INVESTIGATION ON WELDING OF VIRGO 104 LOW CARBON MARTENSITIC STAINLESS STEEL

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ABSTRACT

VIRGO 104 is a low carbon martensitic stainless steel that is applied to the famous Three Gorges Project. By using VOD melting process VIRGO 104 has low carbon and [H] [O] contents, and shows excellent mechanical properties and weldability. The best solution to guarantee welding quality is PWHT by 600℃×8h.

KEYWORDS

Hydro-turbine runner, martensitic stainless steel, simulated HAZ, impact toughness, MIG

1. Introduction

For hydro-turbine runners, low carbon martensitic stainless steels such as CA 6NM, Virgo 104 and ZG0Cr13Ni4Mo are widely applied because of good mechanical properties, cavitation and erosion resistance and other metallurgical and technical performances. For the famous Three Gorges Project composed of 26 units powerful hydro-turbines with unit capacity of 700MM, the casting-welded Francis runner with 400 ton-weight and 10 meter-diameter require high casting and welding technology to guarantee runner quality. Especially, the weldability and welding technology have a significant effect on runner quality and the service reliability. In this paper the welding behavior of Virgo 104 (CLI, France) applied to the Three Gorges hydro-turbine runners is investigated, which will supply more information to industrial manufacturing of the gigantic runners.

2. Experiments and the results

2.1 Analysis of chemical compositions and evaluation of mechanical properties of VIRGO 104

Because of the heavy runners components (max. thickness of bucket is 280mm), the size of tested piece is 1000mm (L)× 1000mm (W) ×130~150m m (T). The melting process is vacuum oxygen decarbonation (VOD). The chemical compositions are shown in table 1. The mechanical properties are shown in table 2 and table 3.

Table 1 Chemical compositions of Virgo 104

Testing metal	C	Si	Mn	S	P	Cr	Ni
Standard*	0.06	0.80	0.4~1.0	0.025	0.030	12.5.~13.5	3.5~4.0
Virgo 104	0.037	0.24	0.38	0.0010	0.019	12.39	3.76
Testing material	Mo	V	Cu	W	[N] ppm	[0] ppm	[H]ppm
Standard	0.4~0.7	-	-	-	-	-	
Virgo 104	0.47	0.041	0.20	0.060	320	74	0.22

* Single values are max. percentages.

Table 2 The tension mechanical properties of Virgo 104

Specimen	Specimen Location	Testing temp.	Y.S (N/mm^2)	T.S (N/mm^2)	El (%)	R_A (%)	Y.S/T.S
Standard*			550	750~930	15		
Virgo 104	Center	18℃	660	840	21	58	0.79
Virgo 104	Surface	18℃	830	660	23	68	0.80

* Single values are min. percentages.

Table 3 Charpy -V impact toughness of Virgo 104

Specimen No	Specimen location	Testing temp	E_i(J) *	E_p(J) *	E_t(J) *	E_p/E_I	Lateral expansion (%)
Standard		0℃			32		
Virgo 104-4	Center	0℃	35.4	107.5	142.9	3.04	16.0
Virgo 104-5	Center	0℃	34.1	109.1	143.2	3.20	15.8
Virgo 104-6	Center	0℃	36.2	93.6	129.8	2.58	15.0
Virgo 104-14	Surface	0℃	34.8	114.4	149.2	3.28	17.6
Virgo 104-15	Surface	0℃	35.3	119.9	155.2	3.40	17.0
Virgo 104-16	Surface	0℃	37.1	107.3	144.4	2.89	16.8

The E_i、E_p and E_t are shown in Instrumental diagram of Charpy -V impact toughness (Fig.1).

The results shows that contents of carbon and impurities such as S [H] [O] in Virgo 104 are rather low, especially the very low contents of S and [H], which is contributed to VOD melting process. Virgo 104 has an excellent combination of tension strength, ductility and impact toughness at low temperature. The higher E_p/E_i (~3.0) and lateral expansion (~15%) show excellent resistance to brittle fracture.

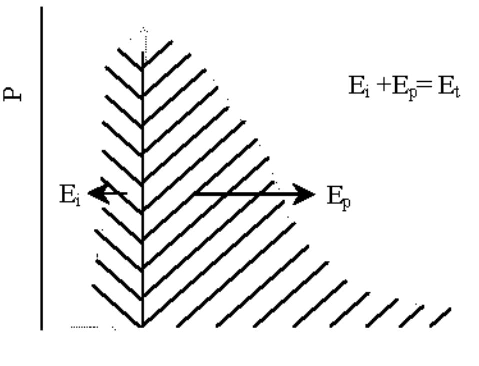

Fig.1 Instrumental diagram of Charpy-V impact toughness

2.2 Evaluation of CCT diagram and impact toughness in simulated HAZ of Virgo 104

CCT diagram of Virgo 104 shows that transformation temperatures are as following：A_{C3}=875℃ A_{C1}=646℃ M_s=270℃ M_f=120℃. In the CCT diagram the cooling speed $t_{8/3}$ (800℃~300℃) of TIG – MIG – SAW – ESW welding procedures are simulated. The microstructures are completely Martensite without any other metallic phases, which indicates no matter what welding techniques it is not necessary to worry about the brittle metallic phases precipitation. Based on the A_{C1}=646 ℃ the tempering temperature 600 ℃ ~630 ℃ recommended by NFA 32–059 is more reasonable than the tempering temperature 580℃~620℃ recommended by DIN 17445 in order to get higher ductility and impact toughness.

The simulation of HAZ is finished with Gleeble-1500. The results are shown in Table 4. Compared with the base metal the impact toughness in simulated HAZ is obviously lower whether single thermal cycle to simulate the root pass welding or three thermal cycles to simulate the multi-passes welding. However, the impact toughness of simulated HAZ is completely recovered after PWHT by 600℃×8h. The impact values can reach the level of Virgo 104 base metal. X-ray analysis of metallurgical structures of Virgo 104 base metal and simulated HAZ shows that impact toughness in simulated HAZ is determined by retained Austenite. As shown in Table 4, about 6% retained Austenite exists in Virgo 104 base metal. The microstructures at simulated HAZ are completely Martensite without any retained Austenite, but after PWHT the microstructure in simulated HAZ contains 5% retained Austenite that contributes to high impact toughness.

Table 4 Charpy -V impact toughness in simulated HAZ

Specimen No	Thermal cycles and heat treatment	Hardness (HV_5)	Charpy-V impact value (J)			
			E_i	E_p	E_t	E_p/E_i
41	Tmax.=1300℃ $t_{8/3}$=40 s	386	22.3	25.1	47.4	1.13
42		386	29.6	31.6	61.2	1.07
43		386	29.1	28.5	57.6	0.98
44	Tmax.=1300℃ $t_{8/3}$=40 s PWHT: 600℃×8h	286	30.1	93.3	123.4	3.10
45		283	35.4	107.1	142.5	3.03
46		293	32.3	100.2	132.5	3.10
51	Tmax.=1300℃ $t_{8/3}$=40 s + Tmax.=1100℃+T_{max}=600℃	376	24.3	25.0	49.3	1.03
52		356	28.6	32.6	61.2	1.14
53		366	29.0	28.0	58.0	0.97
54	Tmax.=1300℃ $t_{8/3}$=40 s + Tmax.=1100℃+T_{max}=600℃ PWHT: 600℃×8h	285	30.0	97.3	127.3	3.24
55		284	34.4	107.0	141.4	3.11
56		290	33.3	99.2	132.5	2.98

Table 5 X-ray analysis of metallurgical structures of Virgo 104 and simulated HAZ.

Specimen No.	Thermal cycles and heat treatment	Content of retained Austenite (%)
20	Virgo 104 base metal	6.22
40	Virgo 104 base metal + -40°C Low temperature treatment	4.4
10	Single thermal cycle T_{max}=1300°C $t_{8/3}$=40 s	No
11	Single thermal cycle T_{max}=1300°C $t_{8/3}$=40 s PWHT: 600°C×8h	4.97
30	Three thermal cycles T_{max}=1300°C $t_{8/3}$=40 s + T_{max}=1100°C+ T_{max}=600°C	No
31	Three thermal cycles T_{max}=1300°C $t_{8/3}$=40 s +T_{max}=1100°C +T_{max}=600°C PWHT: 600°C×8h	5.07

2.3 Mechanical properties of welded joints

For MIG welding of Virgo 104, HS135L MIG solid wire is used. The chemical compositions of HS135L MIG wire are shown in table 6, and the welding parameters are shown in Table 7.

Table 6 Chemical compositions of HS135L MIG wire

HS135L Φ1.2mm	C	Si	Mn	S	P	Cr	Ni	Mo
	0.017	0.62	0.60	0.010	0.004	12.48	5.07	0.56

Table 7 Welding parameters for mechanical properties specimens

Welding current (A)	Arc voltage (V)	Welding speed (mm/min)	Shielded gas $Ar+CO_2$(Vol. %)	Gas flow (l/min)
220~240	30~32	250~270	97+3	15~20

Table 8 Tension properties of welded joints (at room temp.)

Specimen No.	Location of specimen	PWHT	Y.S (N/mm^2)	T.S (N/mm^2)	El (%)	R_A (%)	Location of fracture
2	Longitudinal	590°C ×12h	660	795	19	63	Base metal
4	Transverse	590°C ×12h	670	805	18	64	Base metal
22	Longitudinal	As weld	890	1000	12	50	Base metal
44	Transverse	As weld	675	850	11	56	Base metal

Table 9 Charpy-V impact toughness of weld metal

Specimen No.	Location of specimen	Testing temp.	PWHT	E_p(J)	E_i(J)	E_t(J)	E_p/E_i	Lateral expansion (%)
114	Root passes	0°C	As weld	18.56	28.07	46.64	0.66	4.8
115				15.84	26.48	42.32	0.60	5.0
4	Root passes	0°C	590°C×12h	22.48	52.14	74.62	0.43	7.4
5				20.75	50.75	71.51	0.41	9.6
8				21.53	50.15	71.69	0.43	8.0
24	Surface	0°C	As weld	15.66	24.55	40.22	0.64	5.2
25				14.94	22.76	37.70	1.53	4.2
14	Surface	0°C	590°C×12h	24.05	59.63	83.68	0.40	11.2
15				25.45	73.20	98.65	0.35	10.8
18				23.68	61.04	84.72	0.39	11.8

The tension properties are shown in table 8, and the Charpy-V impact toughness of weld metal is shown in table 9. The tension properties of welded joints are compatible with Virgo 104 base metal. However, the impact toughness of weld metal is lower even after PWHT.

3. Conclusions

3.1 Virgo 104 is a low carbon martensitic stainless steel with very low impurities and excellent mechanical properties. The excellent combination of tension strength and ductility, and high impact toughness indicates Virgo 104 is particularly appropriate to large hydro-turbine runners such as the Three Gorges hydro-turbines.

3.2 Virgo 104 has good weldability. The impact toughness in HAZ can be completely recovered to the level of Virgo 104 only by tempering after welding. This characteristic is contributed to the retained austenite.

3.3 The mechanical properties of weld metal have good compatible with base metal Virgo 104 but the lower impact toughness.