Loading Test of Simulated Weld Metal during Cooling †

— Studies on Welding Rod for Nodular Graphite Cast Iron (Report 1) —

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Abstract

This paper is a study of a new method to measure the tensile strength of weld metal during cooling. Fe-Ni-Mn-1%C alloy which simulates the composition of weld metal was molten and cast into a copper split mold. Loading started when the temperature of the specimen reached down to about 673K. Besides the strength, some other properties such as solidification temperature, thermal expansion coefficient and micro-Vickers hardness were investigated. The composition of the alloy was changed stepwise from 0 to 19 wt% Ni and 0 to 13% Mn.

The cooling curves of the specimens were similar to those of the implant test of cast iron pre-heated to 573K. The lowest tensile strength was 550 MPa; this value is still over than that of FCD 500 in JIS. This new method is effective to evaluate the strength of weld metal during cooling. The lowest hardness was obtained from the metal containing 19.2% Ni without Mn, while the hardness of all specimens ranged between **Hv** *261 and 745. The results of tests showed that the weld metal containing 14.7% Ni and 5% Mn has the quality needed for cast iron weldings.*

KEY WORDS: (Cast iron) (Weld metal) (Tensile strength) (Casting method) (Fe-Ni-Mn alloy)

1. Introduction

From the viewpoint of welding structures as a whole, welding is an operation to apply locally the thermal cycle of rapid heating and rapid cooling to component members to be welded. Local heating-cooling of a member causes thermal stress in it, and makes stress remain in the member. This residual stress results in the deformation or cracks of a weldment. Crack-type defects are generally called weld cracks. They are classified into low-temperature and high-temperature cracks in terms of crack-generating temperatures; weld metal, heat affected zone and base metal cracks in terms of crack-generating positions; and longitudinal, transverse and star shape cracks in terms of shape[1].To examine the sensitivities for these weld cracks, many weld cracking tests methods are specified by the Japanese Industrial standard (JIS) or the Japan Welding Engineering Society Standard (WES). In most of these methods,cracking susceptibility is evaluated by percentage of total length of cracks divided by test bead length. In addition, these methods can measure neither crack-generating temperature nor stress. To overcome these demerits, the Rigid Restraint Cracking test (RRC test)[2] and oblique Y-groove weld cracking test[3] in which a strain gauge is stuck to the side of a specimen have been proposed. However, these are cracking tests for welded joints, and can not detect separately the cracking behavior in heat-affected zones and weld metals. To investigate the properties of heat-affected zones, therefore, there is a synthetic heat-affected zone test, in which the same thermal cycle as to the heat-affected zones is given to the base metals. This is a test to reproduce the heat-affected zones, and metal mold casting is the only technique at present for reproducing weld metals in which the compositions of welding rods and base metals are fused and diluted to form special solidifieation structures.

Taking the above into account, this paper describes the feasibility of measuring the mechanical strength of weld metals by using a method similar to an implant cracking test, in which molten alloys with Fe-Ni-Mn weld metal compositions are cast into copper molds, solidified, cooled and then load is applied during the course of cooling. Besides the above, several properties were investigated for reporting.

2. Experimental

Solidification of weld metals in arc welding is identical to the case where molten metals are cast into molds and cooled rapidly. The resultant microstructures are typically columnar[4]. In fusion boundaries, the properties of the weld metals are not completely identical with those of

† Received on July 30,1993

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Transactions of JWRI is published by Welding Research Institute, Osaka University, Ibaraki, Osaka 567, Japan

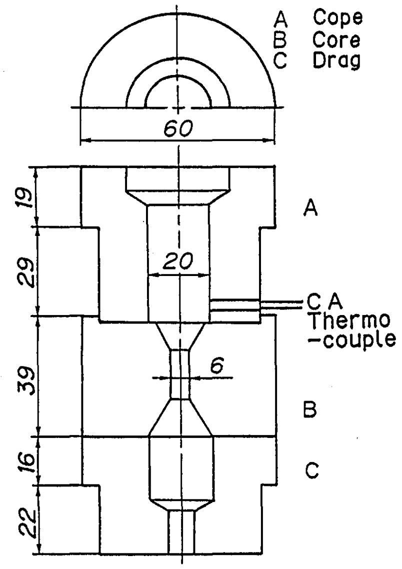

Fig.1 Copper mold configuration of the loading test

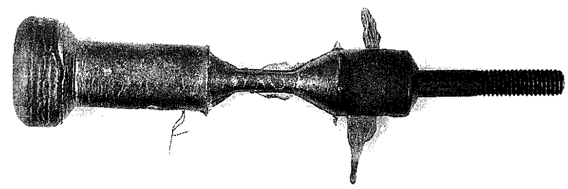

Fig.2 Appearance of loading test specimen

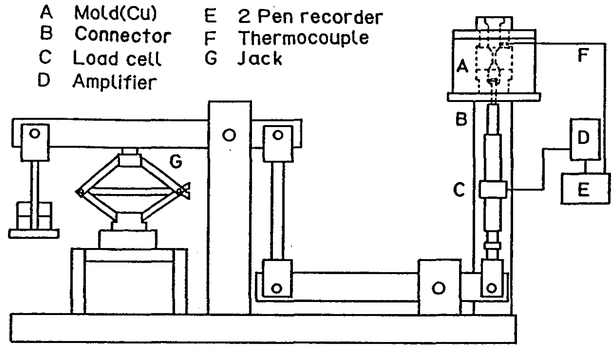

Fig.3 Schematic drawing of loading test apparatus

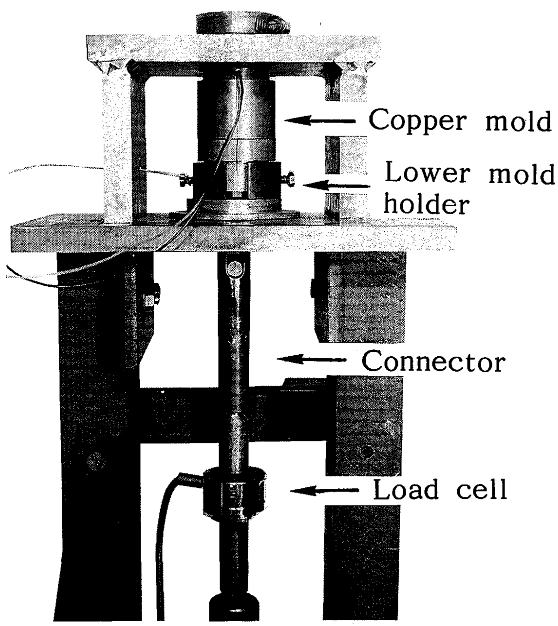

Fig.4 Loading test setup

the rapidly cooled cast metals in that the columnar crystals of the weld metals result from the epitaxial growth of the crystal grains of the heat-affected zones of base metals, and in that since the heat source moves, the maximum temperature gradients in each position of a weld bead are different and the growth directions of the columnar crystal grains gradually change toward the moving direction of the heat source.However, so long as the purpose of examining the mechanical properties of the weld metals alone is concerned, it is considered reasonable to reproduce rapid cooling showing the near-actual cooling states of the weld metals by metal mold casting. In this experiment, therefore, alloys having the same chemical compositions as those of the weld metals were melted, and loads were applied to metal-mold-cast specimens while they were cooled to investigate the feasibility of loading test during cooling the simulated weld metals. The shape and dimensions of the mold used in this experiment are given in **Fig.1**. To make cooling rate faster, copper was used as the metal mold for higher coefficient of thermal conductivity. In order that the mold is not subjected to part of load during the loading test, it was of three-stage type-cope, core and drag-with each stage separable right and left. Before loading, the drag was released to apply the load to be given only to the test zone of the specimen. The diameter and length of the test zone were 6 and 16mm, respectively. A high-tensile-strength bolt with 8 mm diameter. was inserted into the drag at the time of casting to wrap it with the molten metal, and then load was applied. The bolt-inserted specimen is shown in **Fig.2**. Since the slit is provided for the drag for degassing, molten metal flows in it, forming a casting fin. **Figure 3** schematically shows the loading test apparatus, whereas **Fig.4** shows the loading test setup with the copper mold set.

The drag was released 15 sec after the molten metal was poured, and load was gradually applied by using the jack 30 sec after pouring the molten metal (test zone temperature ; about 673K). This tester can apply 17350N load (about 614 MPa stress for 6-mm-dia. test zone) at a maximum. In welding, two separate members are connected through a zone which are formed by rapid melting and rapid solidification. Upon cooling the

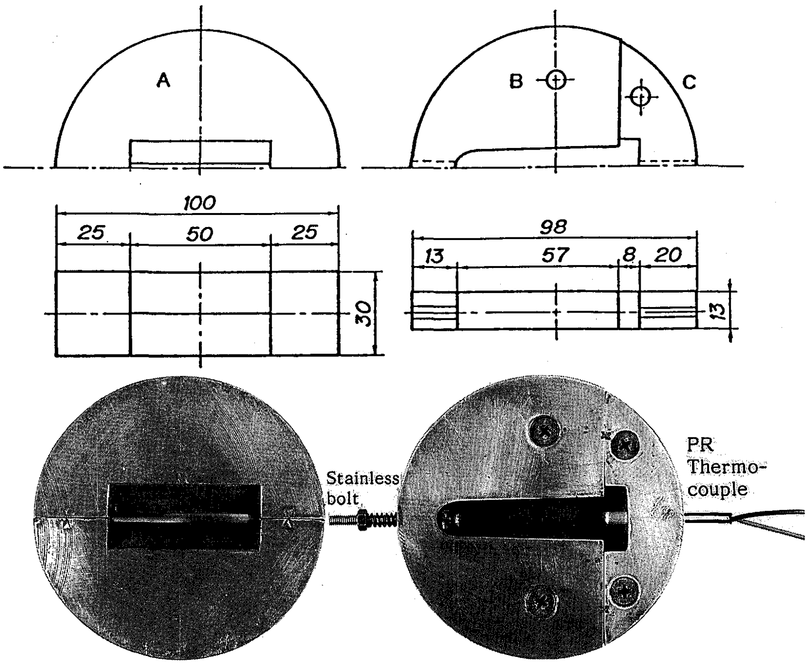

Fig.5 Copper mold configuration of the shrinkage test

peripheral zone or to external constraint, resulting in crack generation when the weld or members can not withstand the shrinkage stress.Accordingly, the amount of shrinkage of the weld metal due to cooling should be as small as possible. Besides a series of tensile tests, this study examined the relation between the amount of shrinkage and the temperatures of the weld metal from its solidification to room temperature. **Figure 5** shows the shape and dimensions of the copper mold for measuring the amount of shrinkage. The cope (A) plays the role of a gate and runner, and is placed on the core (B, C) without being fixed so that the cope may open right and left if the runner shrinks vertically. The core is the actual test zone, and the top of the specimen comes into contact with the C side of the core so that the shrinkage of the specimen may appear in one direction. The drag is a 100mm-diam, 150mm-long copper cylinder, the core being fixed to it with bolts. Figures 5 and 6 give the photograph of the core and external appearance of the specimen, respectively. As the two figures indicate, temperatures were measured by the PR thermocouple inserted from the C side, whereas the amounts of shrinkage were detected by the electric dial gauge through the 4mm-diam stainless bolt inserted into the other side of the specimen. The state of measurement is shown in **Fig.7**.

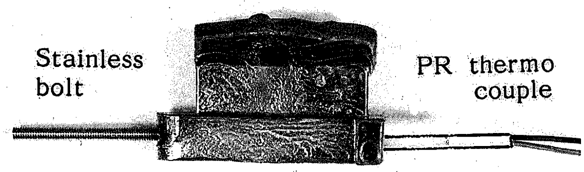

Fig.6 Appearance of shrinkage test specimen

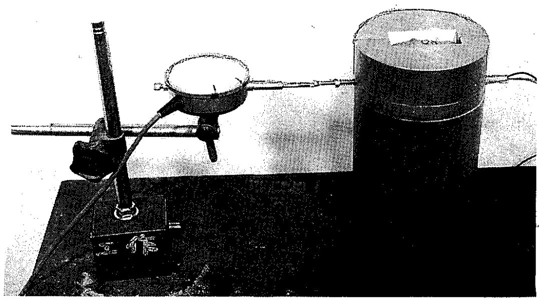

Fig.7 Shrinkage test setup

As part of the authors' studies on the weld cracking of cast iron, we made experiments for weld metals which are formed by fusion and dilution of cast iron and welding rods for cast iron. Bead welding was carried out for spheroidal graphite cast iron plates using four kinds of covered electrodes; D4301, D310-16(25Cr-20Ni), DFCNiFe (55%Ni) and 9% Ni. The resultant penetration rates were around 30%, so about 800g of Fe-Ni and Fe-Ni-Mn alloys containing 0 ~ 20% Ni and 0 ~15 % Mn were prepared by blending the materials shown in **Table 1** and by melting them in air in a high-frequency induction furnace, aiming at the carbon content of 1 mass%. Although melting temperature varies with the composition of the alloy, the molten metals were cast into cartridges for solidification temperature measurement, and molds for specimens for measuring tensile strength, the amount of shrinkage and for emission spectral analysis immediately after heating the molten metal up to 1873K, taking into account the fact that the temperature of a molten weld pool becomes

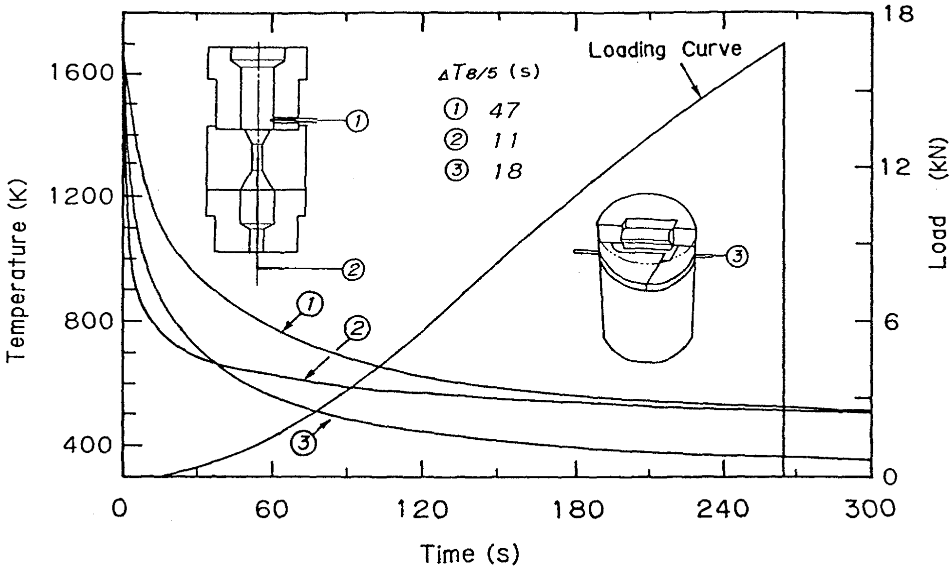

Fig.8 Examples of cooling curves and loading curve

Table 1 Chemical composition of raw materials used (mass%)

	C	Si	Mn	P	S	Ni
FC	3.48	1.68	0.48	0.035	0.02	—
S25C	0.24	0.27	0.44	0.022	0.018	0.05
FeMn	0.97	1.36	75.50	0.19	0.006	—
Ni	0.01	—	—	—	—	99.97

extremely high in arc welding.

3. Results and Discussions

Figure 8 shows the examples of cooling and loading curves of the specimens for measuring tensile strength and the amount of shrinkage. The temperatures of the tensile test zone in Fig. 8 are measured by the thermocouple inserted into the center of the specimen from its bottom, but only the temperatures of the upper zone of the specimen (curve (1)) were measured during the experiment. The cooling curve (curve (2)) for the test zone indicates that the cooling rate immediately after pouring the molten metal is fast, and that although the cooling time from 1073K to 773K is 11 sec, the cooling rate becomes slower halfway due to heat conduction from the thick upper and bottom zones of the specimen. As the authors reported in the implant test[5], the cooling curve (2) resembles that of 573K-preheated spheroidal graphite cast iron. The cooling rate of the specimen for measuring the amount of shrinkage is slower than that of the tensile test zone at higher temperatures, but the time reaching room temperature becomes shorter because of the greater heat capacity of the mold.

Figure 8 also shows the example of a loading curve. Load begins to be given 30 sec after pouring molten metal, and slight restraint stress occurs 14 sec after releasing the drag because of the shrinkage of the specimen due to cooling. The core surrounding the test zone is released around 120 sec after load begins to be applied. Loading rate was adjusted to about 4 kN/min. In the example given in Fig. 8, rupture takes place 265 sec after pouring molten metal and when temperature drops down to about 520K. In this case, load is 16660N, corresponding to 590 MPa rupture stress. Load reaches a maximum 240 to 270 sec after pouring molten metal. The specimen which did not rupture after cooling down to room temperature was further tested by using an universal testing machine to measure tensile strength.

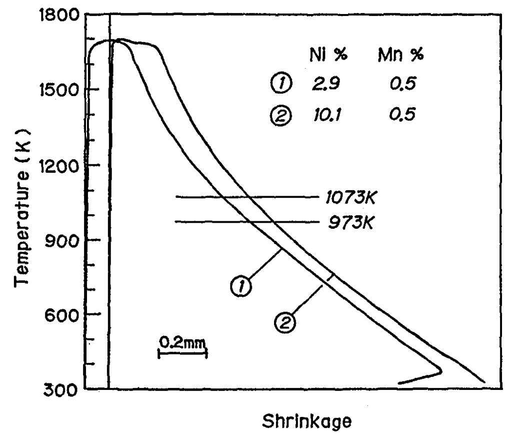

Fig.9 Examples of shrinkage curve . Ni 2.9% specimen shows martensite transformation expansion below 373K

The shrinkage curves are shown in **Fig.9**. Because the measured amount of shrinkage includes the expansion and contraction of the copper mold and stainless steel bolt, the expansion and contraction of those ones are separately measured in advance, and the results of correction are shown in Fig. 9. Using the curves in Fig. 9, the average thermal expansion coefficient from 973K to 1073K for 50 mm specimen (distance from the stepped

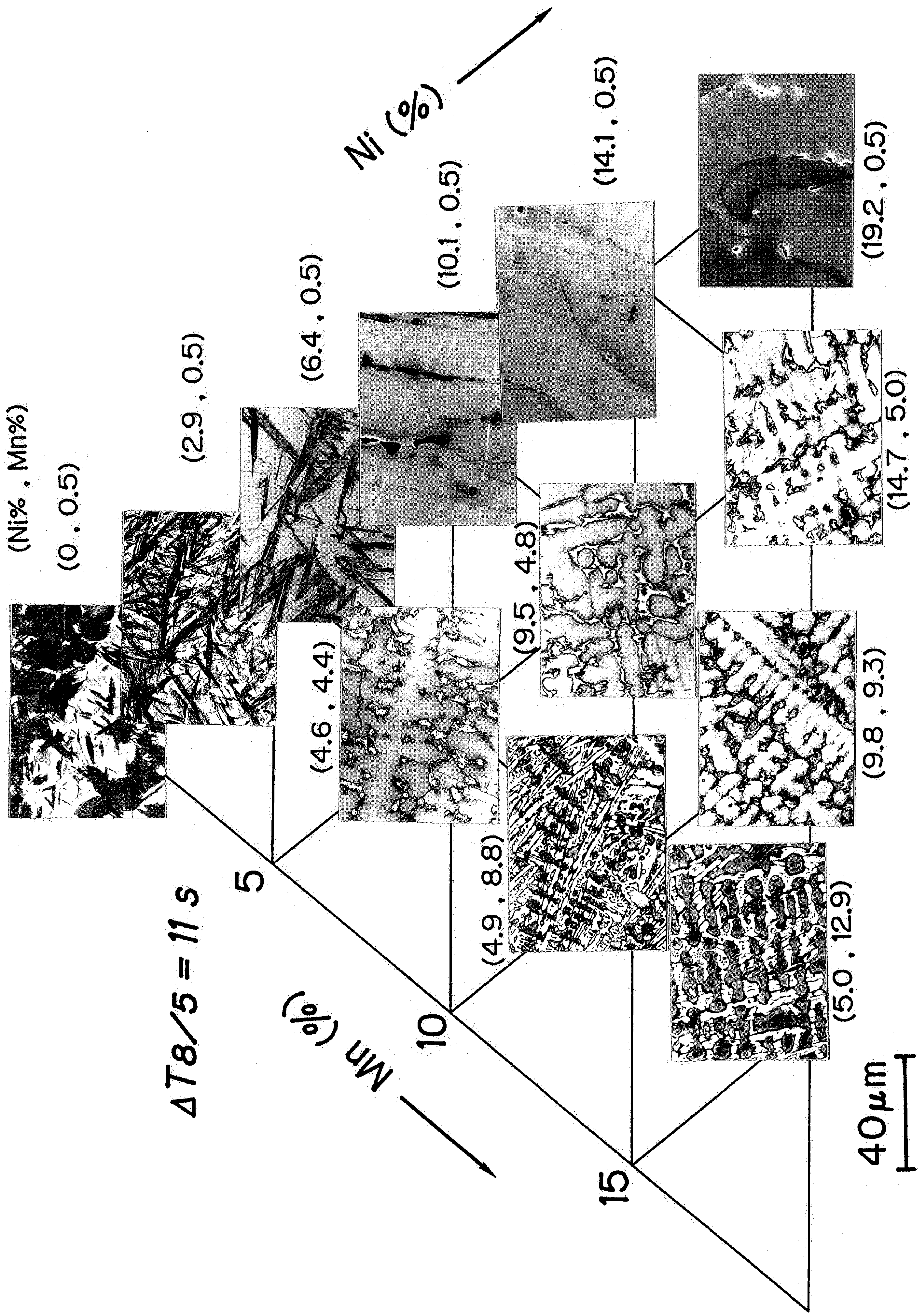

Fig.10 Microstructres as a function of the content of nickel and manganese

zone to the top of the stainless steel bolt) was 21.6 $\times 10^{-6}$/K for the Ni 2.9% specimen, and 19.2 $\times 10^{-6}$/K for the Ni 10.1% specimen . These values are greater to some extent than the thermal expansion coefficients of ordinary spheroidal graphite cast iron [6] or low-alloy spheroidal graphite cast iron at around 1073K (13 ~ 14 $\times 10^{-6}$/K)[7]. The total amounts of shrinkage of the two alloys from pouring the molten metal to 100K were 1.44mm. In the Ni 2.9% specimen, however, 0.17mm expansion was observed at 373K or less due to martensitic transformation. In Fe-Ni alloys containing 1 ~ 7% Ni, expansion of this kind due to phase transformation took place at 373K or less, and the value of expansion was about 0.15mm for 50mm test zone length. Tamura et al.[8] have already reported the method of relaxing restraint stress and thereby preventing weld cracks from occurring by making use of expansion at the time of martensitic transformation. The microstructures of the tensile test zones are shown in **Fig.10**, in which mass percentages of Ni and Mn are given within the left and right sides of the parentheses, respectively. As described in the explanation of the cooling curves, since cooling as a whole was as slow as that for the 573K-preheated specimen in the implant test, the microstructure of (0, 0.5) specimen to which neither Ni nor Mn was added consisted of bainite, martensite and residual austenite. Despite slower cooling rate than in water quenching, martensite appeared in the specimens containing 1 ~ 7% Ni that may delay A_3 and A_1 transformation. When Ni content exceeds 10%, no martensite is observed except austenite, which is typically columnar and has grown to a great extent. When Mn is added, columnar austenite changes into dendritic, carbide appears between dendrite grains, and austenitic dendrite grains become finer than those of 0.5% Mn specimen. The amount of carbide clearly increase as the amount of added Mn increases.

Figure 11 shows the micro-Vickers hardnesses of the tensile test zones. In the light of the microstructures in Fig. 10, the hardness of the 0% Ni, 0.5% Mn specimen is Hv 478, but those of the specimens containing 1 and 3% Ni and the greater amount of martensite are higher. In the specimens containing 5 and 7% Ni, since the amount of austenite is far greater than that of martensite, their hardnesses are nearly identical with that of the 0% Ni, 0.5% Mn specimen. The hardness of the 10%-or-more Ni specimen consisting of austenite alone is lower, and becomes Hv 261 for the 19% Ni specimen. The addition of Mn makes the specimen harder because of the appearance of double carbide. In particular, in the 4.9% Ni, 8.8% Mn specimen which contains a greater amount of carbide and whose microstructure is nearly eutectic, its hardness becomes Hv 644 .

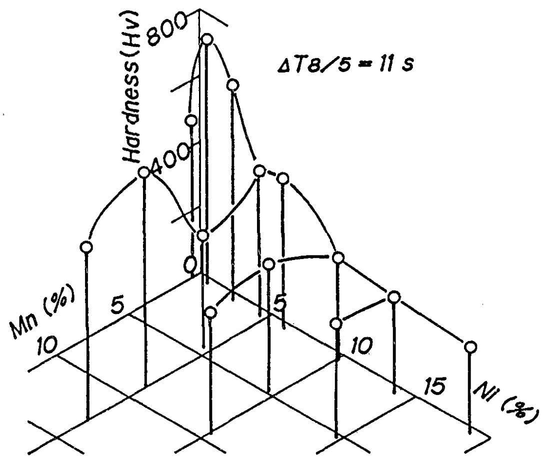

Fig.11 Micro-Vickers hardness

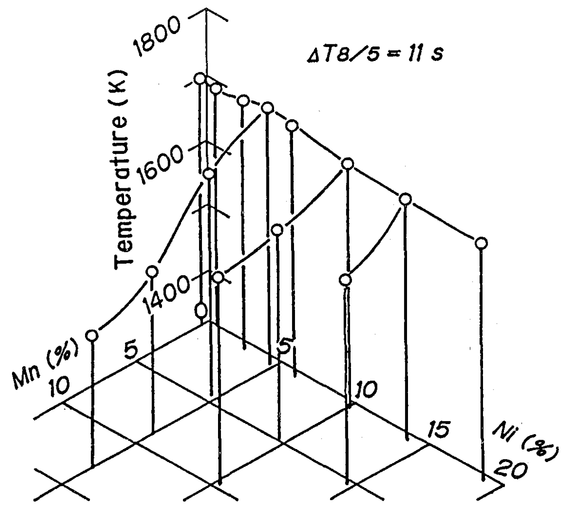

Fig.12 Solidification temperature

Figure 12 shows the solidification temperatures of various alloys. One of the advantages of Ni-series welding electrodes which have been widely used for cast iron has been considered to lie in their solidification temperatures close to that of cast iron [9]. As shown in Fig. 12, however, the solidification temperatures of Fe-Ni-C alloys to which Ni alone is added are around 1690K, which is still higher in comparison with that of cast iron around 1423K. On the other hand, the increase in the added amount of Mn makes the solidification temperature lower. The addition of Mn by 5% lowers the solidification temperature to about 1640K, and in the 5% Ni, 12.9% Mn specimen it decreases to 1523K. If the solidification temperature of the weld metal is higher than that of the base metal in the weld joint, the weld metal is first solidified, followed by the solidification of an unmixed zone. Under these conditions, the unmixed zone undergoes undesirable shrinkage stresses from both the weld metal and base metal. The solidification temperature of the weld metal, therefore, is desirably

Table 2 Experimental results

Set %		Chemical composition (mass%)			Tensile strength	Shrinkage length	Thermal expansion coeff. $\times 10^{-6}$/K	
Ni	Mn	C	Ni	Mn	(MPa)(1)	(mm)(2)	1073-973	573-373
0	0	0.94	0.06	0.48	563.5	0.854	19.6	19.9
1	0	0.97	1.00	0.49	588.3	0.776	18.6	15.6
3	0	0.91	2.88	0.50	563.5	1.036	21.6	26.1
5	0	0.99	4.63	0.49	595.5	0.761	18.6	18.1
7	0	0.94	6.36	0.49	590.0	1.021	20.6	26.1
10	0	0.98	10.06	0.50	613.5	1.056	18.6	29.1
15	0	0.93	14.11	0.53	550.1	0.896	18.6	20.6
20	0	0.89	19.17	0.54	631.1*	0.896	19.6	22.1
5	5	1.57	4.55	4.42	656.6*	0.901	18.6	27.6
5	10	2.42	4.91	8.82	582.1	0.976	22.6	24.1
5	15	2.80	4.99	12.90	554.7	1.096	22.6	31.6
10	5	1.69	9.54	4.80	775.0*	0.981	20.6	23.1
10	10	1.46	9.82	9.30	792.4*	0.991	17.6	28.1
15	5	1.60	14.70	4.99	789.3*	1.046	17.6	28.1

(1) * mark shows the strength of the specimen at room temperature which was not fractured under loading test during cooling.
(2) Shrinkage length is obtained from the temperature-shrinkage curve from 1273K to 373K.

close to that of the base metal.

Table 2 shows the results of a series of experiments. Because mold releasing was carried out at about 670K and thereby the state of slow cooling became nearly identical with that for the 573K preheated specimen of the implant test [5], the strengths of all the weld metals are 550MPa or more. The values without the star mark indicate the rupture stresses of specimens rupturing during the experiments. For example, the 10% Ni, 0% Mn specimen did not rupture at 523K after the completion of loading, but ruptured when temperature went down to 331K. The 7% Ni, 0% Mn and 3 % Ni, 0 % Mn specimens ruptured at 473 and 510K, respectively, during the course of loading. In the experiments carried out this time, the initial target of measuring the strengths of alloys with rapidly solidified structures was achieved, but the tensile strengths of all the specimens were high, suggesting that high-temperature cracking did not occur. It has been pointed, however, that high-temperature cracking often took place in austenitic-stainless-steel weld metals [10]. Taking into account the fact that the specimens containing 10%-or-more Ni and 0% Mn (the alloys within the range of the experiments performed this time) had the austenitic structure, more detailed investigation is required for high-temperature cracking.

The thermal expansion coefficients given in Table 2 are the average values at 1073-973K and at 573-373K. It also gives the amounts of shrinkage at 1273-373K obtained from the temperature shrinkage curve, but no clear relations of thermal expansion coefficient and the amount of shrinkage to the amounts of Ni and Mn were found. As can be understood from the percentage of carbon shown in the chemical analysis, one of the causes for this may be the negligence of the carbon content of the Fe-Mn alloy added for adjusting the amount of Mn. Based on the above, the authors are performing new experiments using the specimens containing 0 ~ 60% Ni and 0 ~ 15% Mn. The results will be reported in the next paper.

4. Conclusions

The alloys simulating the Fe-Ni and Fe-Ni-Mn weld metals were melted in air in the high-frequency induction furnace, cast into the split-type copper mold, and load is applied from about 670K during the course of cooling to measure the strengths of the alloys in accordance with the implant test. Besides, several other properties of the above alloys were also investigated. The results are as follows:

(1) This paper describes the testing method in which the

metal-mold-cast specimens simulating the weld metal structures are subjected to load during the course of cooling. This method enables the strengths of the weld metals during the course of cooling to be estimated.

(2) To make the solidification temperatures of the weld metals approach to that of cast iron, the addition of Ni alone is not sufficient, but the addition of Mn is effective.

(3) Although the cooling curves resemble that obtained in the implant test for the 573K-preheated specimen, martensitic transformation occurs at 373K or less in the Fe-Ni alloys containing 1 ~ 7% Ni, resulting in high hardness. When Ni content exceeds 10%, the resultant austenitic structure becomes coarse and columnar, and hardness decreases.

(4) When Mn content exceeds 5% , Fe-Mn double carbide begins to appear and hardness increases. The dendritic structure of the alloy containing 5%-or-more Mn is finer than the alloy containing a great amount of Ni alone.

(5) So long as the experiments carried out this time are concerned, the 14.7% Ni 5.0% Mn weld metal is recommended from the viewpoints of high tensile strength, low solidification temperature and of reasonable hardness. Taking penetration rate into consideration, the weld metal corresponds to the 21% Ni, 7% Mn welding electrode.

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