A Newly Developed Nickel-Iron Electrode with Superior Hot Cracking Resistance and High-Strength Properties for Welding Perlitic Nodular Iron

A high-strength electrode with good machinability was developed from experiments that determined the optimum element levels to resist hot cracking

BY X. Y. ZHANG, Z. F. ZHOU, M. L. XIE AND Y. M. ZHANG

ABSTRACT. Using the HRL-1-type hot cracking tester, which is based on the theory of critical deformation rate, the influence of several alloying elements on hot cracking of nickel-iron electrodes was studied. Based on these experiments, the optimum contents of molybdenum, tungsten, vanadium, rare earth yttrium and rare earth cerium, which can improve weld hot cracking resistance properties, were determined and a new nickel-iron electrode was successfully developed. The hot cracking resistance of the new nickel-iron electrode is higher than those of the similar types of domestic and foreign electrodes, and the yield and tensile strength of its weld metal can match those of QT600-3 perlitic nodular iron. The machinability of the welded joint is also good.

Introduction

Perlitic nodular iron is used widely in manufacturing. Many methods and materials for welding nodular iron have been developed. Most of the repairs and assemblies of nodular iron have been made by manual shielded metal arc welding, in which homogeneous and heterogeneous electrodes are often employed. Homogeneous electrodes are only used to weld larger defects. But if homogeneous electrodes are utilized, postweld heat treatments must be made. Of all heterogeneous electrodes, the ENiFe-CI electrode is preferred because alternative types of electrodes possess inherent problems. For example, nodular iron joints welded with high-vanadium electrodes possess poor machinability (Ref. 1). In addition, when austenitic stainless steel electrodes (Ref. 2) are used to weld nodular iron, the carbon segregation at the phase boundary of ferrite and austenite and the higher yield strength cause cracking in the heat-affected zone. Chromic carbide in the weld also causes a worsening of weld cracking resistance properties when austenitic stainless steel electrodes or electrodes containing chromium are used (Ref. 3).

However, there is a problem with ENiFe-CI electrodes. The joint strength values of the perlitic nodular iron are much lower than those of the base metal and the electrode (Refs. 4–6). Some research workers have attempted to improve the strength of these welded joints by postweld heat treatment (annealing or normalizing). This heat treatment proved to be unsuccessful, and actually decreased the strength of the welded joints (Refs. 7–10). Previously, we studied crack initiation and propagation in QT600-3 nodular iron joints welded with ENiFe-CI electrodes by the Moire fringe method (Ref. 11), and calculated the complex elastoplastic deformation of these welded joints by the hybrid/mixed nonconforming finite element method (Ref. 12). The results show that one of the causes of the nonuniform deformation and the low strength of these welded joints under the uniaxial tensile process is the low yield strength of the weld metal. In order to improve the weld metal properties and make the welded joint deformation conform, it is necessary to develop a new welding material.

The weld metal of a ENiFe-CI electrode is composed of austenite, graphite, carbide and a small amount of interdendritic impurity, so the main methods for increasing weld yield strength are to strengthen austenite, improve graphite distribution and decrease interdendritic impurity. In addition, when ENiFe-CI electrodes are used for welding cast iron, the welds are comparatively susceptible to hot cracking (Ref. 1), especially, with increasing weld stress. Therefore, the hot cracking resistance properties must be considered when developing the high-strength ENiFe-CI electrode.

KEY WORDS

Hot-Crack Resistance
Nickel-Iron Electrode
QT600-3 Nodular Iron
Weld Metal Strength
Critical Deform. Rate
Crack Testing
Pearlitic Nodular Fe
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SMAW

X. Y. ZHANG, Z. F. ZHOU, M. L. XIE and Y. M. ZHANG are with Jilin University of Technology, Chang Chun, China.

Based on Z408 ENiFe-CI electrodes (Ref. 13), a new nickel-iron electrode with superior hot cracking resistance and high-strength properties was developed.

Experimental Materials and Method

Experimental Materials

The test plates used were the perlitic nodular iron QT600-3. Its chemical composition and mechanical properties are listed in Tables 1 and 2, respectively. Test plate dimensions were 140 x 140 x 14 mm (5.5 x 5.5 x 0.55 in.). The experimental electrodes had a core diameter of 3.2 mm (1/8 in.) and chemical composition of 55 wt-% Ni, 45 wt-% Fe. Different amounts of molybdenum, tungsten, vanadium, Al-9.6 wt-% Y alloy, Al-9.6 wt-% Ce alloy and Si-Fe-Ce alloy are added to the original coating of the Z408 ENiFe-CI electrode to examine their influence on hot cracking susceptibility and yield strength of nickel-iron electrodes.

Experimental Method

The weld hot cracking susceptibility was studied by a HRL-1-type of hot-cracking test machine, which was able to continuously adjust the deformation speed. As shown in Fig. 1, two nodular iron test plates were arranged on the tester to form a T joint; the vertical plate was fixed, while the base plate was revolved around the fixed axis OZ at a certain preselected angular velocity ω. A single pass weld was carried out toward point O, and the brittleness temperature range (BTR) moved with the welding bath.

By measuring the distance R from the crack tip to the center of rotation at an arbitrary time, the deformation rate V at this point could be calculated

$$V = R\,\omega \text{ mm/s}$$

From the above formula, it can be seen that V is a variable. As R decreases, V also falls. When the BTR moves to some point, the strain produced by the deformation rate is less than the weld metal ductility within the BTR, crack growth stops, and the tester stops automatically. The value of R at this point is called the critical radius R_L. The critical deformation rate is

$$V_{bl} = R_L\,\omega \text{ mm/s}$$

V_{bl} can be used as a weld metal hot cracking susceptibility index. The higher the V_{bl} value, the better the weld metal hot cracking resistance properties. The average value of three test results from the T joint is reported in this paper.

Table 1 — Chemical Composition of the Nodular Iron QT600-3 (wt-%)

C	Si	S	Mn	Mg	ΣRe
3.10	3.06	0.022	0.60	0.031	0.037

The weld was made by the shielded metal arc welding process. The experimental welding machine was operated on AC at 120 A. The welding speed was approximately 2.5 mm/s (6 in./min).

Experimental Results and Discussion

Influence of Several Elements on Hot Cracking Susceptibility of Nickel-Iron Electrodes

The influence of molybdenum. Different amounts of molybdenum powder were added to the Z408 ENiFe-CI electrode coating (the deposited metal composition of the Z408 ENiFe-CI electrode is 2.27 wt-% C, 0.40 wt-% Ti, 0.29 wt-% Co, 0.18 wt-% Nb, 0.0021 wt-% Y) (Ref. 13), the relationship between weld molybdenum content and V_{bl} value is shown in Fig. 2. From a weld content of 0.03 wt-%, V_{bl} increases with the increase of weld molybdenum content, and V_{bl} reaches peak value (0.232 mm/s) when weld molybdenum content reaches 0.13 wt-% . At the peak point of V_{bl}, weld hot cracking resistance properties are optimum. Afterwards, V_{bl} decreases with the continuous increase of weld molybdenum content.

Molybdenum is an element that can promote carbide formation, easily forming MC. The melting point of MC is as high as 2965°C (5369°F), so it serves as a heterogeneous nuclei for crystallization. When weld molybdenum content is increased from 0.03 wt-% to 0.13 wt-% , grain refinement occurs. The grain refining effect causes a reduction in low melting point substance segregation, and increases the value of V_{bl}. After molybdenum content exceeds 0.13 wt-%, excessive molybdenum and sulfur form the low melting point impurities (Mo_2S_3 and MoS_2). Molybdenum and phosphorus can form a complex eutectic, and the carbides of molybdenum are in many forms. When molybdenum content is small, it is mainly in spot MoC distribution. When molybdenum content is excessive, it forms M_6C and M_2C, as well as the complex carbides of several elements, which are in the forms of spot, flake and intergranular film distribution, which weaken intergranular strength. All three aspects above decrease weld high-temperature ductility, increase weld hot cracking susceptibility and decrease the value of V_{bl}.

Table 2 — Mechanical Properties of the Nodular Iron QT600-3

Tensile strength σ_b MPa	Yield strength σ_s MPa	Elongation δ%
640–680	420	2.5–3.5

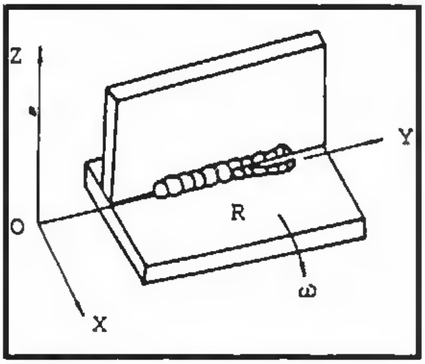

Fig. 1 — Hot cracking test method.

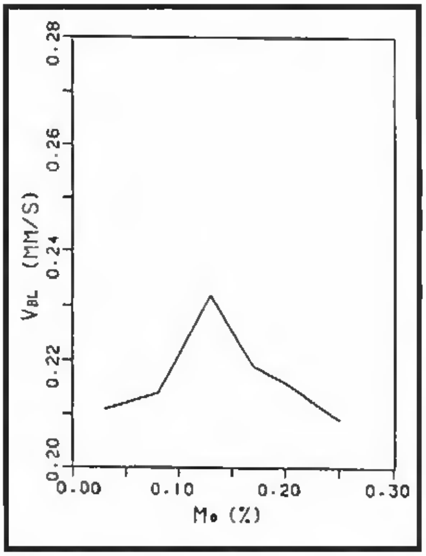

Fig. 2 — The influence of molybdenum on V_{bl}.

The influence of tungsten. Different amounts of tungsten powder were added to the electrode coating with an optimum molybdenum content in order to examine the influence of tungsten on weld hot cracking. As shown in Fig. 3, when weld tungsten content is 0.10 wt-%, weld hot cracking resistance properties are optimum. When weld tungsten content is less than 0.10 wt-%, V_{bl} increases as tungsten content increases. When weld tungsten content is more than 0.10 wt-%, weld hot cracking resistance decreases.

Tungsten is an element that can promote carbide formation. The melting point of W_2C is 3130°C (5666°F). When

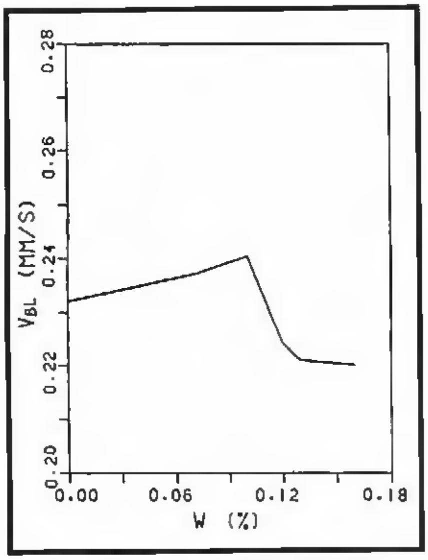

Fig. 3 — The influence of tungsten on V_{bl}.

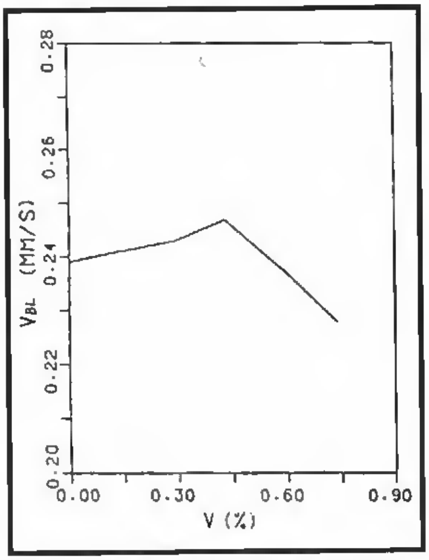

Fig. 4 — The influence of vanadium on V_{bl}.

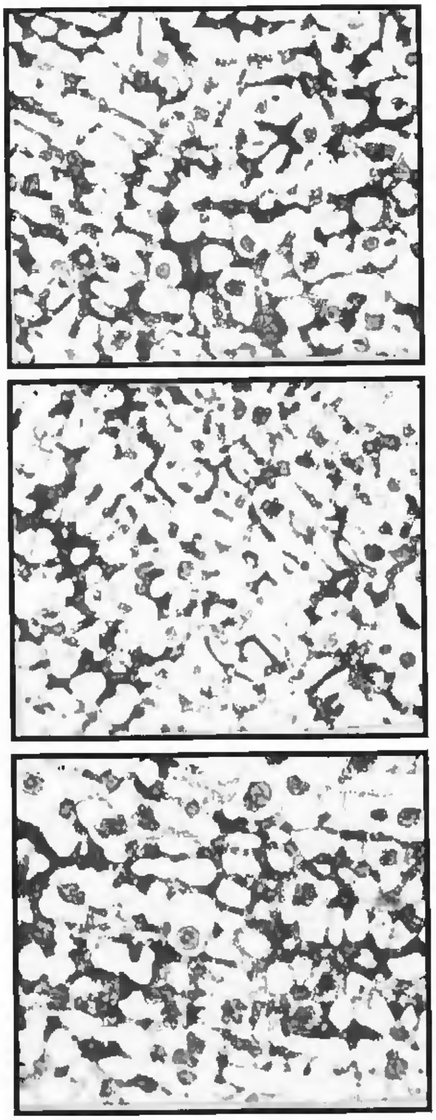

Fig. 5 — The grain refining effect of vanadium.

the weld pool crystallizes, W_2C carbide separates out of the liquid as crystalline nuclei. Within a specified range of increased tungsten content, the amount of carbides increase, grain refinement occurs, and the low-melting point substance segregation reduces, which result in the increase of weld high-temperature ductility and hot cracking resistance. When the weld contains an excessive tungsten content, a large amount of carbide forms. In addition, the carbides of tungsten are in many forms. The more the tungsten content, the more the flake, network and film intergranular carbides form, so intergranular strength weakens and weld hot cracking resistance decreases.

The influence of vanadium. Different amounts of vanadium powder were added to an electrode coating with optimum Mo and W content. The influence of vanadium on weld hot cracking resistance property index V_{bl} is shown in Fig. 4. The curve has a peak value (0.2470 mm/s) with a corresponding weld vanadium content of 0.43 wt-%; *i.e.*, weld hot cracking resistance properties are optimum at this point. Vanadium is an element that can promote carbide formation and grain refinement. When weld vanadium content is increased from 0 to 0.43 wt-%, the grain refines, as shown in Fig. 5. The melting point of VC is 3023°C (5473°F), and VC carbide can be crystalline nuclei in the welding pool. Because the influence of vanadium on V_{bl} is similar to that of Mo, it will not be discussed further here.

The influence of Al-9.6 wt-% Y alloy. In order to keep the optimum content of Mo, W and V in the weld metal, different amounts of Al-9.6 wt-% Y alloy were added to the electrode coating. The influence of Al-9.6 wt-% Y alloy on weld hot cracking resistance property index V_{bl} is shown in Fig. 6. The value of V_{bl} changes with the increase of weld aluminum, yttrium. When the weld metal contains 0.015 wt-% Y and 0.27 wt-% Al, V_{bl} reaches a peak value of 0.2746 mm/s, and weld hot cracking resistance properties are optimum. The analysis of why it happens is stated below.

Rare earth yttrium has a marked capability for desulfurizing, dephosphorizing (Ref. 14), and de-oxiding, reducing impurities and purifying the grain boundary effect. It also can improve the form and distribution of low-melting-point impurities.

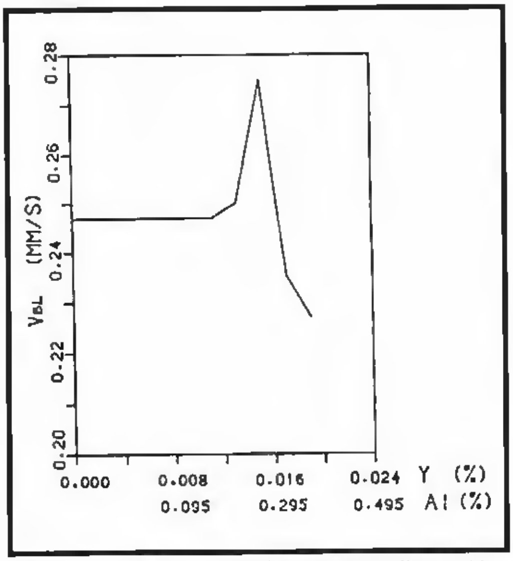

Fig. 6 — The influence of Al-9.6 wt-% Y alloy on V_{bl}.

Rare earth yttrium can promote graphite nodularization and reduce intergranular network graphite. Therefore, within a specific yttrium content range, the increase of weld yttrium content contributes to improved weld hot cracking resistance properties. However, when weld yttrium content is more than 0.015 wt-%, intercrystalline yttrium segregation is comparatively severe, and yttrium can form low-melting point eutectics with iron and nickel, for example: Y-YFe_2 (900°C), Y_3Ni-Y_3Ni_2 (802°C). Therefore, excessive Y causes weld hot cracking resistance properties to deteriorate.

Aluminum and oxygen can form Al_2O_3. Its melting point is 2030°C (3686°F). Some of Al_2O_3 floats on the surface of the weld pool, but the remainder can be crystalline nuclei, refined grain structure, reduced intergranular low-melting-point eutectic and increased weld hot cracking resistance properties. But excessive aluminum and

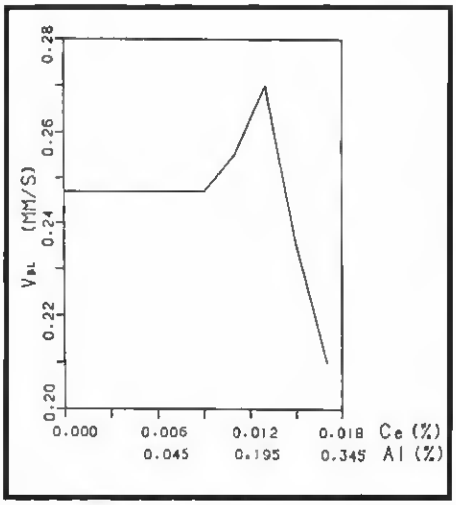

Fig. 7 — The influence of Al-9.6 wt-% Ce alloy on V_{bl}.

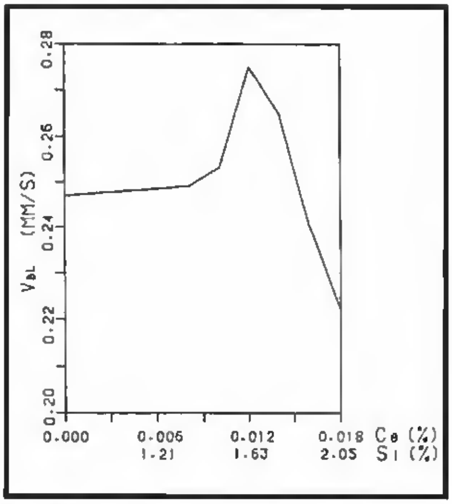

Fig. 8 — The influence of Si-Fe-Ce alloy on V_{bl}.

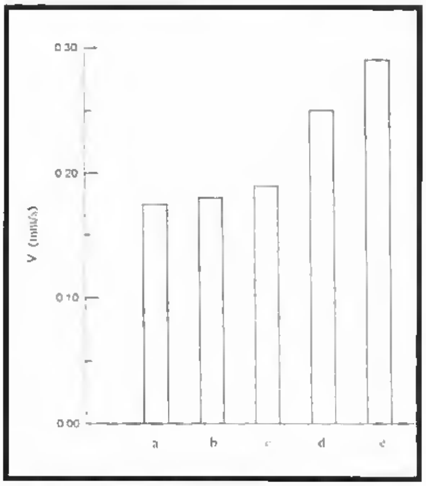

Fig. 9 — Comparison of the hot cracking resistance properties of the different nickel-iron electrodes. A — Commercial ENiFe-CI electrode made in China; B — commercial ENiFe-CI electrode made in Switzerland; C — commercial ENiFe-CI electrode made in U.S.; D — commercial ENiFe-CI electrode made in Japan; E — new nickel-iron electrode.

nickel form a low-melting-point eutectic, which causes a worsening of weld hot cracking resistance properties.

The influence of Al-9.6 wt-% Ce alloy. Graphite nodularization in weld metal is an efficient way to increase weld yield strength. Rare earth cerium is the best element in promoting graphite nodularization, so under the previous same condition, different amounts of Al-9.6 wt-% Ce alloy were added to the electrode coating to examine their influence on weld hot cracking susceptibility. As shown in Fig. 7, when weld cerium content is increased from 0.009 to 0.013 wt-%, there is a corresponding increase in V_{bl}. When cerium is further increased, the value of V_{bl} decreases.

Because the effect of Ce on the V_{bl} index of the weld metal is similar to that of Y, it will not be discussed further.

The influence of Si-Fe-Ce alloy. Under the previous same condition, different amounts of Si-Fe-Ce alloy were added to the electrode coating. Figure 8 shows the influence of Si-Fe-Ce alloy on the value of V_{bl}. The curve has a peak value when the weld metal contains 0.012 wt-% Ce 1.63 wt-% Si, the value of V_{bl} reaches 0.2747 mm/s. At this point, weld hot cracking resistance properties are optimum.

Influence of Several Elements on Weld Strength of Nickel-Iron Electrodes

Nickel-iron electrode containing Al-9.6 wt-% Y alloy. Based on the above experiments, the electrodes containing the different elements were used to weld QT600-3 nodular iron plates. In order to obtain the tensile strength, yield strength and elongation of the weld metal, round specimens of all-weld metal were taken longitudinally from the weld. The nickel-iron electrodes containing Al-9.6 wt-% Y alloy with the optimum hot cracking resistance properties were used to examine the weld strength, as shown in Table 3. The weld yield strength reaches 360.15 MPa (52.2 ksi), which is higher than that of the Z408 ENiFe-CI electrode (Ref. 13) and lower than that of the base metal. The weld tensile strength values are more than 600 MPa. The reasons for the increase of weld yield strength is as follows: molybdenum, tungsten and vanadium can promote weld grain refining and strengthen austenite, and in addition, rare earth yttrium can promote graphite nodularization and reduce the intergranular graphite.

Nickel-Iron Electrode Containing Al-9.6 wt-% Ce Alloy. When weld metal contains 0.013 wt-% Ce, 0.22 wt-% Al and the optimum contents of other alloying elements, hot cracking resistance properties and weld tensile strength are optimum, but the weld yield strength only reaches 368.97 MPa (53.5 ksi), as shown in Table 4. Compared with the electrode containing Al-9.6 wt-% Y alloy, the addition of a suitable amount of Al-9.6 wt-% Ce alloy cannot cause a marked increase of weld yield strength.

Nickel-Iron Electrode Containing Si-Fe-Ce Alloy. Table 5 lists the yield strength of weld metal containing 0.012 wt-% Ce, 1.63 wt-% Si and the optimum contents of other alloying elements. As

Table 3 — Strength and Elongation of the Nickel-Iron Electrode Containing Al-9.6wt-% Y Alloy

Specimen No.	Yield Strength (MPa) unit	Yield Strength (MPa) avg.	Tensile Strength (MPa) unit	Tensile Strength (MPa) avg.	Elongation (%) unit	Elongation (%) avg.
1	369.46	360.15	617.48	610.25	7.5	7.75
2	350.84		603.02		8.0	

Table 4 — Strength and Elongation of the Nickel-Iron Electrode Containing Al-9.6wt-% Ce Alloy

Specimen No.	Yield Strength (MPa) unit	Yield Strength (MPa) avg.	Tensile strength (MPa) unit	Tensile strength (MPa) avg.	Elongation (%) unit	Elongation (%) avg.
1	369.46	368.97	623.30	627.38	7.8	8.0
2	378.28		631.46		8.2	

Table 5 — Strength and Elongation of the Nickel-Iron Electrode Containing Si-Fe-Ce Alloy

Specimen No.	Yield Strength (MPa) unit	Yield Strength (MPa) avg.	Tensile Strength (MPa) unit	Tensile Strength (MPa) avg.	Elongation (%) unit	Elongation (%) avg.
1	407.68	414.93	618.72	632.10	7.9	7.35
2	422.18		645.48		6.8	

Table 6 — Deposited Metal Chemical Composition of the New Nickel-Iron Electrode (wt-%)

C	Si	Ti	Nb	Co	Mo
2.11	1.10	0.52	0.25	0.42	0.13
W	V	ΣRe	Al	Ni	Fe
0.09	0.62	0.017	0.24	46.2	surplus

can be seen, the weld yield strength is much higher than those of the above electrodes, and can match the yield strength requirement of QT600-3 nodular iron. There are three reasons for the marked increase of weld yield strength. Firstly, a suitable amount of cerium and silicon can refine weld grain; Secondly, solution strengthening effect of silicon in austenite contributes to improve weld yield strength; finally, weld silicon and cerium cannot only promote graphite nodularization but also refine nodular graphite, so the harmful effect caused by nonregular graphite is decreased.

Properties of the New Nickel-Iron Electrode

On the basis of the above experiments, a new nickel-iron electrode was developed, and its deposited metal composition is given in Table 6. The yield strength of the new electrode reaches 414.93 MPa (60.2 ksi), the tensile strength reaches 632.1 MPa (91.7 ksi), and the elongation reaches 7.35%, which match the mechanical properties of QT600-3 nodular iron. Compared with similar types of domestic and foreign electrodes from the U.S., Japan and Switzerland, the new electrode has superior hot cracking resistance properties, as shown in Fig. 9. Production practice has demonstrated that when the new electrodes are used for welding a severe defect in high-strength nodular iron QT600-3 without preheating, there is no hot crack in the weld metal, while using similar types of domestic and foreign electrodes, hot cracks appear.

Table 7 — Weldment Maximum Hardness (HB)

Weld		HAZ	
average	maximum	average	maximum
175	181	284	296

The hardness test results of the QT600-3 nodular iron joint welded with the new nickel-iron electrodes are listed in Table 7. The white iron distributes on the partial fusion zone discontinuously, and the maximum value of welded joint hardness is less than HB300, so weldments possessed good machinability.

Conclusions

1) The addition of molyhdenum, tungsten, vanadium, silicon and rare earth cerium in a specific range can bring about a marked effect on weld hot cracking resistance properties.

2) Weld hot cracking resistance properties of the newly developed nickel-iron electrode are much higher than those of the similar types of domestic and foreign electrodes from U.S., Japan and Switzerland.

3) The yield strength, tensile strength and elongation of the newly developed nickel-iron electrode can match those of the high-strength perlitic nodular iron QT600-3.

4) The maximum value for welded joint hardness is less than HB300 when the newly developed nickel-iron electrode is used for welding the high-strength perlitic nodular iron QT600-3, so weldments have good machinability.

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