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The Improvement of Heat Treatment in High Pressure Pipe Bends using High Frequency Induction Heating

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Summary

The bend parts of high pressure pipings by using high frequency induction heating are to be heat treated for stress relieving in compliance with many application standard, the requirements of the rules and regulations of classification societies and the power plant engineering standard for example.

The new bending technique was developed in order to do away with heat treatment of the bend parts of steel pipings, which are satisfactory and adequate in mechanical property and change in wall thickness and shape of the bend parts.

1. Introduction

Hot bending of pipes intended for shipboard installation used to be a complicated process as each individual length of pipe had to be sand-loaded prior to bending in order to prevent its cross section from becoming elliptical where it was to be bent. Though the process has been greatly streamlined since several years ago by adoption of the high frequency induction heating method of pipe bending, the pressure pipes (chiefly those for use under the working pressure of 30 kg/cm^2 or more) designated for marine application are required under the existing classification societies' rules to undergo stress-relief annealing after bending and, accordingly, such a postheating is being conducted as a matter of accepted practice.

It has been felt, however, that the postheating can frequently become a considerable burden in the maintenance of day-to-day production activities and, therefore, there would be very much to be gained if pipe bending were carried out without the need for the subsequent heat treatment.

It has been observed while processing the pressure pipes, nearly all of which are of either carbon steel (STPG38) or low alloy steel (Cr-Mo, STPA22), that the water cooling applied in conjunction with the high frequency induction heating hastens the cooling of the bends produced on pipes and thus tends to cause the hardening of the pipe metal but a change in the cooling method, from water cooling to air cooling, appreciably lessens the degree of such metal hardening, especially in Cr-Mo steel pipes.

A series of tests conducted this time were therefore designed to determine, by using STPA22 steel pipe, what conditions should be met when bending pipes by the high frequency induction heating without postheating and what difference there would be between the postheated and nonpostheated pipes in mechanical and metallurgical properties.

2. Test Pipe

Of the pressure pipes manufactured for marine use, the Cr-Mo steel pipe is considered to offer the toughest challenge as regards the omission of postheating. The STPA22 steel pipe of Japanese Industrial Standard (1 Cr-0.5 Mo, 216.3 $\phi \times$ 18.2 t) was therefore used in the tests, of which the chemical

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Table 1 Chemical composition and mechanical properties of Low Alloy Steel Pipe

Kind of pipe Pipe diameter & thickness (mm)	Chemical composition (%)							Mechanical properties	
	C	Si	Mn	P	S	Cr	Mo	Tensile strength (kg/mm^2)	Elongation (%)
1Cr-½Mo *1 216.3×18.2	≦0.15	≦0.50	0.30 ~0.60	≦0.035	≦0.035	0.80 ~1.25	0.45 ~0.65	*2 42≦	*3 24≦

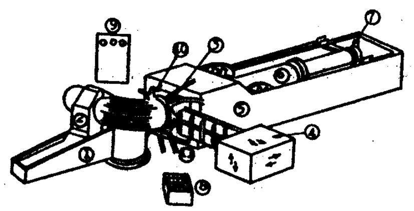
*1 STPA22 (JIS), KST4, LRP12, ABS12, NV2P12
*2 JIS
*3 Test piece of JIS No. 4

composition and mechanical properties are given in Table 1.

3. High Frequency Induction Heating Pipe Bending Machine

So much have already been written on the high frequency induction heating method of pipe bending that no detailed explanation about its principle, etc., would seem necessary.[1),2),3)] However, a brief description of the bending machine may be given as follows.

The pipe bending machine comprises a high frequency generating apparatus and a bender. A 325 kW, 2400 c/s, 880 V motor-generator is used in the high frequency generating apparatus, and the components of the bender include the clamping device, high frequency induction heating coil, arm, driving gear, control panel, etc. Fig. 1 illustrates the general view of the bending machine and Photo. 1 the machine at work.



1. Arm
2. Clamp
3. High Frequency Induction Heating Coil
4. Transformer
5. Body
6. Motor Driven Device
7. Tail Stock
8. Operating Board
9. Control Panel
10. Side Roll
11. Hose for Water Cooling

Fig. 1 High frequency induction heating pipe bender

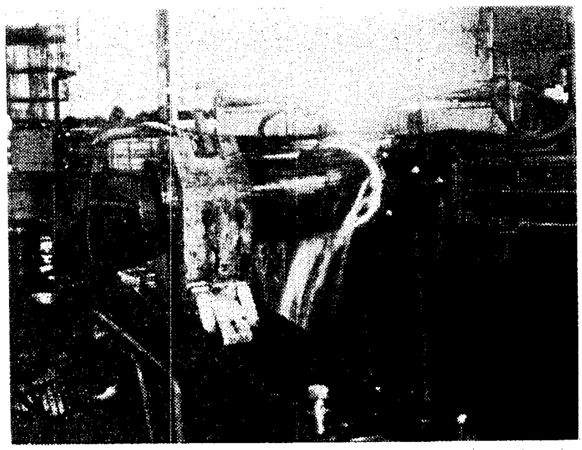


Photo. 1 Pipe bending using high frequency induction heating

4. Bending Method

Bending of pipe, of mild steel, by the high frequency induction heating is immediately followed by water cooling in order to prevent the pipe deformation. This is accomplished by admitting water to the heating coil and releasing it as a jet at the 45° angle with the pipe wall. However, for material like Cr-Mo steel, which is highly liable to quench hardening, it would seem a dubious proposition to provide cooling with water immediately after hot bending. Two different cooling methods were therefore employed in the tests, one being the air cooling and the other the water-spray cooling (hereinafter called simply the water cooling) designed to cool the pipe wall about 300 mm from the heating coil. Bends were produced in the tests with 3D radius (D=pipe diameter) which was considered to be the severest of the generally followed bending requirements, as well as with 5D radius for reference. Table 2 shows the details of the bending requirements.

Table 2 Bending condition

		Cooling condition	
		Air cooling	Water cooling *1
Bending radius	(mm)	3D (650) 5D (1080)	3D (650) 5D (1080)
Bending speed	(mm/s)	0.56	0.56
Heating temperature	(°C)	900～910	900～910
Exciting voltage	(V)	18	18
Exciting current	(A)	2.5	2.4
Main circuit voltage	(V)	415～420	415～420
Electric power	(kW)	65	65
Time lag *2	(s)	45	40
Clamp pressure	(kg/cm^2)	80	80
Operation		Manual	Manual

*1 Water cooling after lapse of some time
*2 Time lag when pipe bending is begun after heating

5. Measurement of Residual Stress

Generally, the cold and hot worked parts or weld zone in steel retain the residual stresses, and it is for this reason that the classification societies specify the postheating as mentioned in the earlier paragraph. With a view to determining how much of such a residual stress would continue to remain in a bend after hot bending if the postheating were omitted, residual stresses were measured in the tests at the outside wall of the bend where the stress was considered greatest, and the results thereby obtained were checked against the stresses measured on the nonpostheated bend for comparison.

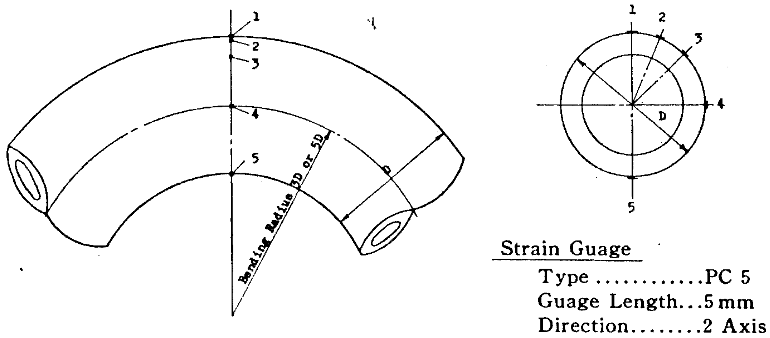


Fig. 2 Measurement positions of residual stress of low alloy steel pipe bends—1 Cr-½ Mo steel pipe bends—by high frequency induction heating pipe bending method

Fig. 2 shows the location where the measurements were made, and Figs. 3 to 5 give the results of the measurements. Also, Photo. 2 shows a scene of measurements. In dealing with the residual stress, the following equation was used.

$$\text{Residual Stress} = \sigma_{x \text{ or } y} = \frac{E}{1-V^2}(\varepsilon_{x \text{ or } y} + V\varepsilon_{y \text{ or } x})$$

$$E = 21 \times 10^3, \qquad V = 0.3$$

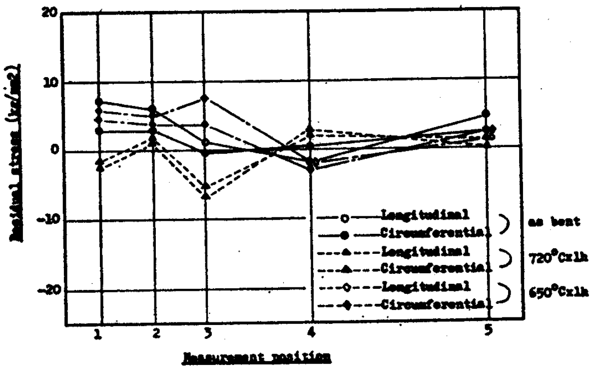


Fig. 3 Residual stress of 3D pipe bends by air cooling

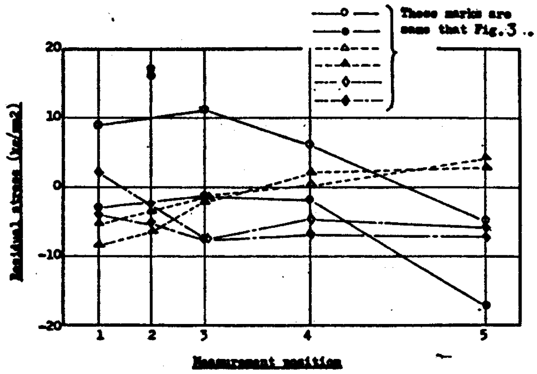


Fig. 4 Residual stresses of 3D pipe bends by water cooling

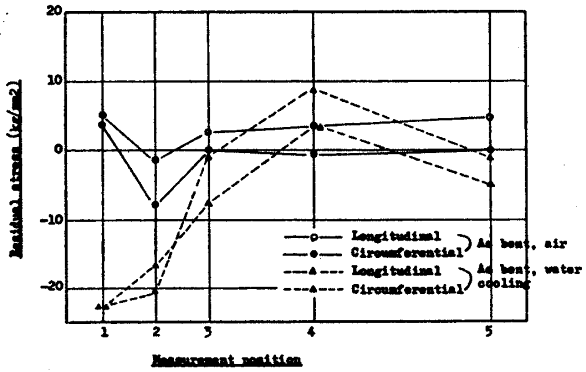


Fig. 5 Residual stresses of 5D pipe bends

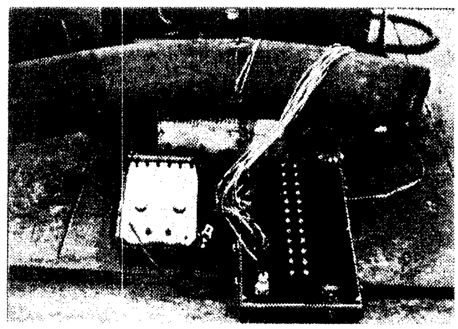


Photo. 2 Residual stresses of pipe bends

Measured at the outside wall of the bend where the residual stress was considered greatest, the highest value on the 3D radius bend was 7 kg/mm² (in longitudinal direction) when cooled with air and 8.7 kg/cm² (in longitudinal direction) when cooled with water while the stress on the 5D radius bend was 5.0 kg/mm² when cooled with air and −22.5 kg/mm² when cooled with water, thus less residual stress being registered on either radius bend with air cooling than with water cooling.

With the postheating, the residual stress of 7 kg/mm² measured on the 3D radius bend when cooled with air would decrease to 5.8 kg/mm² after 650°C F.C. and to −1.5 kg/mm² after 720°C F.C. In the similar manner, the residual stress of 8.7 kg/mm² measured on the 3D radius bend when cooled with water would decrease to −5.5 kg/mm² after 650°F F.C. and to 2.0 kg/mm² after 720°C F.C. A welded joint in a steel pipe with as much wall thickness as that of the test pipe is known to usually retain the residual stress which is close to the yielding point, and the stress will decrease to one third or less after stress relieving. The specified yield point for the test pipe used in the tests is over 21 kg/mm², and one third of 21 kg/mm² is 7 kg/mm². It is considered the residual stress of the order of 7 kg/mm² on the 3D radius bend and 5.0 kg/mm² on the 5D radius bend in as-air cooled condition would do no harm for practical purposes.

6. Material Test and Observation

Various types of test specimens were taken from the outside wall of the bend where the tensile stress was highest. For this purpose, the test pipe was used as bent and as postheated at 650°C and 720°C, so that the test specimens taken in different conditions could be examined for comparison.

Fig. 6 shows the locations where the specimens were taken.

6-1 Tensile Test

Fig. 7 are given the results of tensile tests conducted at room temperature and 550°C, respectively. Tensile strength measured at the room temperature on the 3D radius bend was 60 kg/mm² in as-air cooled condition and about 69.4 kg/mm² in as-water cooled condition as against the strength of about 45 kg/mm² measured in as-received condition, from which a difference one cooling method can make from another in consequential results will clearly be seen. Yield strength, elongation, and contraction of area declined inversely in contrast with the tensile strength but after the post-heat treatment at 650°C and 720°C the properties such as would be observed in as-received condition were obtained. Also, no effect of different post-heating temperatures, 650°C and 720°C, was recognizable.

The difference between the air and water cooling effects was evident to see on the 5D radius bend as well but was not so pronounced as on the 3D radius bend, and the yield strength on the air-cooled 5D radius bend was found slightly high while the tensile properties were the same as those observed in as-received condition.

Tensile properties at 550°C showed the same tendency as they did at room temperature, tensile strength and yield strength being lower by 5-10 kg/mm² and contraction of area being smaller by 5-10% than at room temperature.

It can therefore be said that with a bending radius of the order of 5D, no change occurs in the tensile properties of the pipe metal if cooled with air and, though the tensile strength on the 3D radius bend is 60 kg/mm², elongation percentage of more than 30% is assured.

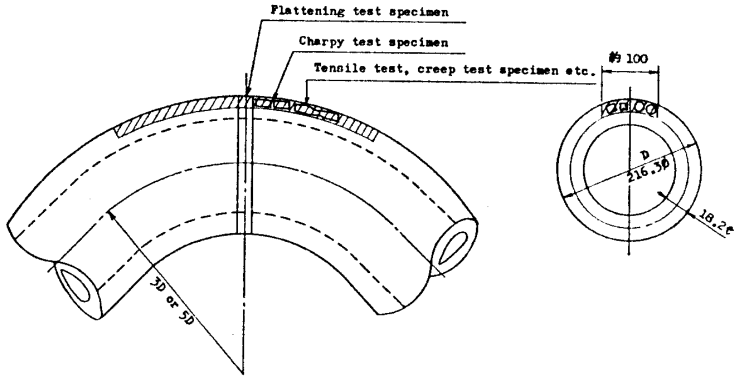


Fig. 6 Test specimens taken of pipe bends

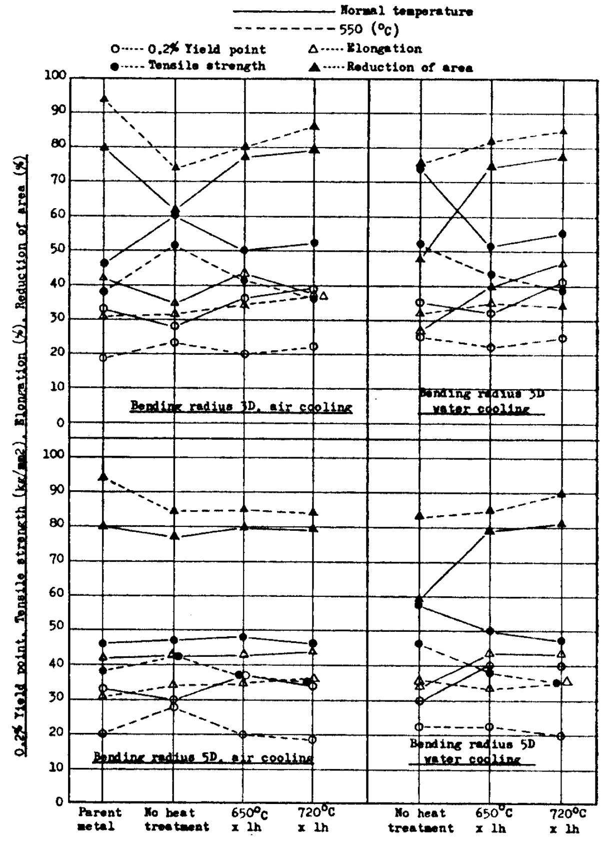


Fig. 7 Relation between mechanical properties and heat treatment at normal temperature and 550°C

6-2 Flattening Test

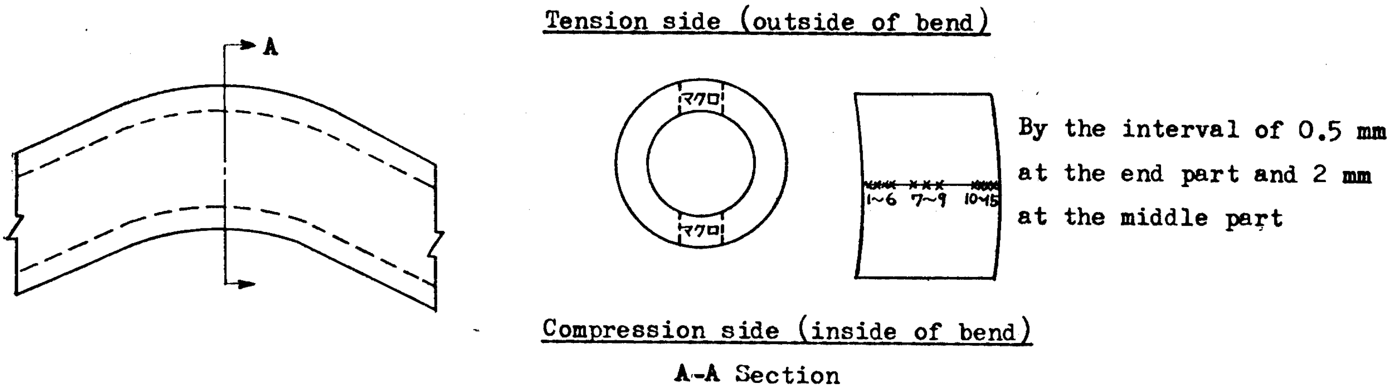
50 mm wide flattening test specimens were taken from the test pipe. In the flattening tests, each specimen was positioned so that its tension side (outside wall of the bend) and compression side (inside wall of the bend) would be on a horizontal line, at the right angles with the direction of the compression force applied by the tester.

The flattening tests were conducted in accordance with the test procedure specified by Japanese Industrial Standard.

The tests were completed with satisfactory results, without an incidence of cracking, etc.

6-3 Hardness Test

Check was made of the distribution of hardness in radial (wall thickness) direction at the tension and compression sides of the bend produced, with the results as shown in Figs. 8 and 9. Hardness readings taken at three to four locations on the outside wall of the bend are averaged; it can be seen that the greater degree of hardening takes places on the small, 3D radius bend, the values being higher by about 40 in Vicker's hardness than on the 5D radius bend. Also, comparison between water cooling and air cooling shows that the former raises the hardness by about 20 over the latter regardless of the bending radius.



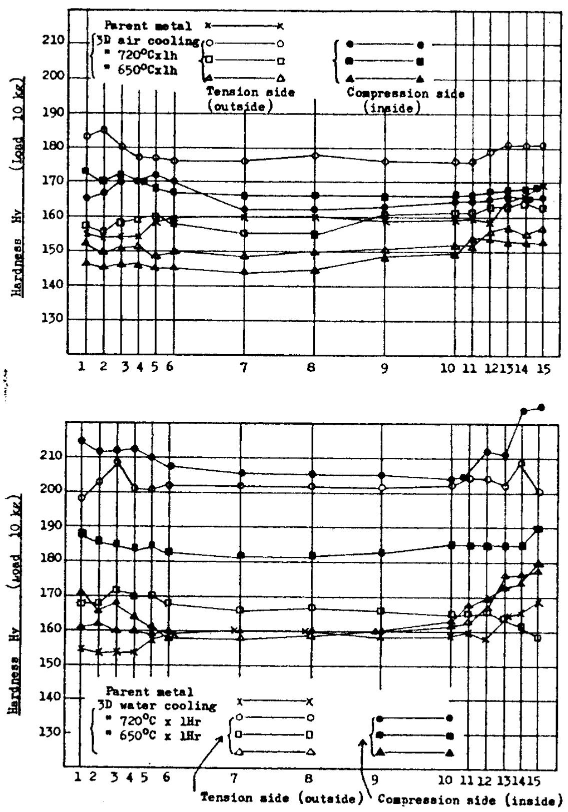


Fig. 8 Hardness of high frequency induction heating pipe bends

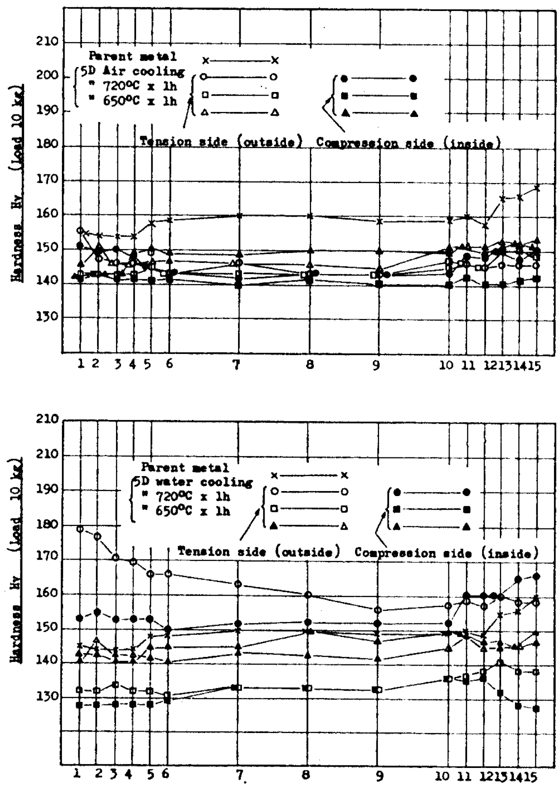


Fig. 9 Hardness of high frequency induction heating pipe bends

The bend produced with the 5D radius and examined in as-air cooled condition showed no effect of hot bending at all, whereas a slight sign of hardening was observed in as-water cooled condition. The bend formed to the 3D radius and examined in as-air cooled condition showed about 180 Vicker's hardness, which value is almost the same as that of the heat affected zone created on steel by arc-welding and stress-relieved, and is therefore considered to suggest no difficulty in practical use.

6-4 Impact Test

2 mm V-notch Charpy impact test specimens were taken from the tension side of the bend, and impact tests were conducted at −60°, −40°, −20°, 0°, 20°, 40° and 60°C, respectively, for determination of the transient temperature curve as shown in Fig. 10. It was at −20°C that 2vTr15 was indicated by the specimens taken from the air-cooled 3D radius bend whereas it was at +40°C by the specimens taken from the water-cooled bend. The impact strength at 0°C was 6 kg-m/cm² with the specimens taken from the air-cooled bend and 2.5 kg-m/cm² with the specimens from the water-cooled bend. With the postheating at 650°C and 720°C thereto added, however, temperature at which 2vTr15 would appear reached near −60°C, evidencing the qualitative improvement, and the transient temperature also dropped to less than −40°C.

It appears that no specific requirements are given in the classification societies' rules as regards the impact strength of the hot-bent part of steel pipe, but the strength of 15 ft-lb (2.6 kg-m/cm², 2vTr15) and above at 0°C would seem sufficient, taking into account the possibility of brittle fracture occurring at the time of hydrostatic pressure test.

The bend produced by the high frequency induction heating to be cooled with air would have the mpact strength of 6 kg-m/cm² if the postheating was iomitted, which is considered to be sufficient for practical purposes.

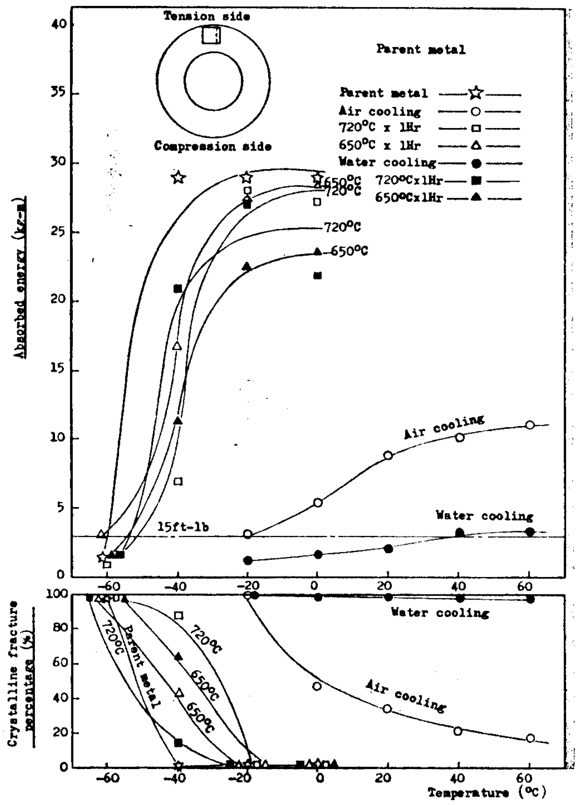


Fig. 10 Transition temperature curves by 2 V Charpy impact test

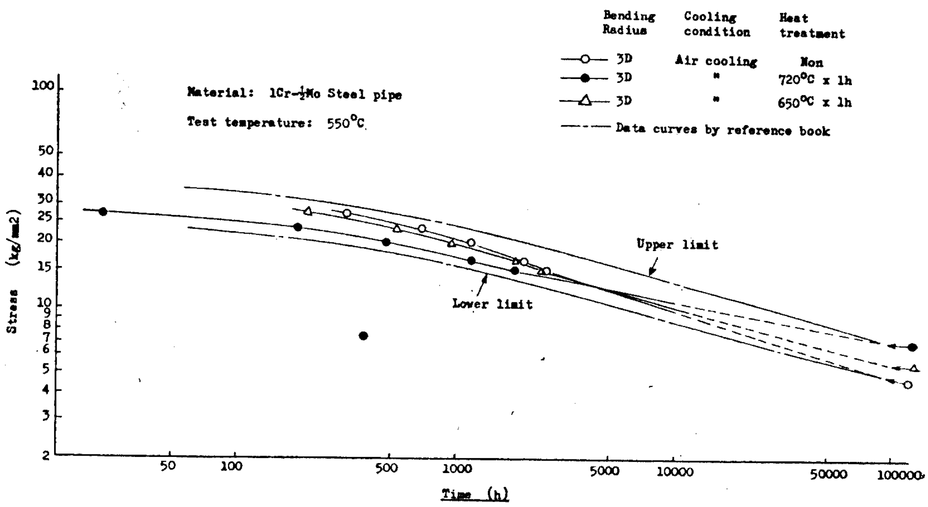


Fig. 11 Creep test result of high frequency induction heating pipe bend

6-5 Creep Rupture Test

The high-pressure steam pipes subjected to sustained service at elevated temperatures are required to have long-lasting strength. The common method of determining the material strength for high-pressure, long-time service is the creep rupture test. In the tests carried out this time, test specimens were taken for that purpose from the 3D radius bends, as air-cooled, as postheated at 650°C and 720°C, and as water-cooled, and from the 5D bends, as air-cooled and as water-cooled, respectively. The creep rupture tests were conducted on these test specimens at 550°C. Actually, the tests were commissioned to Metal Engineering Research Institute of Science and Technology Agency. The tester

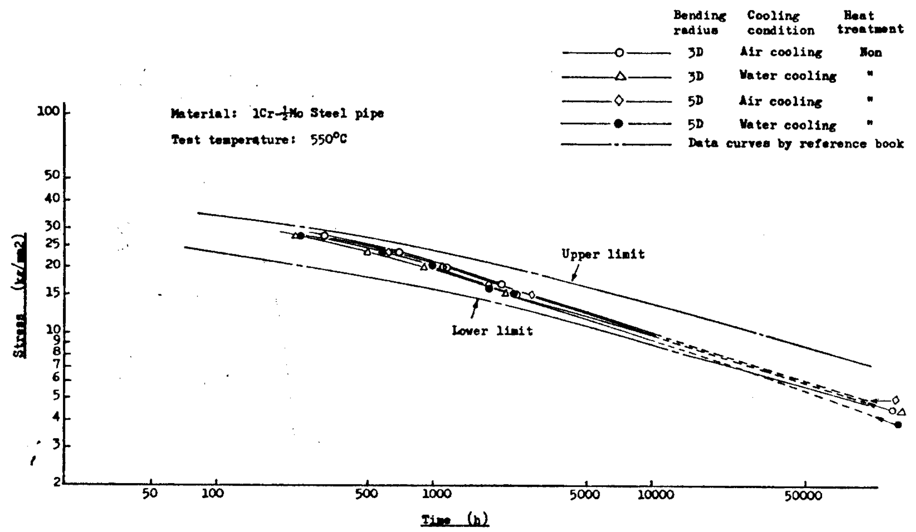


Fig. 12 Creep test result of high frequency induction heating pipe bend

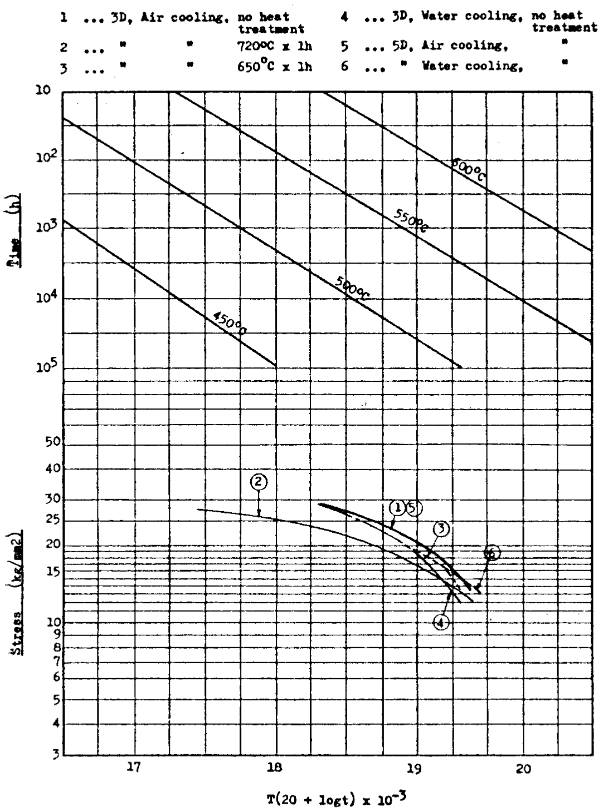


Fig. 13 Master rupture curves by R.M. method

owned by the Institute is of the type which would change the test stress by varying the load applied while keeping the dimensions of test specimens constant.

The rupture curves are shown in Figs. 11 and 12, and the master rupture curve by Larsin, Miller method in Fig. 13, respectively. Figs. 11 and 12 are given the data from experiments made in foreign countries, in a combined from represented by upper and lower limits.

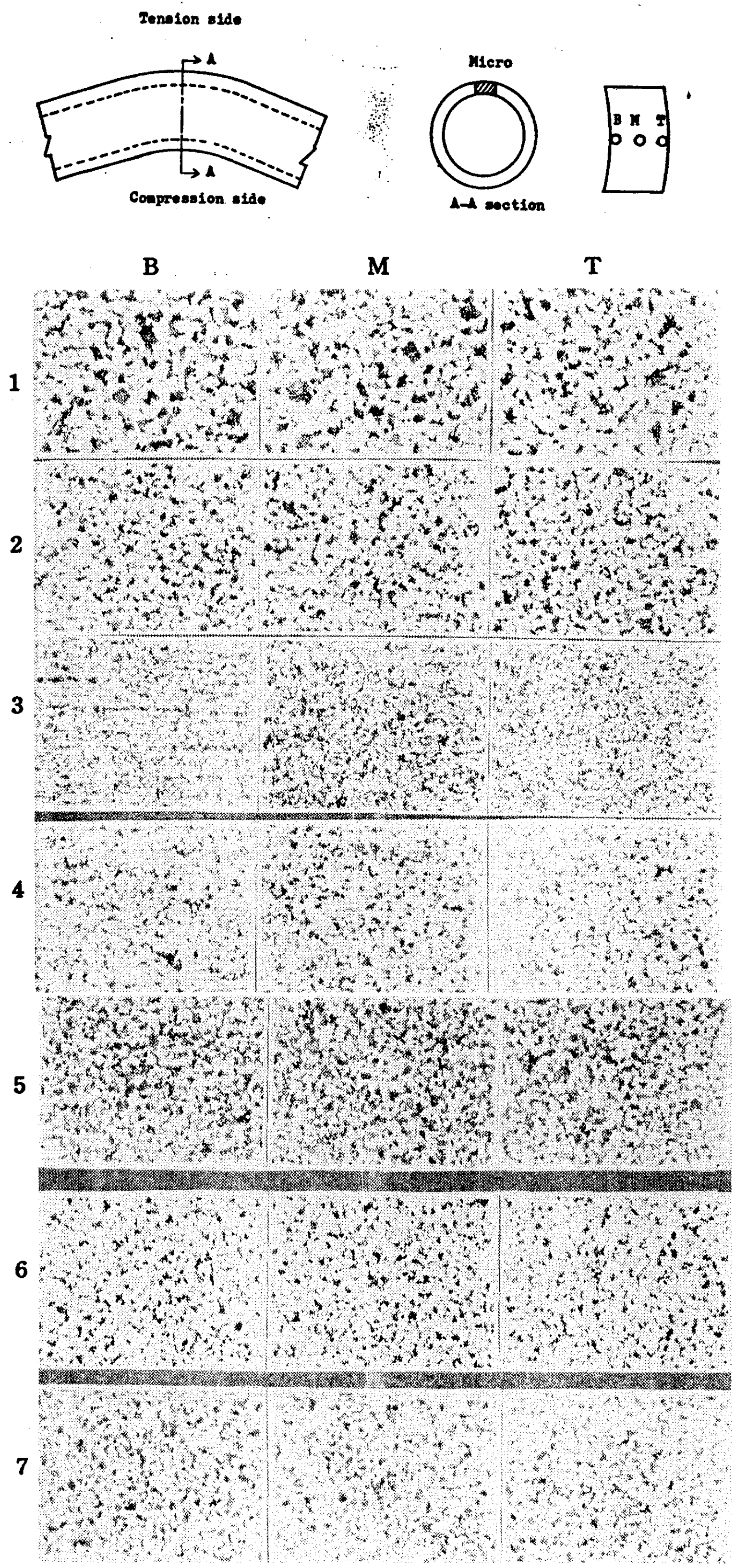
It can be seen from the curve that each non-postheated specimen stands close to the upper limit with 1,000 hours or less but shows a decline toward the lower limit when estimated for 100,000 hours' duration, i.e., all the four test specimens are shown to decline after about 1,000 hours. Fig. 11 shows the behavior of the test specimens taken from the air-cooled 3D radius bend, of which the specimen, as postheated at 650°C, is located midway between the upper and lower limits and that postheated at 720°C stands close to the lower limit while in short-time duration but nears the upper limit when estimated for 100,000 hours' duration with its rupture strength reaching the high of 7.4 kg/mm² as against 5.0 kg/mm² of the specimen taken in as-air cooled condition.

Allowable stress for 1 Cr-0.5 Mo steel at 550°C is specified by the power plant engineering standard to be 3.8 kg/mm² for 100,000 hours and when calculated by the formula specified in the standard, the average strength of not less than 4.75 kg/mm² at 550°C for duration of 100,000 hours can be considered acceptable.

Lloyd's Register of Shipping rules and regulations (1969) specify the strength of 5.0 kg/mm² at 550°C for 100,000 hours as acceptable whereas NK rules make it 4.5 kg/mm².

On the basis of Figs. 6, 7, the specimens taken from the 3D radius bend, as postheated, show the strength of 5.6 kg/mm² after 650°C F.C. and 7.4 kg/mm² after 720°C F.C. while those taken from the 3D radius bend, as air-cooled, show slightly lower strength of 5.0 kg/mm², and those from the air-cooled 5D radius bend the strength of 5.2 kg/mm².

All the specimens, therefore, show the strength values equal to or in excess of the Lloyd's requirements which specify the highest strength. The specimens taken from the 3D radius bend, as water-cooled, registered the strength of 5.0 kg/mm² and those from the 5D radius bend, taken as water-cooled, the strength of 4.5 kg/mm², both of which meet the NK requirements but fail to satisfy either power plant engineering standard or Lloyd's rules.



1. Parent metal 4. 3D, 650°C×1 h 7. 5D, Water cooling
2. 3D, Air cooling 5. 3D, Water cooling
3. 3D, 720°C×1 h 6. 5D, Air cooling

Photo. 3 Microstructure of pipe bends (×100) (Tension side)

6-6 Microstructure

Photo. 3 shows microstructures (at ×100 magnification) taken at the tension side of the bend. All are of ferrite-Pearlite structure, of slightly finer crystal grain structure as compared with those of the specimens taken in as-received condition, the specimen, as heat-treated at 720°C, showing especially fine crystal grain structure. Even with water cooling which exerts the greatest cooling effect, no sign of hard, martensite structure is recognizable.

7. Conclusion

Through a series of experiments made with the air cooling and water cooling in conjunction with the bending of 1 Cr-0.5 Mo test steel pipe by the high frequency induction heating method, in which the bends were produced and then cooled with air or cooled with water-spray applied on the pipe wall about 300 mm from the heating coil instead of being cooled with water from the heating coil mmediately after bending as in usual practice, with or without subsequent postheating, the following conclusions may be drawn.

7-1 The residual stress in non-postheated bends was found to be smaller when cooled with air than when cooled with water. In fact, the stresses in 3D and 5D radius bends were not more than 7 kg/mm^2 showing no appreciable difference from those observed in the postheated bends.

With air cooling applied, the residual stress in non-postheated bends would therefore be of no such order as to suggest difficulty for practical purposes.

7-2 Mechanical properties in the non-postheated, air-cooled bend showed relatively small amount of increase as regards the hardness and strength as compared with the water-cooled bend; even the small, 3D radius bend showed only slight increases in the tensile strength and hardness, and the elongation percentage of not less than 30% was assured. The 5D radius bend, as air-cooled, among others showed nearly the same properties as the postheated bend with no sign of effect from bending.

Notch toughness in the 3D radius bend, as water-cooled, was shown to be notably insufficient but, as air-cooled, indicated 2vTr15 at −20°C and impact strength of 6 kg-m/cm^2 at 0°C, which are considered to be relatively high. With the postheating applied after bending, nearly the same properties as in as-air cooled condition were obtained.

7-3 Creep rupture strength of the 3D radius bend, as air-cooled, when estimated for 100,000 hours' duration at 550°C, was 5.0 kg/mm^2 and that of the 5D radius bend 5.2 kg/mm^2, whereas the 3D radius bend, as water-cooled, indicated the strength of 5.0 kg/mm^2 and the 5D radius bend, also as water-cooled, 4.5 kg/mm^2. It can therefore be seen that of the non-post-heated bends those cooled with air offer sufficient strength to meet the rule requirements.

From all the foregoing it is concluded that the postheating can be omitted for the 1 Cr-0.5 Mo steel pipe by adoption of air cooling after bending where its diameter and wall thickness approximate those of the test pipe used in the above tests.

References

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