount of carbon and alloy elements such as Cr and Mo, the weld zone is too hard, causing workability problems during flattening and expanding, including low machinability. For this reason, these pipes require heat treatment after pipe-making. Re-heating treatment may even at times become necessary after welding and assembly.

Labor cost for time spent in heat treatment and pickling and production costs including that of alloying elements have increased. The situations are considered similar with steel pipes for automobiles, motorcycles, and furniture.

Against this background, the authors attempted to develop high strength pipe steels of sufficient strength to replace STKM and STKS, and possessing excellent workability, machinability, and fatigue strength without

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heat treatment. As a result of these efforts, 50–60 kgf/mm^2-class high tensile steel pipes meeting the above-mentioned requirements have been successfuly developed, using low-carbon precipitation-hardened steel with a basic composition of 0.05%C-1.3%Mn-0.06%Ti. These pipes are already in general production for motorcycle frames and handlebars.

This report describes the results of examination of the chemical composition obtained during research and development, as well as mechanical properties of the newly developed steel and steel pipes.

2 Examination of Chemical Composition

2.1 Test Method

2.1.1 Test specimens

Table 1 shows the chemical composition and sheet thickness of sample steels. A continuously cast slab reheated to 1 300°C was rough-rolled to a specified thickness by a 7-stand hot strip finishing mill. The steel sheet was slit, and pipe specimens of 19.1 to 22.2 mmϕ were produced under the pipe-making welding conditions shown in **Table 2**. The cold rolled steel sheet 1.8 mm thick shown in Table 1 is the conventionally-used STKM 18A, a solid-solution hardened steel.

2.1.2 Test conditions

(1) Tensile test

A tensile test was conducted using a JIS No. 11 tensile test piece and placing the core metal in the grabbing portion.

Table 2 Condition of electric resistance weld

Speed (m/min)	Voltage (V)	Amperage (A)	Upset (mm)
100-120	9-10	20-22	1.0

(2) Hardness test of electrical resistance weld

Measurement was made at a cross-sectional 1/4-thickness portion which included an electrical resistance weld, using a Vickers hardness tester (load: 1 kgf).

(3) 90° flattening test

A pipe 100 mm in length was pressed as shown in **Fig. 1** so as to give the maximum bending deformation to the weld zone. When cracks developed, the height of the pipe was measured. On the basis of the measured values, the following five ratings were assigned.

0: No crack at a flat bend ($H = 2t$)
0.5: Hairline crack at a flat bend ($H = 2t$)
1: Small crack at a flat bend ($H = 2t$)
2: Crack at a bending from $H = D/2$ to full flattening
3: Crack before a $D/2$ bend

Problems in practical application exist at ratings of 2 and 3.

(4) Flaring test

A pipe 40 mm in length was flared by the procedure shown in **Fig. 2**, until pipe end developed necking. Evaluations were based on the ratio (D/D_0) of post-testing diameter (D) to original diameter (D_0).

Table 1 Chemical composition of steel used

(wt %)

TS grade (kgf/mm^2)	Steel No.	t (mm)	C	Si	Mn	P	S	Al	Ti	Nb	V	Cr	C_{eq}*2)
60	A	1.6	0.04	0.03	1.26	0.015	0.003	0.025	0.061				0.251
	B	1.6	0.05	0.55	1.25	0.019	0.003	0.028	0.060				0.281
	C	1.6	0.08	0.19	1.33	0.013	0.002	0.010		0.049			0.309
	D	1.8	0.06	1.03	1.42	0.021	0.002	0.050				1.00	0.540
	E	1.8	0.13	0.27	1.36	0.019	0.006	0.036		0.031	0.038		0.368
	F	1.8	0.11	0.26	1.32	0.019	0.007	0.030		0.026	0.076		0.346
	G	1.6	0.11	0.38	1.48	0.025	0.005	0.045		0.038			0.372
	H	1.8	0.11	0.30	1.42	0.014	0.003	0.028		0.030			0.359
	I	1.8	0.11	0.53	1.49	0.023	0.005	0.034		0.052			0.380
	J	1.6	0.13	0.30	1.34	0.018	0.003	0.029		0.035			0.363
50	K	1.6	0.05	0.51	0.88	0.020	0.003	0.025	0.035				0.218
	L	1.8*1)	0.18	0.48	1.41	0.017	0.007	0.023					0.435

*1) Cold (STKM 18A)
*2) $C_{eq} = C + Si/24 + Mn/6 + Ni/40 + Cr/5 + Mo/4 + V/14$

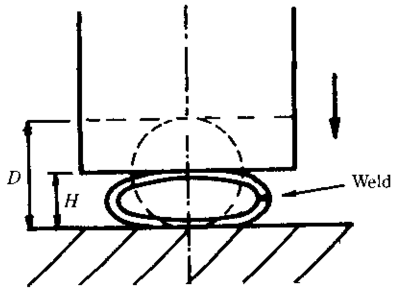


Fig. 1 90° flattening test method

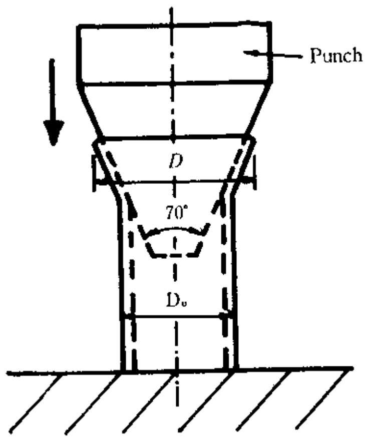


Fig. 2 Flare forming test method

2.2 Test Results and Discussion

2.2.1 Hardness of weld and effects of chemical composition

Figure 3 shows the hardness of an electrical resistance weld with conventionally manufactured STKM 18A, a C-Si-Mn solid-solution hardening type cold rolled sheet steel. The maximum hardness of the weld is exceptionally high at about HV 500. Since machinability and formability deteriorate in this state, annealing for softening is required. The maximum hardness of the weld zone drops to about HV 230 with softning annealing at 700°C for 3 min. However, base metal hardness also drops, and consequently, pipe tensile strength drops. For this reason, the manufacture of high strength steel pipes exceeding 60 kgf/mm^2 is difficult using solid-solution hardening type steel sheets with the abovementioned composition.

Figure 4 shows the hardness of weld zone in precipitation-hardening type steel with varying carbon contents and carbon equivalents. As carbon content and carbon equivalent decrease, weld zone hardness also decreases. It was found that steel A with 0.04% carbon shows little difference in hardness between the weld zone and base metal, thereby indicating a uniform structure. The maximum hardness of steel A of this composition

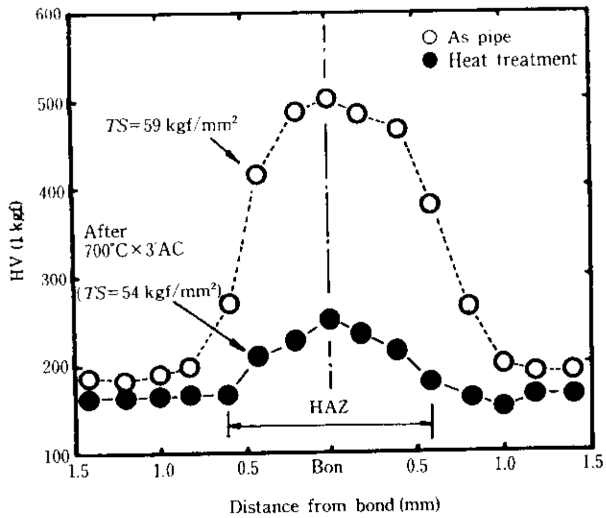


Fig. 3 Hardness profile of welded portion in solid solution hardening type STKM 18A (steel: L)

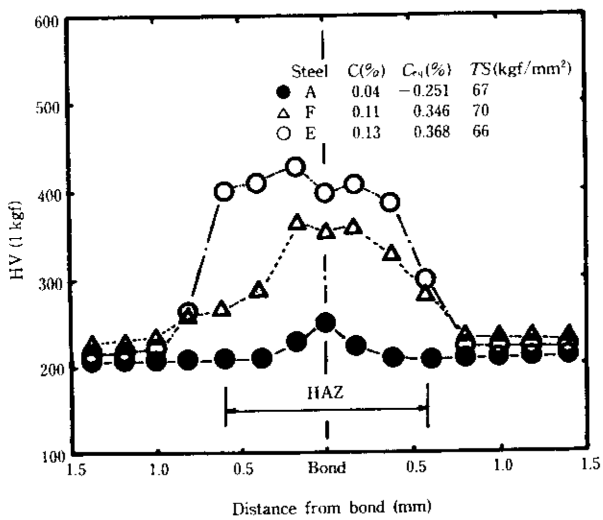


Fig. 4 Effect of C contents and C_{eq} on hardness profile of welded portion

showed no marked difference from that of softening-annealed steel of the cold-rolled material STKM 18A. Further, the tensile strength of pipe of steel A is as high as 67 kgf/mm^2, thereby indicating the possibility of manufacturing a 60 kgf/mm^2-grade steel pipe which will not develop hardening at electrical resistance welds.

Figure 5 shows the relation of the maximum hardness of the weld zone to carbon content and carbon equivalent. Carbon content is found to be the principal factor governing the weld zone hardness.

This suggests that even with high carbon equivalent steel containing alloying metals such as chromium, weld zone hardness can be relatively lowered by decreasing carbon content.

The close correlation of the weld zone hardness to

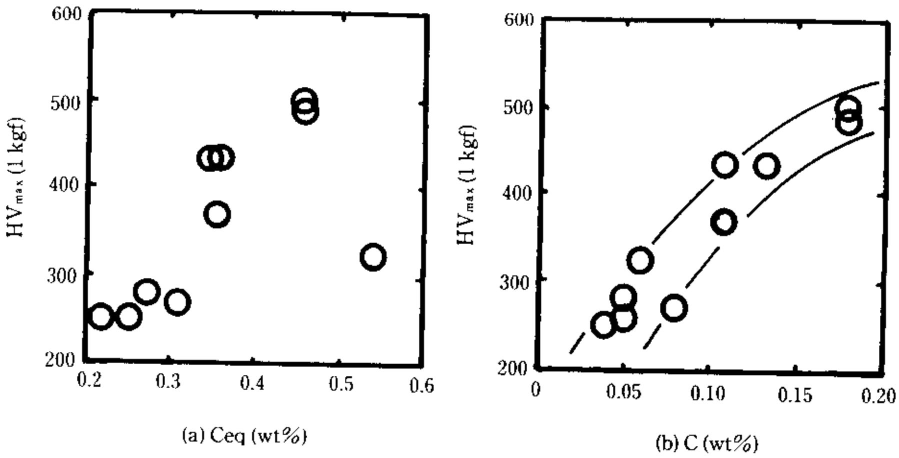
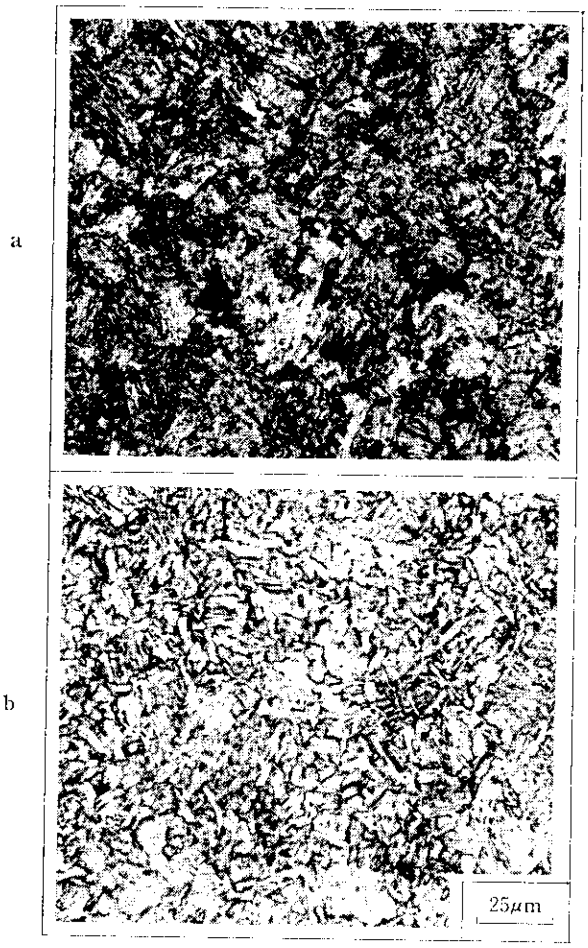


Fig. 5 Effect of C_{eq} and C contents on maximum hardness of welded portion



a: 0.11% C-0.346% C_{eq} (steel F)
b: 0.04% C-0.251% C_{eq} (steel A)

Photo 1 Microstructures of welded portions

carbon content is explained by some particular welding conditions peculiar to thin-walled ERW pipe manufacture, such as small heat input and a rapid cooling after welding, which cause formation of a hard martensitic phase. **Photo 1** shows examples of such weld zone microstructures. With steel F, which has a high carbon content of 0.11%, almost the entire weld zone shows a lath-like martensite structure. Weld zone hardness depends on the hardness of the martensite phase, which in turn is governed by carbon content. It is known that the hardness of the martensite phase due to carbon content is HV 500 for steel with 0.20% carbon, decreasing to HV 350 with a 0.10% carbon steel.[5] Results of the present investigation are in agreement with this finding.

Steel A, with a low carbon content of 0.04%, has a structure consisting mainly of pro-eutectoid ferrite and bainite, with a small quantity of martensite phase, as shown in Photo 1. Because the martensite phase is small in this low carbon steel, the degree of weld zone hardening is exceedingly slight. The reason for the tendency, shown in Fig. 5(b), towards a steep drop in maximum hardness with low carbon steel of 0.08% carbon content and under is the development in the steel of a structure consisting mainly of ferrite and bainite, with a relatively small quantity of martensite, as mentioned above. That is to say, the relation between weld zone hardness and carbon content depends on changes in the hardness of the martensite in the high carbon content region, and on changes in the martensite phase ratio, in addition, in the low carbon content region. Therefore, reduction in carbon content is extremely effective in inhibiting the tendency towards the hardening of weld zone.

2.2.2 Flattening test results

Figure 6 shows the relation of carbon equivalent and tensile strength to flattening test values.

No correlation of carbon equivalent and tensile strength to flattening test values appears to exist. However, the correlation between carbon content and flattening test values can be seen in **Fig. 7**. When carbon content increases, the flattening test values deteriorate, mainly due to the effect of increased weld hardness.

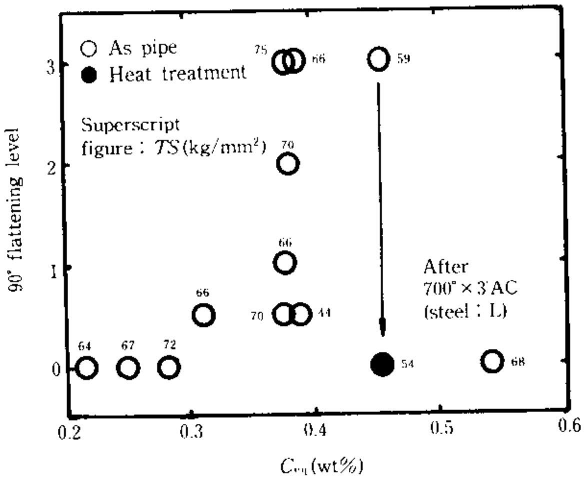


Fig. 6 Effect of C_{eq} and TS on 90° flattening properties

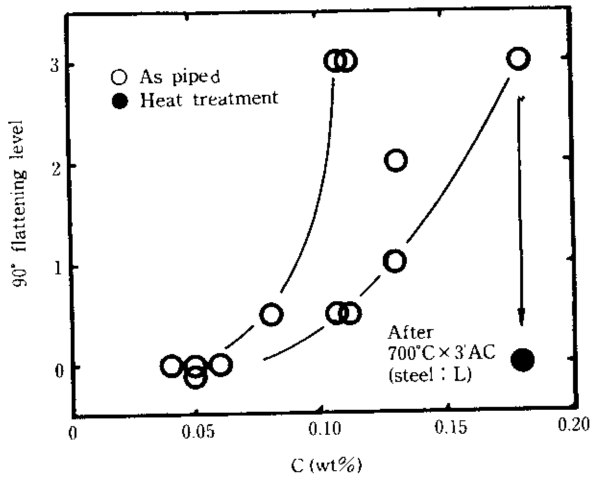


Fig. 7 Effect of C contents on 90° flattening properties

Electric resistance weld zones show a rise in metal flow on upset working. In the flattening test, therefore, the same type of deformation appears as observed in the sheet-thickness-direction tensile test of the base metal, and cracking is liable to occur. For tensile elongation in the thickness direction, sulfide inclusions in the steel are particularly detrimental. Consequently, sulphur content can be expected to affect flattening test values. Lower base metal sulphur content gives improved flattening properties, as shown in **Fig. 8**. As clearly shown in Table 1, however, steel with lower sulphur content also had lower carbon content, and thus a lower degree of weld hardness. However, because STKM 18A, with both high carbon and sulphur contents, shows a satisfactory flattening test value after softening annealing, it can be concluded that carbon content and related weld hardness have a greater effect on flattening test values than does sulphur content.

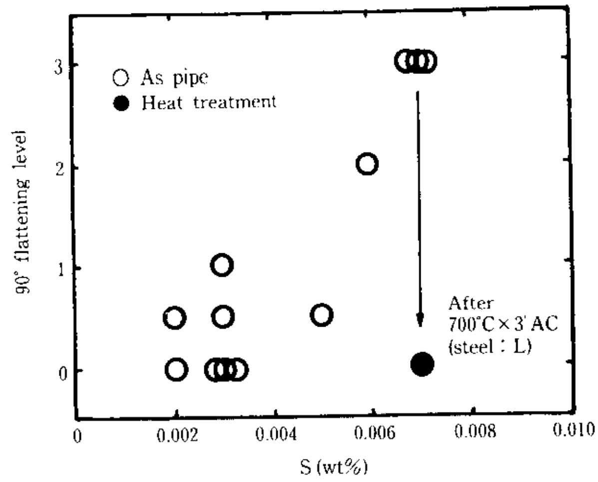


Fig. 8 Effect of S contents on 90° flattening properties

2.2.3 Flaring test results

Figure 9 shows the effect of carbon content and the addition of titanium on flaring ratio. The flaring ratio varies greatly with carbon content; when carbon content increases, weld hardness becomes higher and the flaring ratio becomes lower. The most important effect of titanium addition is reduction of weld hardening. Titanium addition, because of the high capacity of precipitation hardening, permits low carbon content design. The low C–Ti steel which has been developed by the authors shows excellent flaring at equal strengths, as shown in **Fig. 10**.

The flaring ratio indicates the stretch flangeability of the pipe end and is considered to be affected by sulphur content. **Figure 11** shows the effect of sulphur content on the flaring ratio, indicating that as sulphur content increases, the flaring ratio decreases. The Ti-addition steel shows an excellent flaring ratio, sulphur levels

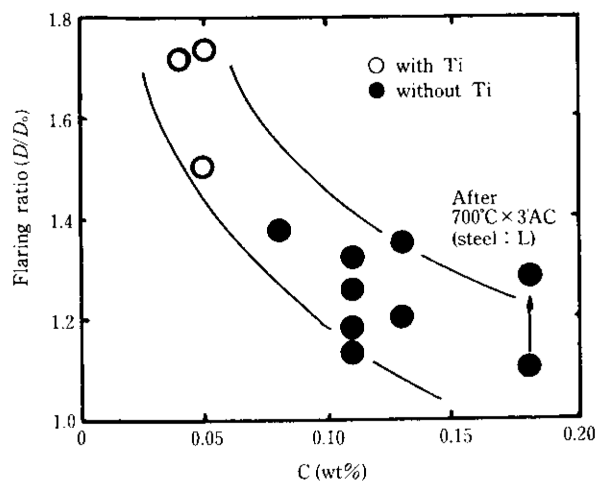


Fig. 9 Effect of C contents and Ti-addition on flare forming

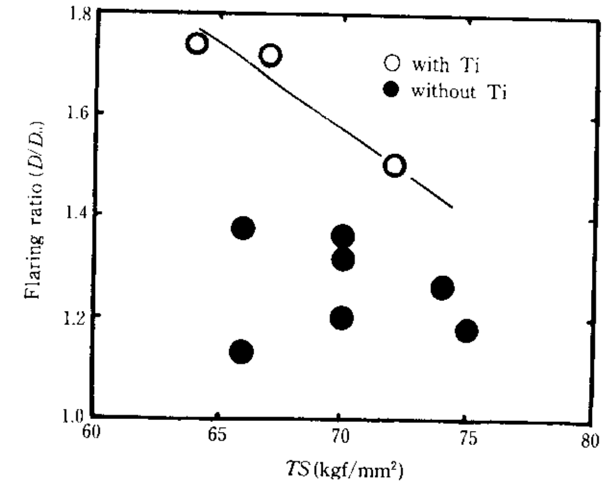


Fig. 10 Effect of *TS* and Ti-addition on flare forming

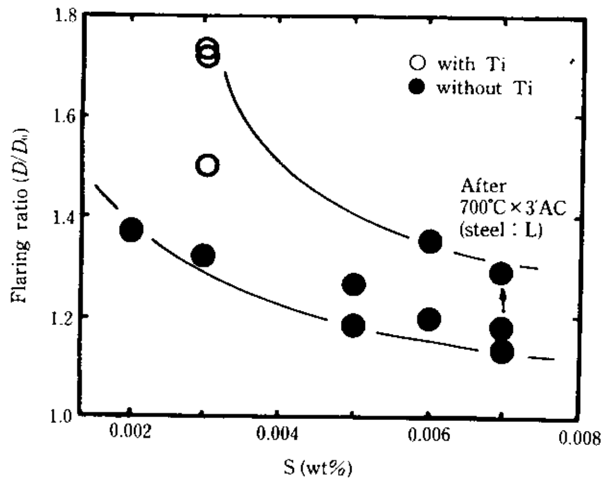


Fig. 11 Effect of S contents and Ti-addition on flare forming

being equal. Although the weld hardness of softening-annealed STKM 18A is on the same level as that of Ti-addition low carbon steel and the tensile strength of this STKM 18A pipe is lower than that of the low C–Ti steel, the former shows a lower flaring ratio than the latter.

This phenomenon is attributed to high sulfur content in STKM 18A steel: thus, it can be seen that sulfur content as well as weld hardness has a great effect on flaring ratio.

Titanium in Ti-added steel has a greater precipitation hardening capacity than other precipitation hardening elements such as niobium or vanadium. Since an increase in the Ti-addition quantity can therefore be expected to effectively improve precipitation hardening, it is possible to design low carbon and low carbon equivalent steels by using Ti-addition steel.[6] Since titanium addition is also expected to be effective in sulfide shape control, Ti-addition steel allows optimum composition design for flare formability.

3 Properties of Low C–Ti Pipe Steel and Steel Pipes

From test results, it has become clear that for improving flare formability, Ti-addition low C steel with low sulphur content is desirable as material for high strength pipe. Such steel has already been adopted for frames, handlebars, and head pipes of motorcycles. The properties of the newly developed pipe steel and also of pipe made from that material, are described below.

3.1 Composition Design and Material Properties of Pipe Steel

Table 3 shows chemical composition and mechanical properties of the pipe steel which has been put into practical use, that is, the newly developed 50 to 60-kgf/mm^2-grade hot rolled high strength steel of a titanium-added

Table 3 Chemical compositions and mechanical properties of hot-rolled high strength steel with 1.6 mm thickness

TS grade (kgf/mm²)	Chemical composition (wt %)							Mechanical property								
	C	Si	Mn	P	S	Al	Ti	Direction	*YP* (kgf/mm²)	*TS* (kgf/mm²)	*El* (%)	Bend (R=Ot)	*NEl** (%)	*SEl*** (%)	$\bar{n}$	$\bar{r}$
50	0.05	0.03	0.95	0.015	0.003	0.025	0.044	L	46.9	54.4	29	Good	12	45	0.134	1.04
								C	47.9	55.3	28	〃	11	48		
55	0.04	0.04	1.07	0.016	0.003	0.023	0.052	L	50.5	56.8	27	〃	11	42	0.127	1.05
								C	51.4	58.1	25	〃	10	37		
60	0.05	0.04	1.26	0.017	0.003	0.025	0.061	L	54.1	61.6	25	〃	11	35	0.123	0.99
								C	58.3	63.5	26	〃	10	30		

* Notch tensile elongation
** Side bend elongation

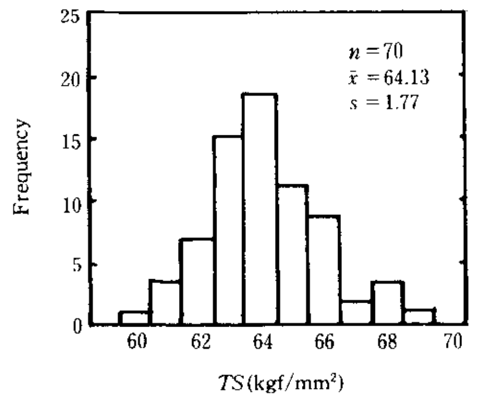


Fig. 12 Histogram of *TS* in 60 kgf/mm^2 grade high strength hot-rolled steel ($t = 1.4$ to 1.7 mm)

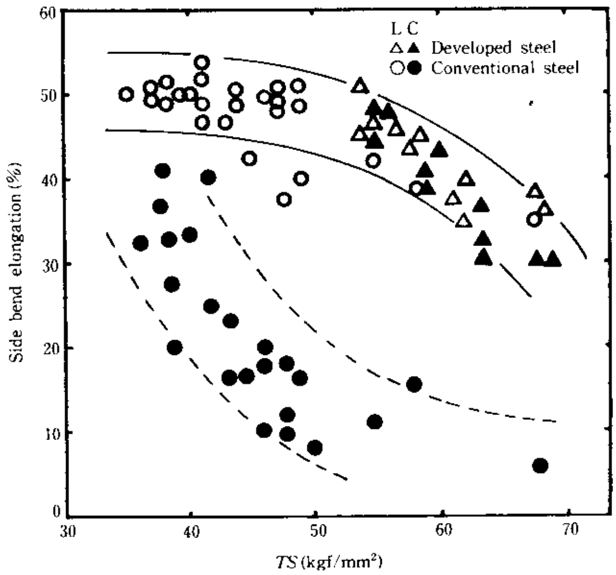


Fig. 13 Relation between *TS* and stretch flangeability (side bend elongation)

0.05%C-Mn composition.

Figure 12 shows a histogram of the tensile strength of the 60-kgf/mm^2-grade steel. The figure shows results of the manufacture of 1.4 to 1.7-mm-thick sheets of this steel. The results indicate its feasibility for use in stabilized production.

Figure 13 shows the relation between tensile strength and the side bend elongation value[7] which expresses stretch flangeability, indicating that the newly-developed steel sheets show better stretch flangeability than that of ordinary steel sheets. For instance, 60-kgf/mm^2-grade high strength steel sheets show the same excellent stretch flangeability as that of conventional 35 kgf/mm^2-grade steel sheets. In addition, the difference in tensile strength between the rolling and lateral directions in the former steel sheets is very small.

3.2 Welded Joint Properties

Steel pipe applications often require welding. For instance, motorcycle frames are of welded construction. The tensile strength of welded joints in the newly developed high strength pipe steel and steel pipes is not particularly different from that with the original pipe steel or pipes, as shown in **Fig. 14**, indicating no problems exist for practical applications. When manual arc welding is performed, however, the combined effect of comparatively higher welding heat input due to a large welding rod diameter and the thinness of the steel sheet causes an increase in the width of the softened area of the HAZ, and may result in lower welded joint tensile strength than with the original sheet or pipe. Thus careful consideration of the welding methods and conditions is necessary. **Figure 15** shows results of an investigation of the amount of softening and the width of softened areas in welds. CO_2 gas arc welding heat input is relatively lower, and produces a smaller amount of softening and narrower softened areas than manual welding. As a result, the tensile strength of the joint is higher than that of the base metal as shown in Fig. 14.

3.3 Fatigue Properties

Properties required of automobile and motorcycle parts made of steel pipes include static strength, rigidity, weldability, workability, and formability. Besides these properties, fatigue strength is considered necessary for determining the strength and thus the required size of parts made of steel pipes. In particular, fatigue strength of welded joints on the high cycle side is considered an important property.

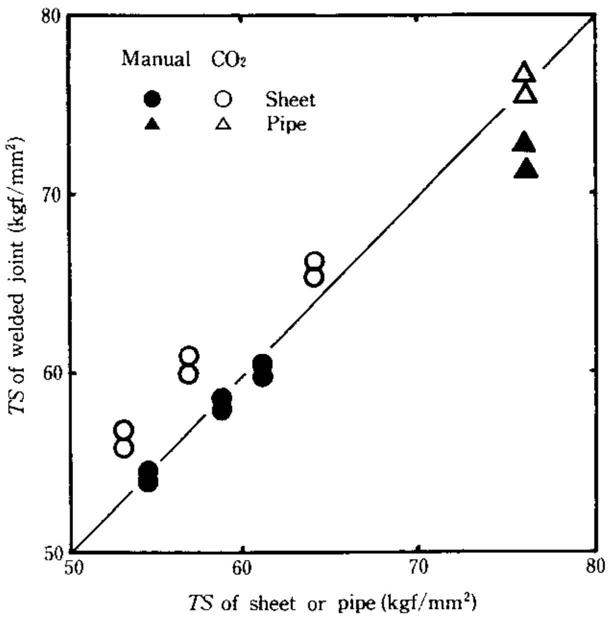


Fig. 14 Relation between *TS* of sheet or pipe and *TS* of arc welded joint

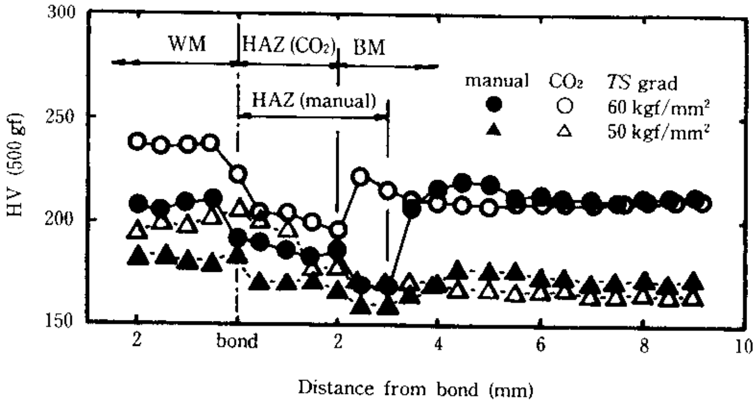


Fig. 15 Hardness profile of manual-arc-welded and CO_2-gas-arc-welded joints

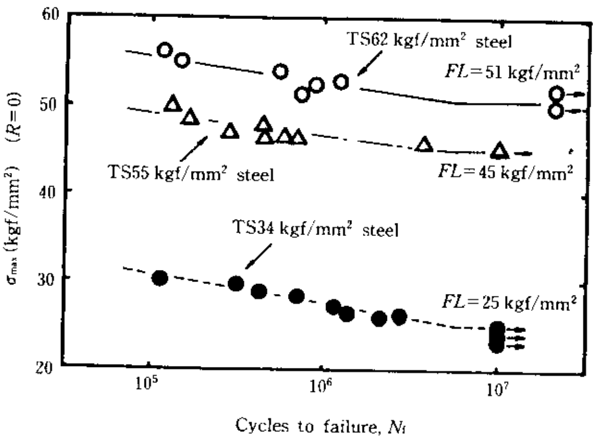


Fig. 16 Fatigue behavior of hot-rolled steel sheet

3.3.1 Fatigue properties of high strength pipe steel

Fatigue strength of steel sheets is known to be proportional to the static strength of material. **Figure 16** shows the results of a tensile fatigue test of high strength pipe steel and soft steel sheets used for STKM 11A and 13A. The new high strength pipe steel shows a higher fatigue limit than the soft steel sheets. When its fatigue limit is expressed in ratio to the tensile strength of its original material, the high strength steel sheet shows a better fatigue property, as high as 82%, in contrast to 74% for soft steel sheet, for a pulsating tensile stress of R (min. stress/max. stress) = 0.

3.3.2 Fatigue properties of high strength steel pipes

A 4-point-bending fatigue test was conducted on the 60-kgf/mm^2-grade high strength steel pipe and a seamless Cr-Mo steel pipe of STKM 1C of equal strength. **Figure 17** shows the test method. The diameter at the center of the test piece was reduced by machining, so that even steel pipe of high rigidity could be expected to a crack at the center. The test conditions included fully-reversed load control and a repetitive frequency of 8 Hz. Stress was obtained by the following equation:

$$\sigma = \frac{M}{Z} = \frac{\frac{F}{2} \cdot a}{\frac{\pi}{32} \cdot \frac{D^4 - d^4}{D}} \quad \cdots\cdots\cdots\cdots\cdots\cdots (1)$$

where,

M: Moment (kgf · mm)
F: Vibrating force (kgf)
D: Outside diameter (mm)
Z: Section modulus (mm^3)
a: Distance to vibrating point (mm)
d: Inside diameter (mm)

Figure 18 shows the test results. The fatigue limit of the high strength pipe shows a higher value than that of the Cr-Mo steel pipe. Fatigue limits may be expressed as a ratio to the tensile strength of the original pipe. The high strength steel pipe then shows a fatigue property, in the case of alternating stress, as high as 43%, and is better than the 37% for the Cr-Mo steel pipe. It is believed that this is because the high strength steel pipe has higher yield strength than the Cr-Mo steel pipe.

3.3.3 Fatigue properties of welded T type joint of high strength steel pipe

Samples of the same original pipe as that subjected to the bending fatigue test were given a welded T type joint fatigue test, as shown in **Fig. 19**. The test conditions included fully-reversed load control and a repetitive frequency of 10 Hz. Stress was obtained by the following equation in a similar manner to the bending fatigue test:

$$\sigma = \frac{M}{Z} = \frac{W \cdot l}{\frac{\pi}{32} \cdot \frac{D^4 - d^4}{D}} \quad \cdots\cdots\cdots\cdots\cdots\cdots (2)$$

W: Vibrating force (kgf)
Z: Section modulus (mm^3)
l: Distance to vibrating point (mm)

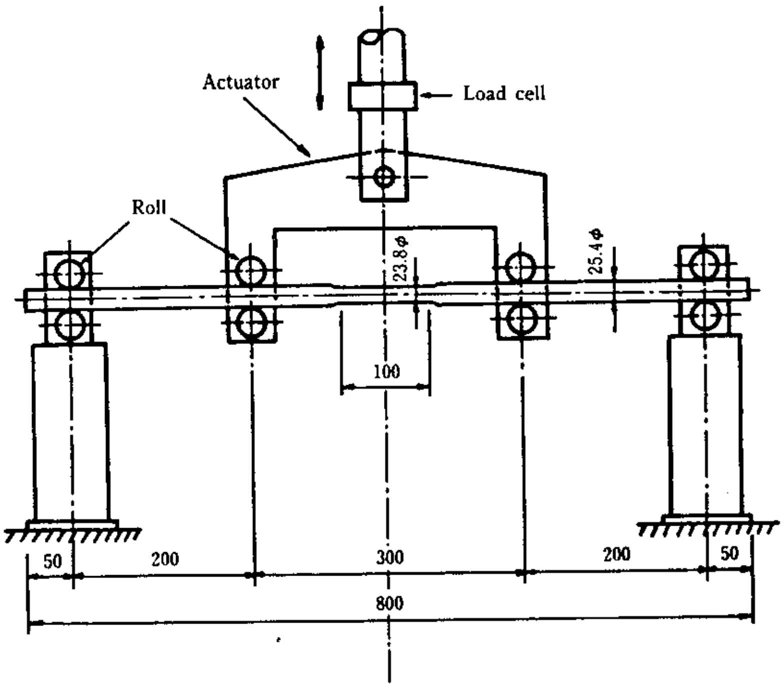


Fig. 17 Bend fatigue test method of pipe

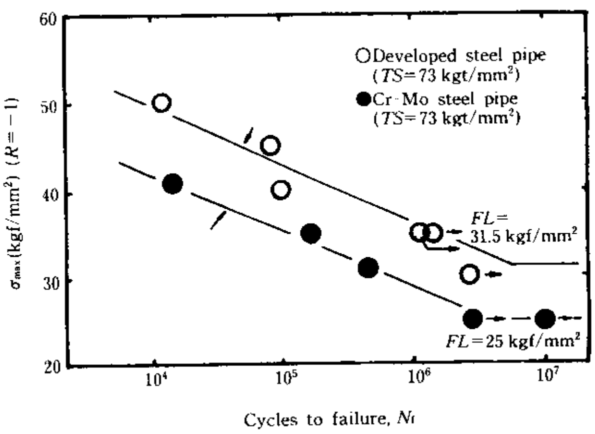


Fig. 18 Fatigue behavior of high strength pipe (pipe size: 1.6 × 25.4ϕ)

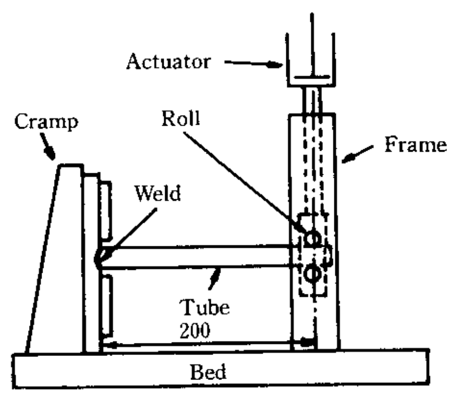


Fig. 19 Fatigue test method for T type welded pipe joint

Figure 20 shows the test results. The fatigue strength of the high strength steel pipe is slightly lower than that of the Cr-Mo steel pipe on the low cycle side, but is higher on the high cycle side. The fatigue limit value of 7 kgf/mm^2 for the high strength steel pipe is twice the 3.5 kgf/mm^2 value for the Cr-Mo steel pipe. The reason for the lower fatigue limit of the Cr-Mo steel pipe is considered to be the effect of hardening at the HAZ, as shown in **Fig. 21**. It is considered that when bending stress is applied to the Cr-Mo steel pipe, stress is concentrated at the toe of the fillet weld, and since the Cr-Mo

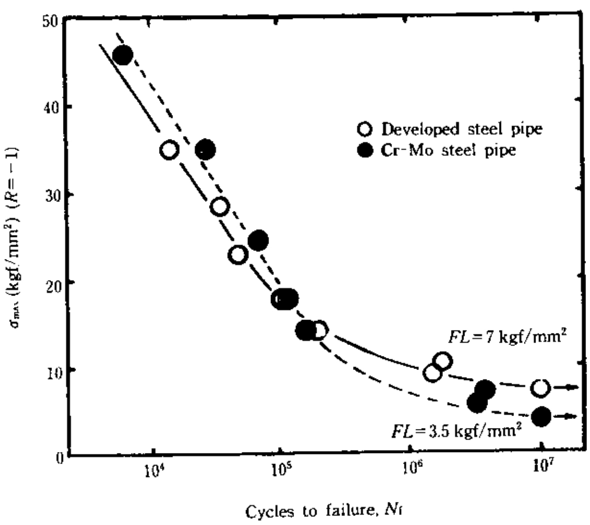


Fig. 20 Fatigue behavior of T type welded pipe joint pipe joint (pipe size: 1.6 × 25.4ϕ)

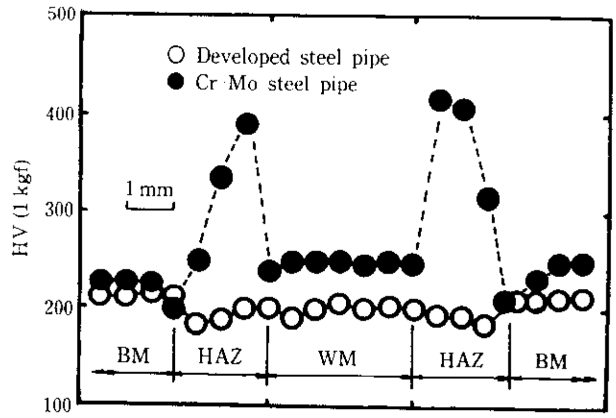


Fig. 21 Hardness profile of arc welded portion

steel is quench-hardened, the notch sensitivity of the toe becomes higher, resulting in the drop in fatigue strength.

3.4 Changes in Tensile Strength due to Degree of Pipe Forming Work

In general, tensile properties of steel pipe depend on the ratio (t/D) between sheet thickness (t) and diameter (D). This ratio is an expression of the degree of cold forming. In designing a mother material of optimum strength to match the tensile strength requirements of steel pipe, it is necessary to determine beforehand the amount of work-hardening which will result from working. **Figure 22** shows an example of investigation of the relation between tensile strength and elongation, with vaious diameter pipes produced from the same coil of the newly-developed steel. The figure indicates that with a larger diameter, thinner walled pipes, the increase in pipe tensile strength above that of the base metal is small. However, when t/D increases, and particularly at t/D of 6% or above, the strength increase will be 10 kgf/mm^2 or more. Depending upon the value of t/D, it may become necessary, as discussed above, to lower the strength of the mother material.

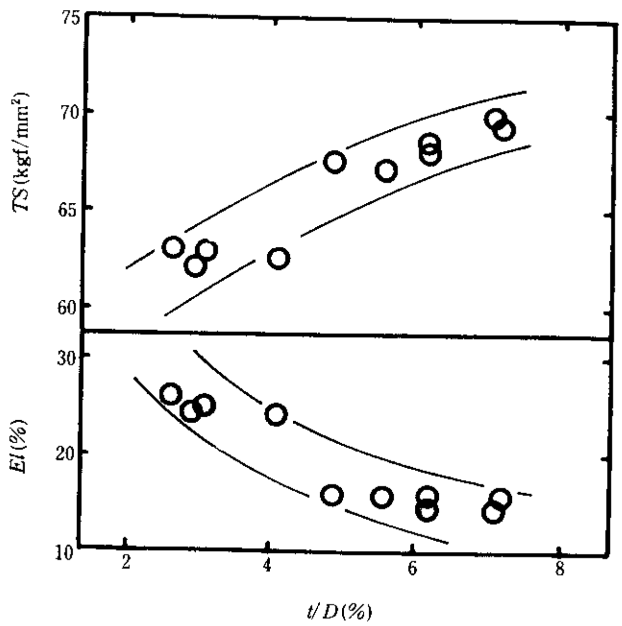


Fig. 22 Relation of t/D ratio and tensile properties of pipe (*TS* of steel sheet-57 kgf/mm^2)

4 Concluding Remarks

New high strength pipe steel and steel pipes have been developed for automobile and motorcycle part applications and various mechanical-structural uses. The features of such steel sheet and pipes are as follows:

(1) These sheets and pipes are of low-carbon-equivalent high strength steel, and the design makes use of the precipitation-hardenig capacity of titanium.
(2) Since little hardening develops at electrical resistance welds, excellent machinability and workability are realized without resort to heat treatment.
(3) Weldability is high, and joint strength and fatigue strength are both excellent.
(4) In contrast to conventional high strength steel pipes of carbon steel and alloy steel, no heat treatment is required, and further, the reduction in alloying elements also contributes to lowering production costs.
(5) Improvements in productivity in machining, welding, and working can be expected with adoption of this steel.

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