A Fe-Ni-Cr system filler metal for brazing of stainless steel [*]

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Abstract *New Fe-Ni-Cr system brazing alloys were designed, in which elements Si and B as well as Cu-Ti binary alloy were added as the temperature depressants. The brazing alloys were fabricated into filler foils by a rapidly-solidifying technique. It was found that, to acquire a suitable liquidus temperature of the filler alloy, the addition of Cu-Ti binary alloy decreased the needed amount of Si and B, and it had an effect on improvement in mechanical properties of the brazed joints. Based on the results of melting and wettability experiments, one filler metal was used to join stainless steel at* 1 140 ℃ *for* 15 min. *The microstructure of the joint was analyzed by means of a scanning electron microscope (SEM) equipped with X-ray energy-dispersive spectroscopy (EDS). It was found that the typical joint was mainly composed of solid solution with a small quantity of Cr-rich borides strips, Ti-rich boride blocks and Cu-rich silicide particles. The brazed joints show an average tensile strength of* 270.8 MPa *and an average impact toughness of* 35.6 J/cm^2.

Key words brazing, stainless steel, Fe-Ni-Cr filler metal, microstructure, mechanical properties

0 Introduction

Austenitic stainless steel with alloying elements of Cr and Ni shows good corrosion resistance in any of oxidizing, neutral or light reductive medium. Due to its good plasticity and toughness as well as cold-workability, the austenitic stainless steel has been widely used in the fields of automotive industry, food industry, medical apparatus and instruments, petrochemical industry and aerospace[1]. The brazing technique of stainless steel covered a wide range of filler metals such as silver-based filler metal[2], manganese filler metal[3], nickel-based filler metal[4-5], gold-based filler metal and copper filler metal[6]. In a vacuum environment the majority of stainless steel brazing is carried out using nickel-based filler metals, but the gap clearances of the brazing joints should be strictly controlled to achieve good properties. Due to the fluctuating costs of raw materials such as nickel, new Ni-based filler metals with lower nickel content or Fe-Cr-based filler metals were investigated recently[7-8]. And in automotive industry, pure copper filler was previously used for the brazing of oil cooler[9], but the copper brazed joints were easy to be corroded in an oil medium, resulting in the failure of brazed oil coolers. Besides, for the stainless steel joints brazed with either Ni-based or copper filler, their mechanical strength and toughness remain to be improved in fact.

To solve the above problem, new types of Fe-Ni-Cr system filler metal were designed and fabricated in this paper. To ensure corrosion- and oxidation-resistance of these filler alloys, sufficient Ni and Cr were added in them. And elements of Si and B were added to lower their melting temperature. But the amount of Si and B should be strictly limited, because it is easy for them to combine with Ni to form brittle compound[6, 10]. According to the binary phase diagram, element Cu and element Ti can react with each other forming various low melting point intermetallics. So Cu and Ti were added in these filler metals to lower the melting temperature further and accordingly it can decrease the needed amount of Si and B.

1 Experiments

The experimental base metal is 1Cr18Ni9Ti stainless steel, and its nominal composition is shown in Table 1.

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New designed filler alloys were prepared by vacuum arc-melting method, and subsequently the achieved ingots were broken up to pieces. Then every two pieces chosen randomly from these alloys were heated to 1 140 ℃ for 15 minutes in the ZKH-1 vacuum brazing furnace in order to study their melting behaviors and wettability on the base metal. In this paper, the selected alloy is named F46 with a nominal composition shown in Table 2. According to a differential thermal analysis (DTA), the solidus temperature and liquidus temperature of this filler alloy are 1 101 ℃ and 1 124 ℃, respectively. The brazing foil of F46 filler metal was fabricated in a vacuum and argon-protecting furnace with a rapidly-solidifying technique. Then, vacuum brazing was conducted with these foils under 1 140 ℃/15 min.

The mechanical properties of the brazed joints were tested and contrasted to the copper brazed joints under the same brazing and testing conditions. The microstructure of the joints brazed with F46 filler metal was analyzed by means of scanning electron microscope (SEM) and X-ray energy-dispersive spectroscopy (EDS), moreover the fracture location of the strength testing specimen was also observed.

Table 1 Nominal composition of 1Cr18Ni9Ti stainless steel (wt. %)

C	Mn	Si	Cr	Ni	S	P	Ti	Fe
≤0.12	≤2.0	≤0.80	17.00 – 19.00	8.00 – 11.00	≤0.025	≤0.035	5(C – 0.05) – 0.8	Balance

Table 2 Nominal composition of F46 filler metal (wt. %)

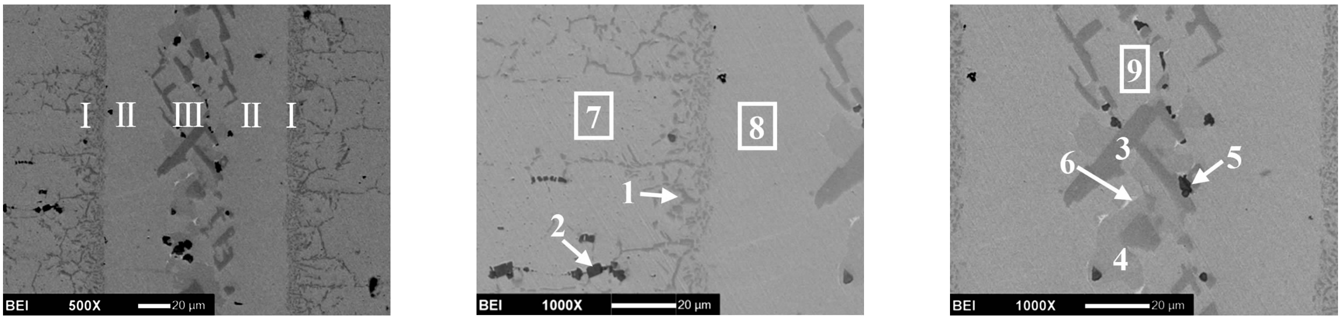
Ni	Cr	Si	B	Cu + Ti	Fe
16.0 – 21.0	6.0 – 15.0	3.0 – 4.5	2.0 – 3.5	3.0 – 11.0	Balance

2 Results and discussion

2.1 Microstructural examination

Fig. 1 shows the microstructure of the typical joint brazed at 1 140 ℃ for 15 min with F46 filler metal. A sound joint has been achieved and it is composed of base metal, diffusion-reaction zone (Ⅰ), solid solution zone (Ⅱ) and central zone (Ⅲ). During the brazing procedure, the elements of B and Si diffused into the base metal and reacted with Fe, Cr and Ni forming grayish phase (labeled "1" in Fig. 1b). Near the interface in the base metal, there exist some small black blocks which should be titanium carbides as labeled 2 shows. There are two solid solution zones between the diffusion-reaction zone "Ⅰ" and central zone "Ⅲ". At the beginning of cooling stage after the brazing process, solid solution formed along the interfaces and grew into the seam center, accordingly low melting point liquids were pushed to the seam center and solidified with previous solution at a relatively low temperature[11]. So the central zone is composed of solid solution and low melting point compounds of dark strips (microzone "3"), grayish blocks (microzone "4"), and a few of small black blocks (labeled "5") as well as bright particles (labeled "6"). Thereby the central zone might be the weak zone determining the mechanical properties of the joint.

EDS analysis was carried out to detect the phase composition of the joint. According to the results shown in Table 3, the microzone "7" exhibited approximately the nominal chemical composition of the base metal, and microzone "8" in "Ⅱ" zone and microzone "9" in "Ⅲ" zone have similar compositions and are both Fe-based solid solutions with dissolved elements of Ni, Si, Cu and Cr, but the amount of Si in microzone "9" is a bit higher than that in microzone "8" due to its diffusion into base metal and gathering in the brazing seam center[12]. Combined with Fe-Si and Ni-Si phase diagrams, the grayish phase in "Ⅰ" zone should be secondary $(Fe, Cr, Ni, Si)_{SS}$ in which Si is diffused from the filler metal into the Fe-based solid solution. Because of the big size of silicon atom, it is hard to diffuse further into the base metal, so zone "Ⅰ" is very thin, only about 10 μm. The black blocks as labeled "2" shows in the base metal near the interface contain lots of Ti and should be TiC compounds. In the "Ⅲ" zone, the dark strips contain lost of Fe, B and Cr, thereby they may be (Fe, Cr)B according to the Fe-B and Cr-B phase diagram. And the grayish blocks containing more Si may be Si-rich Fe-based solid solution. The black blocks and bright particles in the center of "Ⅲ" zone are rich in Ti, B and Cu, Si elements respectively, then they may be complex compounds such as (Ti, Fe, Cr)B_2 and (Cu, Fe, Ni)$_x$Si$_y$.



(a) The whole joint (b) Diffusion-reaction zone (c) Central zone

Fig. 1 The microstructure of the 1Cr18Ni9Ti brazed joint using F46 filler metal with different magnifications

Table 3 EDS analysis of the typical phases and regions (at. %)

Microzone/point	Fe	Ni	Cr	Si	B	Cu	Ti	Mn	Possible phases
"1" grayish phase	63.55	6.74	25.90	3.30	—	0.61	—	—	(Fe, Cr, Ni, Si)$_{SS}$
"2" black block	4.20	0.47	1.67	—	—	—	93.66	—	TiC
"3" dark strip	36.61	1.49	9.27	0.31	52.32	—	—	—	(Fe, Cr)B
"4" grayish block	54.20	21.30	3.06	20.08	—	1.36	—	—	Si-rich solid solution
"5" black block	7.21	1.97	3.19	1.08	72.01	—	14.54	—	(Ti, Fe, Cr)B_2
"6" bright particle	32.03	17.37	1.03	15.99	—	37.98	—	—	Complex compound: (Cu, Fe, Ni)$_x$Si$_y$
"7" solid solution	68.87	7.97	20.00	1.29	—	—	0.48	1.39	(Fe, Cr, Ni)$_{SS}$
"8" solid solution	65.36	15.63	4.49	11.18	—	3.34	—	—	(Fe, Ni, Si, Cr, Cu)$_{SS}$
"9" solid solution	60.44	19.49	2.46	14.93	—	2.68	—	—	(Fe, Ni, Si, Cu, Cr)$_{SS}$

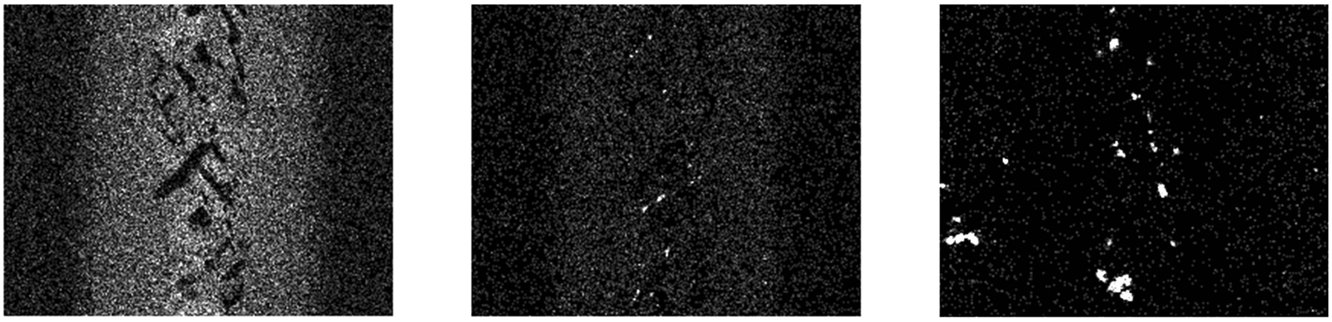
Element area distribution of the joint shown in Fig. 1a is presented in Fig. 2. Element Cr intends to react with element B to form CrB compounds as dark strips in "Ⅲ" zone. Most of Cu uniformly distributed in the whole brazing seam, but only a few gathered in bright particles in "Ⅲ" zone. Then, almost all of element Ti concentrated in the compounds of black blocks only in "Ⅲ" zone. So a small quantity of Cu and Ti, added in the filler metal, can form some compounds to lower the melting temperature of the filler metal, and these small blocks and particles may strengthen the brazed joints to some extent. Because the size of Si atom is big and not easy to diffuse, most of them remained in the brazing seam and especially precipitated in "Ⅲ" zone.

2.2 Mechanical properties

Table 4 shows the notched bar impact toughness and tensile strength of the brazed joints using F46 filler metal compared with those using copper filler under the same joining conditions. After 1 140 ℃/15 min brazing procedure, the average impact toughness of the joints using F46 filler metal is 35.6 J/cm^2, more than 3 times higher than that using copper filler metal (10.8 J/cm^2). In particular, an individual impact toughness value even reached 43.7 J/cm^2 with F46 filler metal. The average tensile strength of the F46 filler metal brazed joints is 270.8 MPa, about 10% higher than that of copper brazed joints.

The fracture location of specimen brazed with F46 filler metal is presented in Fig. 3. Obviously, the fracture occurred at the weak zone "Ⅲ" which determines the mechanical properties of the joint. The edges of the fracture section are relatively rough and present ragged fracture pattern, indicating the relatively high strength and toughness.

(a) Fe (b) Ni (c) Cr

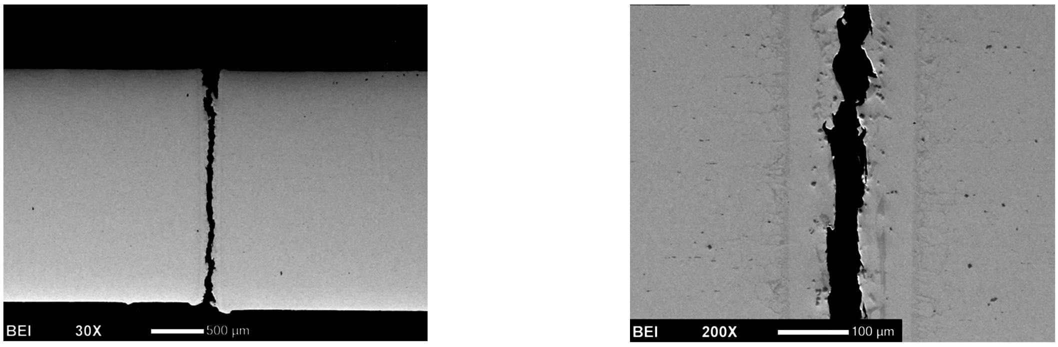


(d) Si (e) Cu (f) Ti

Fig. 2 Element area distribution maps of the brazed joint using F46 filler metal

Table 4 Mechanical properties of the brazed joints using F46 and copper filler metals

Filler metal	Impact toughness α_{KU} / J · cm^{-2}				Tensile strength σ_b / MPa			
	Individual value			Average value	Individual value			Average value
F46 (Fe-Ni-Cr based)	27.4	43.7	—	35.6	269.1	264.7	278.7	270.8
Copper	11.6	9.9	11.0	10.8	227.5	258.1	245.5	243.7



(a) Fracture section of a typical joint (b) Fracture section at a high magnification

Fig. 3 Fracture position of specimen

It is very important that the newly developed Fe-Ni-Cr system filler metal may be used to braze the oil coolers instead of pure copper filler metal to solve corrosion failure problem and it should be much cheaper than the traditional Ni-based filler metal.

3 Conclusions

Furnace vacuum brazing of 1Cr18Ni9Ti stainless steel was carried out under 1 140 ℃/15 min using new developed Fe-Ni-Cr system filler metals and sound joints were achieved in this paper. The mechanical properties of the brazed joints using new filler metal were evaluated compared with those using pure copper filler metal, as well as the microstructure examination in this study. Primary conclusions are summarized in the following:

(1) Typical joint is made up with base metal, diffusion-reaction zone, solid solution zone and central zone.

(2) The diffusion-reaction zone bases on primary Fe-based solid solution with secondary solution containing some Si element, and the central zone is composed of solid solution and compounds of Cr-rich boride strips, Ti-rich boride blocks and Cu-rich silicide particles.

(3) The brazed joints show an average impact toughness of 35.6 J/cm^2, more than 3 times of that brazed with copper filler, and an average tensile strength of 270.8 MPa, 10% higher than that of copper brazed joints, under the same joining conditions.

(4) Fracture of specimen occurred at the central zone (zone "Ⅲ") which determines the mechanical properties of the joint. And the fracture edges are relatively rough and present ragged pattern indicating high strength and toughness.

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