Development of Abrasion-resistant Pipe (NK-SL80) for Slurry Transportation Systems

Akira Tohyama*, Tatsuo Takaoka*, Hidetoshi Furukawa**, Hidenori Hori***, Toshihiko Fukui**** and Yusuke Minami*****

* Manager-Specialty Tube, Product Design and Quality Control, NKKTUBES
** Manager, Quality Assurance, NKKTUBES
*** Engineer, Technology Development, NKKTUBES
**** Senior Research Engineer, Heavy Steel Products Research Dept., Materials & Processing Research Center
***** Chief Researcher, Dr. Eng., Heavy Steel Products Research Dept., Materials & Processing Research Center

Excellent abrasion resistance is required of pipes that are used in slurry transportation systems such as those for transporting coal ash in pulverized-coal-firing boilers. We have developed an abrasion-resistant pipe named "NK-SL80" for transporting slurry. This paper reports properties and test results of the newly developed pipe. NK-SL80 is a 0.15%C-1.5%Si-1.5%Mn-Fe steel pipe with dual-phase microstructure composed of ferrite and martensite. The martensite phase provides abrasion resistance and the ferrite phase provides workability. The newly developed pipe contains smaller amounts of elements such as C and Mn than conventional abrasion-resistant pipes, and hence shows excellent field weldability compared with high-carbon abrasion-resistant pipes.

1. Introduction

Since the oil crisis in early 1970s, Japan has intensified efforts to diversify its energy sources. In electric power generation, nuclear power generation has become a base power source, and coal-fired power generation has increased its share in thermal power generation compared to LNG- and oil-fired power generation[1]. Thermal power generation is recently characterized by large output capacities of boilers utilized there. Most now have capacities exceeding 600 MW per unit and pulverized coal is used for large-scale coal-fired power generation[2]. A power generation system that uses pulverized coal is an integral system involving equipment for unloading, storing, and transporting raw coal, equipment for feeding pulverized coal, equipment for combustion, and equipment for transporting and treating coal ash generated by combustion. Generated at a rate of 6500000 tons per year in Japan, coal ash is a waste transported in a form of slurry. Approximately 65% of generated coal ash is used as cement and construction materials[3].

The steel pipe that has chemical composition of 0.15C-1.4Si-1.5Mn (hereinafter referred to as NK-SL80) is an abrasion-resistant pipe developed mainly to transport this type of waste[4),5)]. As abrasion resistance basically depends on the hardness of a material, conventional abrasion-resistant steels typically obtained abrasion resistance at the cost of weldability. The newly developed NK-SL80 steel has excellent properties for field working such as weldability and formability while maintaining abrasion resistance. This paper reports on the characteristics, abrasion resistance, and weldability of NK-SL80.

2. Outline of NK-SL80

2.1 Chemical compositions and mechanical properties of NK-SL80

Steel pipes used for slurry and waste transportation systems are required to have excellent abrasion resistance. As abrasion resistance basically depends on the hardness of a material, most conventional abrasion-resistant pipes achieve their hardness by increasing the carbon content or by adding alloying elements such as Ti and V. These approaches are effective for increasing abrasion resistance, however weldability deteriorates as the resulting product requires higher preheating temperatures for welding. These approaches likewise deteriorate formability. The combination of poor weldability and poor formability leads to poor field workability. Further, the addition of alloying elements increases manufacturing costs. NK-SL80 is an abrasion-resistant pipe that solves these problems and economically provides excellent field workability. **Table 1** shows the ranges of chemical compositions of NK-SL80, which is a carbon steel not containing expensive alloying elements such as Ti and V.

Table 1 Chemical compositions of NK-SL80

(mass %)

	C	Si	Mn	P	S
NK-SL80	≦0.20	1.20 ~ 1.60	1.20 ~ 1.60	≦0.040	≦0.040

Table 2 indicates the ranges of mechanical properties of NK-SL80. The hardness of this steel exceeds Vickers 250 to ensure excellent abrasion resistance.

Table 2 Mechanical properties of NK-SL80

	Tensile strength N/mm^2	Yield strength N/mm^2	Elongation* %	Hardness Hv
NK-SL80	≧800	≧400	≧10	≧250

*JIS Z2201 No.5 specimen

2.2 Manufacturing process of NK-SL80

The manufacturing process of NK-SL80 is similar to that of an ordinary carbon steel pipe. **Fig.1** shows the process for manufacturing NK-SL80 seamless pipes with outside diameters of 34.0 to 406.4 mm. **Fig.2** indicates the concept of the special heat treatment applied in this process. Steel pipes with chemical compositions shown in **Table 1** have a structure that consists of ferrite and pearlite in as-rolled conditions. When they are heated to a specific temperature zone (dual-phase region), pearlite is transformed into austenite while ferrite remains unchanged. Thus a dual-phase structure of ferrite and austenite is formed. During cooling after heating, ferrite grains grow and become larger. Austenite remains along the ferrite grain boundaries and forms a network structure. When quickly cooled down from this state, austenite along the ferrite grain boundaries is transformed into martensite, and a dual-phase structure of ferrite and martensite is formed.

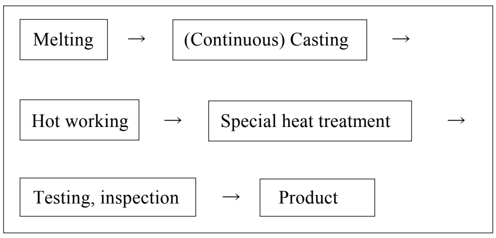


Fig.1 Manufacturing process of NK-SL80 seamless pipe

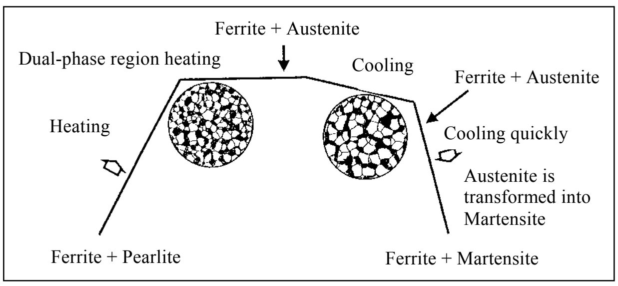


Fig.2 Special heat treatment process of NK-SL80 seamless pipe

2.3 Characteristics of sample pipe

A sample pipe, which had chemical composition shown in **Table 3** and an outside diameter of 318.6 mm and thickness of 17.00 mm, was prepared to evaluate the characteristics. The process employed for preparing the sample pipe is the same as that shown in **Fig.1**. **Table 4** shows mechanical properties of the sample pipe. Specifically, its hardness was 264 in Vickers scale and all mechanical properties were within the ranges specified in **Table 2**. **Photo 1** indicates the microstructure of the sample pipe. The white background area is the ferrite phase and the black network structure is the martensite phase. An ultra-micro-Vickers hardness tester was used with a load of 1 gram to measure local hardness at individual phases. The ferritic microstructure indicated the hardness values of Hv 120 to 150 while the martensitic microstructure indicated Hv 300 to 450. This measurement confirmed that the steel has a characteristic microstructure where the hard martensite phase is dispersed like a network along the boundaries of soft ferrite grains that compose the matrix (background).

Table 3 Chemical compositions of NK-SL80 sample pipe

(mass %)

	C	Si	Mn	P	S
NK-SL80	0.15	1.43	1.50	0.010	0.004

Table 4 Mechanical properties of NK-SL80 sample pipe

	Tensile strength N/mm^2	Yield strength N/mm^2	Elongation* %	Hardness Hv
NK-SL80	945	469	14	264

* JIS Z2201 No.5 specimen

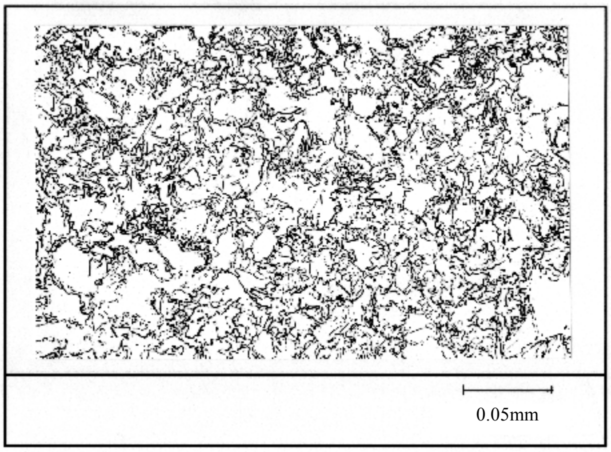


Photo 1 Microstructure of NK-SL80 sample pipe

3. Practical properties

3.1 Abrasion resistance

3.1.1 Abrasion resistance of NK-SL80 and various steel materials

General properties of abrasion resistance were evaluated by specimen-rotating-type abrasion tests in wet environment. **Fig.3** is a schematic drawing of the abrasion test machine and the dimension of the specimens. The specimens were 10 mm in diameter and 60 mm in length, and were moved in slurry at a speed of 4 m/sec. Abrasion resistance was evaluated by weight loss of the specimens due to abrasion. In this test environment, the dominant mode of abrasion was collision-type. Steel materials subjected to the rotating-type abrasion tests were carbon steel, abrasion-resistant steel, and stainless steel. In total, 13 grades of steels shown in **Table 5** were tested. **Fig.4** shows results of the tests. The specimens were rotated for four hours in the environment that is composed of silica (JIS No.3: 50 kg + JIS No.5: 25 kg) and water (32 kg). The vertical axis in **Fig.4** indicates the abrasion weight loss ratios, which were derived by dividing the weight loss of various steel materials by that of the standard specimen (STPY400). A lower weight loss ratio represents better abrasion resistance. The horizontal axis indicates hardness values of the specimens. **Fig.4** demonstrates the dependence of abrasion resistance on hardness of material and indicates that abrasion resistance increases with increasing hardness, and that austenitic steels have better abrasion resistance than ferritic steels of the same hardness. Although it is ferritic, NK-SL80 shows excellent abrasion resistance that is at the same level as austenitic steel. Its Vickers hardness is only about 260 and yet it exhibits abrasion resistance two times higher than STPY400. As a carbon steel, NK-SL80 economically provides excellent abrasion resistance exceeding that of austenitic steel containing expensive alloying elements.

In the abrasion tests described below, 400 N/mm^2-grade carbon steel (SS400), which is equivalent to STPY400 in **Table 5**, and high-carbon steel JIS S50C (0.5%C steel) were employed as reference materials.

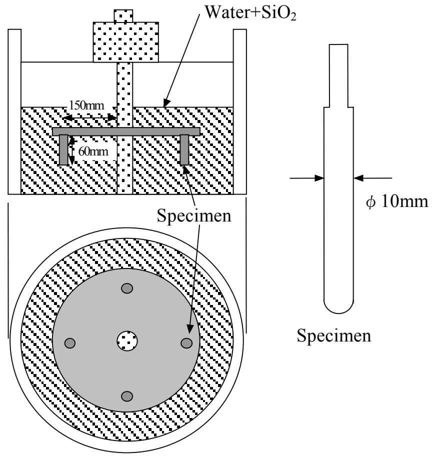


Fig.3 Schematic drawing of the abrasion test machine and dimension of the specimen (specimen rotating type)

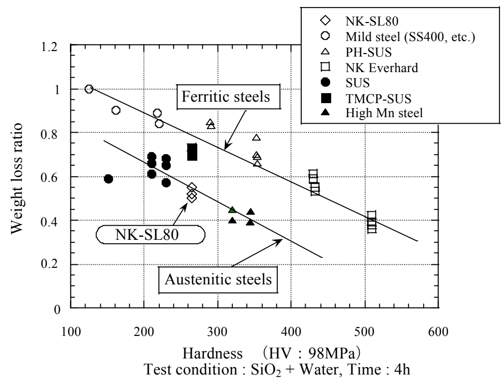


Fig.4 Abrasion resistance of several materials and NK-SL80 obtained by specimen rotating type test

Table 5 Chemical compositions of materials for abrasion test

(mass %)

Material	Grade	Hardness Hv/98N	C	Si	Mn	Cu	Ni	Cr	Mo	Others
C-steel	NK-SL80	260	0.15	1.43	1.50	－	－	－	－	－
	STPY400	125	0.10	0.29	0.56	－	－	－	－	－
	X52	160	0.12	0.28	1.30	－	－	－	－	Nb
Alloy-steel	9 Cr	220	0.08	0.23	0.44	－	0.14	8.35	0.90	Nb,V
NK Ever Hard	360A	440	0.16	0.25	0.96	0.20	－	0.63	0.21	V,Ti,B
	500A	520	0.27	0.31	0.96	－	－	0.61	0.22	V,Ti,B
PH-SUS	17Cr-5Ni	290	0.01	0.57	0.47	0.45	5.11	17.5	0.25	Nb
	15Cr-5Ni	360	0.01	0.50	0.67	3.70	4.91	14.8	－	Nb,Ti
High Mn-steel	12Mn	320	0.95	0.30	12.8	－	－	－	－	－
SUS	SUS304	150	0.04	－	1.02	0.36	8.13	18.2	0.23	－
	SUS304N	220	0.06	－	1.69	0.14	8.10	18.4	0.08	－
TMCP-SUS	SUS317	265	0.01	0.33	1.60	－	13.8	18.2	3.40	－
Dual-SUS	SUS329J1	230	0.02	0.47	0.98	－	5.79	22.5	3.16	－

3.1.2 Results of rotating-type abrasion tests using silica

Rotating-type abrasion tests were carried out using silica in order to simulate the concrete environment. The specimens were subjected to rotating tests for 24 hours under two conditions: condition 1 (silica (JIS No.3: 50 kg + JIS No.5: 25 kg) + water (35 kg)) and condition 2 (silica (JIS No.3: 25 kg + JIS No.5: 25 kg) + 10 mm silica rock (25 kg) + water (30 kg)). **Fig.5** shows test results. Both NK-SL80 and S50C showed abrasion resistance 1.8 times higher than SS400 under condition 1 and 1.4 times higher under condition 2.

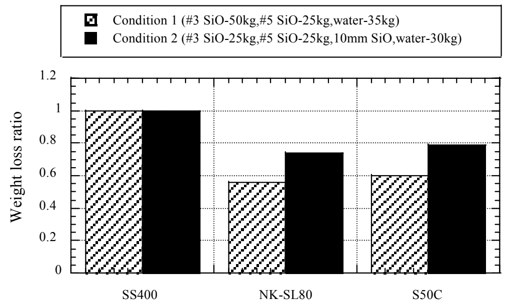


Fig.5 Abrasion test result for water + SiO_2

3.1.3 Results of rotating-type abrasion tests using coal ash (clinker)

Coal ash generated in coal-fired thermal power plants is classified into two types: clinker, which falls down and accumulates in a clinker hopper beneath a boiler combustion chamber, and fly ash, which is collected by a dust collector. Clinker is conveyed in a slurry state by adding processing water, and fly ash is conveyed by vacuum and pressure conveying systems.

Rotating-type abrasion tests were carried out using clinker in order to simulate slurry transportation. The specimens were subjected to rotating tests for 24 hours under two conditions: condition 1 (coal ash (clinker) 39 kg + water (80kg)) and condition 2 (coal ash (clinker) 50 kg + water (70 kg)). **Fig.6** shows test results. Both NK-SL80 and S50C showed abrasion resistance 2.2 times higher than SS400 under both condition 1 and condition 2.

3.1.4 Results of air-blasting-type abrasion tests using fly ash

Fine fly ash generated in association with the combustion of pulverized coal is collected by electric precipitators, etc., and conveyed from precipitator hoppers to ash relay tanks by vacuum conveying. From there, it is further conveyed to ash storage silos by pressure conveying. Ash conveying from the hoppers to the relay tanks and on to

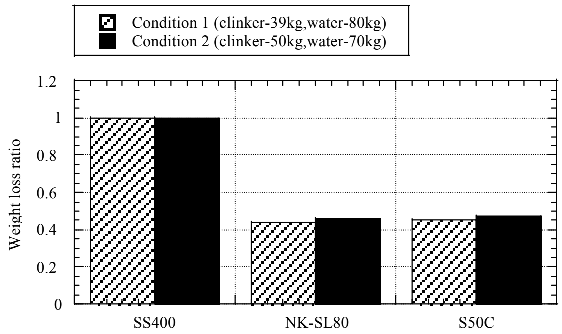


Fig.6 Abrasion test result for coal ash (clinker)

the storage silos is carried out through ash conveying pipes. During vacuum and pressure conveying, fine fly ash repeatedly collides with the inner surface of the pipe at high speed. Thus, abrasion to the inner surface of the ash conveying pipe is dry collision-type abrasion, and therefore a rotating-type abrasion test machine is not appropriate to evaluate abrasion resistance under these conditions. Hence, a fly ash air-blasting-type abrasion test machine as shown in **Fig.7** was fabricated.

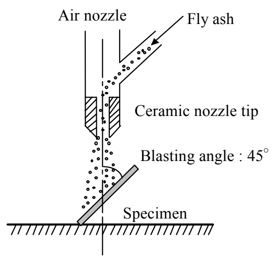


Fig.7 Schematic drawing of the abrasion test machine (fly ash air blasting type)

Photo 2 shows fly ash after pulverized coal combustion that was used for the tests. Two types of ash grains were observed: spherical and polygonal. Observation of polygonal grains at high magnification reveals that they are agglomerates of spherical grains of different sizes. Thus, it was found that unit fly ash grains are spherical, and that they are present as separate unit grains or agglomerates of unit grains.

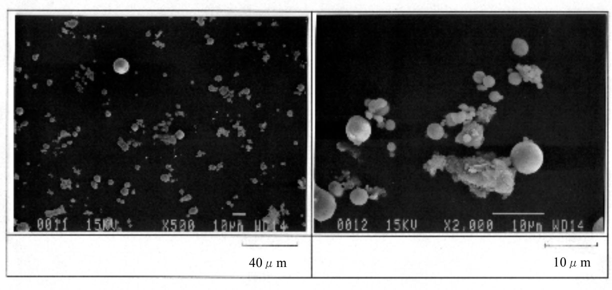


Photo 2 SEM observation result of coal ash (fly ash)

Fig.8 shows measurement results of fly ash grain size distribution. Grain sizes were widely dispersed ranging from 0.11 to 174.6 micrometers. However, ultra-fine grains smaller than 1.0 micrometers accounted for only 3.1% of the whole. In contrast, grains ranging from 10 to 30 micrometers accounted for more than 40%. The 50%-average grain size was 14.59 micrometers.

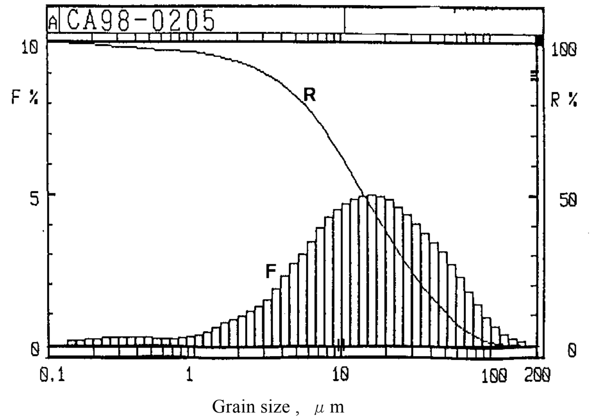


Fig.8 Measurement result of coal fly ash

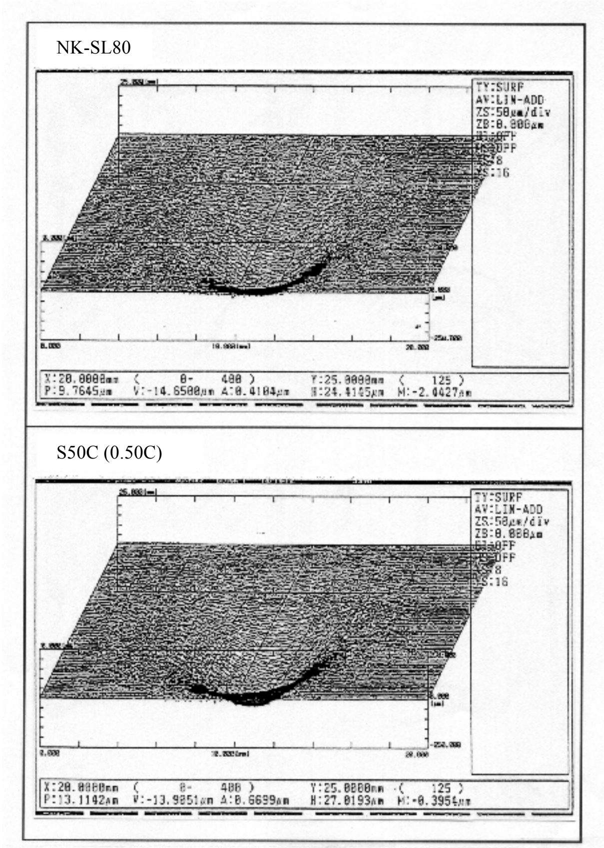
Plate-type specimens were cut out from a NK-SL80 pipe and a reference S50C pipe to evaluate their abrasion resistance by abrasion weight loss after fly ash air blasting using the test machine as shown in **Fig.7**. The test conditions were: air blasting pressure of 4.5 kg/cm^2 at the air nozzle, and fly ash colliding with the specimens at a speed of 170 m/sec. Amounts of fly ash blasted were at two levels: 5 kg and 15 kg. Specimens were prepared with three types of surface finish: mechanically ground (roughness: R_{max} less than 5 micrometers), No. 60 grinder finished, and as pickled after rolling.

Table 6 shows results of fly ash air-blasting-type tests. **Fig.9** shows results of surface roughness measurements of specimens after air blasting. No significant difference in weight loss was found between NK-SL80 and S50C regardless of fly ash amounts blasted and surface conditions, while in the surface roughness measurements, S50 steel showed deeper abrasion than NK-SL80.

Table 6 Abrasion test result for coal ash (fly ash)

(Weight loss : g)

	NK-SL80		S50C(0.50C)	
Fly ash (kg)	5	15	5	15
Ground surface (≦5S)	0.20	0.83	0.23	0.90
Grinder surface #60	0.20	0.53	0.20	0.50
As-pickled surface	0.20	0.58	0.20	0.60



Fly ash : 15kg specimen : ground surface≦5s

Fig.9 Measurement result of surface roughness by 3-dimension method

Photo 3 shows microstructures of both specimens. In NK-SL80 pipe, the hard martensite phase is distributed like a network as described in Section **1.3**. In contrast, S50C has a ferrite-pearlite microstructure, in which the hard cementite phase (Fe_3C) of pearlite is distributed like islands. Abrasion of S50C is presumably promoted because abrasion occurs predominantly at the soft ferrite phase, and when abrasion at the ferrite phase progressed to a certain degree, islands of the hard pearlite phase slip off from the surface. In contrast, the network structure of martensite is distributed three-dimensionally in NK-SL80 so that even when abrasion progressed quickly at the soft ferrite phase, the hard martensite phase exists just under it, which delays the progress of abrasion. This explains why NK-SL80 has superior resistance against local abrasion while it exhibits only an equivalent property to S50C when evaluated by whole-area abrasion weight loss.

3.2 Weldability

3.2.1 Weldability

NK-SL80 is characterized by its excellent weldability. S50C conventionally used for ash conveying pipes has a high (0.5%) carbon content, and requires preheating to

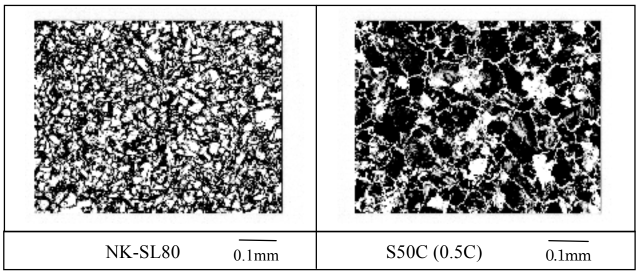


Photo 3 Microstructures of abrasion test specimens

around 200℃ before welding. In contrast, NK-SL80 has a low (0.15%) carbon content, and does not contain any alloying elements. Therefore, NK-SL80 has a low Pcm value, where Pcm is an index that indicates sensitivity to weld cracking and derived from the following equation using chemical compositions of steels.

$$\mathrm{Pcm} = \mathrm{C} + \mathrm{Si}/30 + \mathrm{Mn}/20 + \mathrm{Cu}/20 + \mathrm{Ni}/60 + \mathrm{Cr}/20 + \mathrm{Mo}/15 + \mathrm{V}/10 + 5\mathrm{B}$$

Y-groove cracking tests specified by JIS Z3158 were applied to evaluate the sensitivity to low-temperature cracking at actual weld heat-affected zones. **Table 7** shows the results. No crack was generated at room temperature (25℃), proving a great advantage of NK-SL80 in that it does not need preheating at field welding.

Table 7 Test result of JIS Z 3158 Y-groove cracking test

Pre-heat temperature			Welding condition
R.T. (25℃)	50℃	100℃	Thickness 20mm n=3 Test method JIS Z 3158 The low-hydrogen type covered electrode
No crack	No crack	No crack	

Table 8 indicates welding conditions for NK-SL80. There is no limitation on welding methods that can be applied to it. Standard low-hydrogen-type weld consumables for high-tensile steel can be used. As for weld current, weld voltage, and welding speed, standard values specified to each weld consumable and welding machine are applicable. It does not require preheating or post-heating.

3.2.2 Welding procedure

Ash conveying pipe systems are typically constructed by flange welding and butt welding. **Fig.10** shows an example of flange welding and **Fig.11** butt welding. As described in Section **1.2**, abrasion resistance of NK-SL80 depends on the network structure of martensite that is formed by special heat treatment. This sort of network structure of martensite is not formed in weld metal areas. Weld metal areas, however, have a solidified structure,

Table 8 Welding conditions of NK-SL80 seamless pipe

Welding process	Metal-arc welding with covered electrode, semi-automatic welding, or automatic welding	
Welding consumables *	Metal-arc welding with covered electrode**	JIS Z 3211 D4316 Example:LB-47 by Kobe steel Ltd.
		JIS Z 3212 D5016 Example:LB-52 by Kobe steel Ltd.
	Semi-automatic Welding: gas-shielded metal arc welding	JIS Z 3312 YGW11 Example:MG-50 by Kobe steel Ltd.
		JIS Z 3313 YFW11 Example:DW-100 by Kobe steel Ltd.
	Automatic welding: TIG welding	JIS Z 3316 YGT50 Example:TGS-50 by Kobe steel Ltd.
Welding condition	Heat input:10000～15000 J/cm Preheating・postheating : free Interpass temperature:<150℃ Current, voltage, welding speed : As specified to each weld consumable and welding machine	

* : As for the welding material, the joint tensile strength is made the welding material of 420N/mm^2 or more as shown in the table.
** : When the shielded metal arc welding is used, with a welding rod of low-hydrogen type like the table. And moreover , please use that have to dry immediately before the welding, and note the cold crack prevention about the covered electrode.

which is sufficiently hard. In the base metal, weld heat-affected zones are exposed to a high temperature and the hardness is slightly decreased (Hv: 280 to 240). However, the decrease in abrasion resistance is expected to be small as **Fig.4** indicates. Further, when flange welding is carried out in such a manner as illustrated by the example in **Fig.10**, weld metal areas and weld heat-affected zones are not exposed on the inner surface of the pipe. Therefore, these areas cause no problems. Also in butt welding, when the steps illustrated in **Fig.11** are followed, the effect of welding on abrasion resistance can be minimized.

4. Practical application tests

Results of various abrasion tests were reported above. While abrasion resistance basically depends on the hardness of a material, even when pipes made of a same material are used, their abrasion resistance is greatly affected by properties of the abrasive substances being transported.

【Pipe】NK-SL80 318.5 ϕ ×17.0t×5500L (mm)
【Flange】Material : S25C Flange spec : JPI 150psi
Flange diameter : 300A Flange type : SO-RF

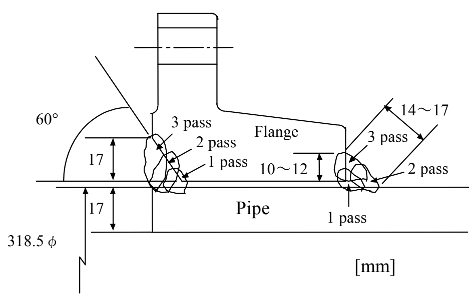


Fig.10 Example of flange welding of NK-SL80

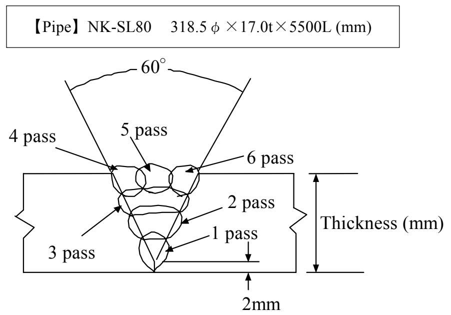


Fig.11 Example of butt welding of NK-SL80

Fly ash air-blasting tests suggested the effectiveness of the network structure of martensite, but they needed to be confirmed at fly ash conveying pipes actually in operation. A one-year demonstration test is currently being conducted at a fly ash conveying pipe system in a commercial coal-fired thermal power plant.

Fig.12 shows the available size range of NK-SL80. The typical market range demanded for coal ash conveying pipes to be used at coal-fired thermal power plants is from 126.3 to 355.6 mm in outside diameter. Therefore, the manufacturing process shown in Section **1.2** was that for seamless pipes. Abrasion-resistant slurry transportation pipes are also used in waste transportation systems and slag transportation systems. Large-diameter steel pipes over 500 mm in outside diameter are manufactured by the UOE process[4]. A practical application test for transporting slag is also under way.

5. Conclusion

The abrasion-resistant carbon steel pipe named NK-SL80 has been developed for transporting coal ash and other abrasive substances. A sample pipe was prepared to evaluate abrasion resistance and weldability. The following conclusions were obtained from testing.

(1) NK-SL80 has a dual-phase microstructure of ferrite and martensite. The martensite phase has a network structure formed by applying a special heat treatment. It has abrasion resistance two times higher than STPY400 that is equivalent to SS400.

(2) Two series of tests, each simulating the slurry transportation of coal ash clinker and vacuum/pressure transportation of coal fly ash, verified the excellent abrasion resistance of NK-SL80, which was higher or equal to that of 0.5C (S50C) steel pipes.

(3) NK-SL80 has a low carbon content and does not require preheating or post-heating at welding. Therefore, it has excellent field workability.

We would like to thank Ash Treatment and Transportation Plant Dept. of Power Plant Div. of Kawasaki Heavy Industries, Ltd., and associated staff members for their cooperation extended to our coal ash abrasion tests.

Nominal dia.		Outside dia. (mm)
A	B	
25	1	34.0
32	1 1/4	42.7
40	1 1/2	48.6
50	2	60.5
65	2 1/2	76.3
80	3	89.1
90	3 1/2	101.6
100	4	114.3
125	5	139.8
150	6	165.2
200	8	216.3
250	10	267.4
300	12	318.5
350	14	355.6
400	16	406.4
450	18	457.2
500	20	508.0
550	22	558.8
600	24	609.6
650	26	660.4
700	28	711.2
750	30	762.0
800	32	812.8
850	34	863.6
900	36	914.4
950	38	965.2
1000	40	1016.0

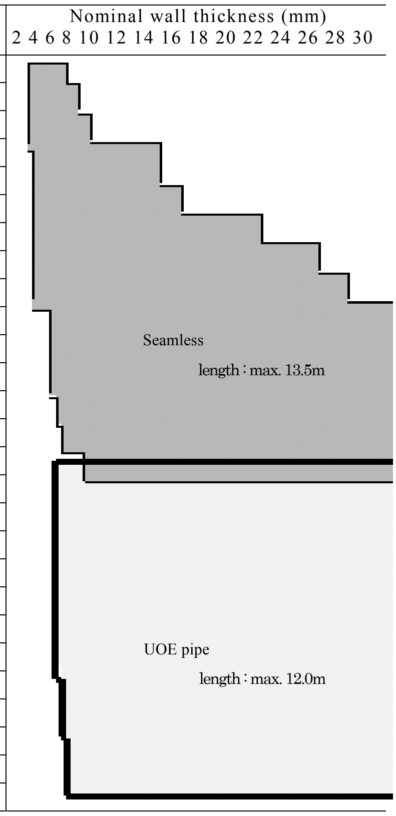


Fig.12 Available size range of NK-SL80

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<Please refer to>
Akira Toyama
Product Design & Technical Services, NKKTUBES
Tel. 044 (322) 1666
E-mail address : Akira_Toyama@ntsgw.keihin.nkk.co.jp
Toshihiko Fukui
Heavy Steel Products Research Dept., Materials & Processing Research Center
Tel. 044 (322) 1735
E-mail address : Toshihiko_Fukui@ntsgw.heihin.nkk.co.jp