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Fracture Toughness of Austenitic Anticorrosive Cladding and Austenitic Welded Joints

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ABSTRACT

It has been shown in a number of russian investigations that metal of austenitic anticorrosive cladding, overlayed on the inner surface of reactor pressure vessels, is subjected to embrittlement under the influence of operating factors. The experimental data are presented on fracture toughness of anticorrosive cladding metal of VVER-440 and VVER-1000 reactor pressure vessel, produced by SAW with strip Sv-07X25H13 and Sv-04X20H10G2B, as well as stainless steels and their weldments, produced by MAW using EA-400/10T and EA-395/9 electrodes, in the wide range of temperatures from -180 to +450°C. The obtained generalized dependencies can be used in structure integrity assessment of piping and other structure elements manufactured from austenitic stainless steels.

INTRODUCTION

In the middle 1980s it was shown in some studies of Soviet [1, 2] and American [3] investigators, that metal of austenitic anticorrosive cladding, overlayed on the inner surface of reactor pressure vessels, is subjected to operating factors. At first glance it would seem that it is meaningless for highly ductile austenitic materials. One of the operating factor, leading to impact strength reduction and DBTT shift to the area of elevated temperatures is neutron fluence attack. The other factor (sometimes it is not less important) is thermal aging, which reveals itself to a greater extent with the increase of the attack of elevated temperatures and the growth of operating temperature.

A comprehensive review of the data of American investigators is given in the document ORNL NUREC/CR-6363 [4]. In the investigation [5] the variation (reduction) of impact strength in anticorrosive cladding metal was noted with increasing the time of thermal influence (tempering time) at the stage of manufacture. At the tempering temperature 620-670°C (which is by more than two times higher, than the operating temperature) the aging process of austenitic-ferritic cladding metal is accelerating.

In the middle 1980s it was shown by the American Institute of Mechanical Engineers that it is unacceptable for welded joints from austenitic steels produced by manual arc welding and submerged arc welding that the assessment of their fracture resistance to based on the method of plastic collapse generation, because, apparently such cannot be attributed to materials of high toughness and their fracture is possible by the mechanism of instable tough tearing. This circumstance and also the use of new criteria in the assessments of fracture resistance of structure elements from austenitic materials by static loading necessitate the study of parameters of ductile and brittle-ductile failures for them. Although formally this is not required in accordance with Russian Code [6]. Besides the investigations on the determination of fracture toughness of anticorrosive cladding metal, there is in limited number investigations of resistance of ductile failure of austenitic steels and their welded joints [7, 8]. The small amount of information on this problem does not permit to construct the generalized temperature dependence (as for ferritic-pearlitic steels). Nevertheless they are necessary for the structural integrity assessment of some elements made from austenitic steels and primarily for piping in the context of the application of the concept leak before break when assessing guillotine failure.

At present, in accordance with the American strength calculation norms [9] it is required to carry out the analysis of permissible defects sizes on the basis of J_C and J-R criteria [10-11] (in Russian Norms such analysis is not required). It is the world practice of NPP designers to carry out the analysis of Russian materials using the above-mentioned criteria of non-linear fracture mechanics. The conduction of such analysis according to the American Rules supposes the division of austenitic materials in two classes in conformity with the fracture mechanism being realized in the process of operation. The first class includes materials of high ductility (plastically strained steels and their welded joints, produced with no flux), in which it is not observed (by static loading at the level above the ultimate load) a remarkable stable increment of initial defect, but the formation of plastical collapse takes place. The second class is cast materials and welded joints obtained with the use of flux or manual arc welding with covered electrodes, i.e. materials of a lower toughness and characterized by crack increment under loading before the critical load achievement. The fracture resistance assessment of these materials should be carried out with the use of elastic-plastic fracture mechanics concepts. Such distinction between materials is necessary to exclude for austenitic materials of the second class a case of instable tough rupture until the ultimate load (determined with nominal permissible stresses) is achieved.

In this study an attempt was made to generalize the available experimental data on fracture toughness of anticorrosive cladding, stainless austenitic steel of the type 08X18H10T and their welded joints in the wide range of temperatures from below zero (-180°C) to above zero (+450°C), corresponding to the operating temperatures.

1. INVESTIGATED MATERIALS

For steel to be investigated the type 08X18H10T stainless steel was selected, which is widely used in nuclear power engineering in the form of plates (sheets), forgings and tubes. All these types of metallurgical semi-products were used for the fabrication of compact and bend specimens for fracture toughness testing. Having been fabricated from base metal of five various heats both large scale 150 mm thick compact specimens and small 10x10x55 mm Charpy specimens with a fatigue precrack were tested. On the whole 10 and 25 mm thick specimens were fabricated and tested on fracture toughness (and only six 40 mm thick specimens). To assess the fracture toughness of anticorrosive cladding metal only specimens having a dimension 10x10x55 mm were fabricated and tested. The basic scope of cladding metal tests was carried out for the following composition (Sv-04X20H10G2B strip). The chemical composition and mechanical properties of investigated materials are given in Tables 1 and 2, respectively.

The main scope of fracture toughness tests of weld metal, produced by manual welding with the types EA-400/10Y(T) and EA-395/9 electrodes was performed on small bend specimens (10x10x55 mm) and compact 25 mm thick specimens. In addition to tests of welds in as-welded condition some specimens were tested after thermal aging at 300°C for $3x10^3$-10^5 hours. The investigations on the determination of the curves J_{IC}=f(T) and J-R in the wide range of temperatures are being continued, and it will permit later on to refine the laws, which were earlier presents.

2. PROCEDURE OF STUDIES

The fracture resistance assessment of second category austenitic materials [(with decreased toughness) including brittle fracture austenitic anticorrosive cladding materials after irradiation and tough, unstable rupture of welded joints (made with no flux, for example MIG and TIG)] should be carried out in view of a stable crack increment, i.e. using the parameters of the non-linear fracture mechanics J_{IC}-integral and J_R curves. By this, it should be taken into consideration that in relation to the taken critical value of crack increment Δa=0, Δa=0.2 mm, Δa=2.0 mm for austenitic materials, having a high rate of the curve J=f(Δa) raising the values K_{JC}, recalculated from the obtained J_I values can differ by times and more. In this study three K_{IC} (K_{CJ}) criteria were taken, namely:

- determined through K_Q by 2% crack increment (in accordance with the standard ASTM E399-90) [12];
- determined on the base of the load of incipient growth of crack P_i, corresponding to zero crack increment, which was recorded with UST (DUK-66) and was in accordance with GOST 25.508-85 [13];
- determined through J-integral value by the crack increment limited by the value 0,2 mm in accordance with the standard ASTM E 813-81 [10].

Besides, some K_{CJ} dots were obtained by the construction of J_R-curves at the registered stable crack increment Δa=2.0 mm. By this the standard ASTM E 1152-87 [11] was used.

It is apparent that the most conservative results were obtained by zero increment (the second criterion), and the least conservative at Δa=2.0 mm. In the latter case the use of the data stated is possible only after the substantiation of the fact, that 2.0 mm increment takes place by the operation of some structure elements with the initial crack in the design regimes of loading.

The comparison of requirements to representative specimen sizes, providing a reliable determination of J_{IC} and K_{IC} values in accordance with various standards shows: specimen size according to the procedure [13] is representative, if specimen thickness (t) and crack length (i) are above $(K_{IC}/YS)^2$ and according to the standard [10] specimen size is representative, if t/l is above $25(J_{IC}/YS)$. It follows that reliable fracture toughness values according to the standard [10] can be obtained even by testing 10x10x55 mm specimens with lateral grooves.

3. RESULTS AND DISCUSSION

According to the active Norms [6] it is allowed not to carry out the brittle fracture resistance calculation of austenitic steels regardless of equipment elements thickness. It is conditioned by their high plasticity and fracture toughness. However, this statement concerns only the case, when the neutron fluence does not exceed $F=10^{22}$ neutr/m^2.In the presence of higher neutron fluences for austenitic steels and their welds it is possible incipient growth and increment of initial cracks. Therefore, for steels and welds from austenitic steels (II class) of decreased ductility it should be determined the calculated fracture toughness curve as by failure plastic collapse is not realizing in all cases. By this, the selection and grounds of correctness criteria of fracture toughness tests proceeding from ASTM E813 standard are very important.

The primary test results on the determination of fracture toughness characteristics of austenitic materials by static loading are given graph form in Figs.1 and 2. Fig.1 presents static test results of five heats of austenitic stainless steel 08X18H10T, nine welded samples, produced by MAW using EA-400/10Y(T) electrodes and three welded samples, produced by MAW using EA-395/9 electrodes. These are all obtained results except the fracture toughness data of austenitic anticorrosive cladding metal. A large scatter of experimental data is obvious. In practice it is possible to use the constructed temperature dependence K_{CJ} in the form of a dotted line in strength calculations.

Fig.2 presents experimental data on fracture toughness of austenitic anticorrosive cladding, produced by SAW using Sv-04X20H10G2B strip electrodes and after various heat treatment regimes. The obtained results include test data for two heats of this composition strip electrodes after the temperings at 670, 700 and 720°C with different exposures. Fracture toughness K_{CJ} values are presented in this figure also after aging at 500 and 550°C and exposure 500 hours. The experimental data for anticorrosive cladding metal are compared with the reference curve for 15X2MFA steel according to the active Russian Code [6] for base metal of reactor pressure vessel. It is evident that all experimental dots are located above the reference curve for base metal.

CONCLUSION

For the first time it has been carried out the generalization of experimental results on fracture toughness determination of austenitic steels and their welds as well as austenitic anticorrosive cladding. It was shown that the generalized dependence for these materials cannot be based on the linear mechanics criteria. The fracture toughness temperature dependencies are given for austenitic steels and their welds including austenitic anticorrosive cladding and are constructed using the criteria of non-linear fracture mechanics (J_{IC} and J_R curves). These dependence are to be considered as preliminary and in future they will be verified when new experimental data are obtained.

REFERENCES

1. Badanin V.I., Ignatov V.A.,Nikolaev V.A., Rybin V.V. & Timofeev B.T., "Brittle fracture resistance of austenitic-ferritic steel cladded on 15X2MFA steel," *Avtomaticheskaya svarka*, Nr.3 (432), 1989, pp.4-7.
2. Zvezdin Yu.I., Timofeev B.T., Galaktionov M.C. & Deich A.Sh., "The procedure selection and fracture toughness determination for anticorrosive cladding metal," *Zavodskaya laboratoriya*, Nr.5, 1988, pp.68-69.
3. Corwin W.R., Berggren R.G., Nanstad R.K., Gray R.J.,"Fracture behavior of a neutron-irradiated stainless steel submerged arc weld cladding overlay," *Nuclear Engineering and Design*, 89, 1985, pp.199-221.
4. Haggag F.M. & Nanstad R.K., "Effects of thermal aging and neutron irradiation on the mechanical properties of three wire stainless steel weld overlay cladding," *NUREC/CR-6363*, Oak Ridge, 1997.
5. Zhitnikov N.P., Volovelsky D.E., Timofeev D.B. etc., "The effect of heat treatment regimes on mechanical properties of anticorrosive metal," *Proceedings of the Seminar "Achievements of scientific and engineering laboratories in welding practice"*, 20-21 April 1989, LDNTP, p.86-92.

6. *PNAE G-7-002-86. Strength calculation norms for nuclear power plant equipment and pipings*, Moscow, Energoatomizdat,1989.
7. Ruscak M., Keilova E., Kocik J., Burda J. & Chvatal P., "Structural aspects of the environmentally assisted cracking of WWER-440 dissimilar weld joints," *International Journal of Pressure Vessel and Piping*, 68, 1996, p.23-37.
8. Ondrouch J., "Mechanical properties of dissimilar weldment after long-term aging," *Proceedings of the Seminar "Dissimilar Welded Joint in NPP Equipment and Pipings: Problems and Means to Solve Them"*. 18-22 September 1995, St.Petersburg,p.70-76.
9. *Pressure Vessel and Piping Codes. Evaluation of Flaws in Austenitic Steel Piping. Section XI, IWB-3640.*
10. *ASTM E813-81. Test for method J_{IC}. A measure of fracture toughness.*
11. *ASTM E1152-87. Standard test method for determining J-R curves.*
12. *ASTM E399-90. Standard test method for plane-strain fracture toughness of metallic materials.*
13. *GOST 25.506-85. Design, calculation and strength testing. Methods of mechanical testing of metals. Determination of fracture toughness characteristics under the static loading,* Gostandard, Moscow, 1985, 60p.

Table 1
Chemical composition of investigated materials

Nr.	Type Content of elements (%)	C	Si	Mn	Cr	Ni	Ti	S	P	Cu	Mo	Co	N	V
SS1	08X18H10T	0.05	0.58	1.21	17.75	9.72	0.52	0.011	0.025	0.16	0.07	0.015		
SS2	08X18H10T	0.07	0.24	1.06	17.50	12.40	0.52	0.006	0.029	0.22	—			
SS3	08X18H10T	0.07	0.63	1.00	17.80	10.02	0.59	0.014	0.008	0.19	—	0.015	0.005	
SS4	08X18H10T	0.07	0.28	1.09	18.00	10.10	0.47	0.007	0.014	0.18	0.03			
SS5	08X18H10T	0.065	0.32	1.10	17.96	9.85	0.50	0.012	0.015	0.15	—			
SSM1	EA-400/10Y	0.075	0.22	3.57	17.35	12.20	—	0.006	0.022	0.10	2.65			
SSM2	EA-400/10Y	0.07	0.33	1.23	18.10	11.20	—	0.006	0.011	0.12	1.76			0.28
SSM3	EA-400/10Y	0.05	0.32	1.19	18.30	11.40	—	0.002	0.024	0.16	1.80			
SSM4	EA-400/10Y	0.10	0.24	2.43	17.60	9.20	—	0.014	0.010	0.075	2.95			0.70
SSM5	EA-400/10T	0.07	0.30	2.35	18.15	11.05	—	0.010	0.015	0.09	2.80			
SSM6	EA-400/10T	0.033	0.42	1.56	18.80	10.54	0.014	0.008	0.014	0.064	2.37	0.024		0.009
SSM7	EA-4000-10T	0.06	0.38	1.78	18.40	10.80	0.010	0.010	0.017	0.050	2.65			
SSM8	EA-400/10Y	0.06	0.36	1.84	18.25	10.77	0.010	0.008	0.015	0.056	2.70			
SSAM1	EA395/9	0.09	0.38	2.17	10.33	16.71		0.015	0.018	0.061	3.29		0.15	
SSAM2	EA395/9	0.11	0.16	1.63	15.66	25.72	0.010	0.003	0.007	0.082	5.62	0.027	0.122	
SSAM3	EA395/9	0.10	0.23	1.80	16.5	23.75	—	0.009	0.013	0.065	5.50		0.17	
SSAM4	UTP-068HH	0.031	0.34	4.73	19.04	68.80	0.15	0.004	0.012	0.08	0.81	0.08		2.22N

Table 2
Mechanical properties of investigated materials

Markirung	Material	At 20°C UTS (MPa)	VS (MPa)	A (%)	Z (%)	At 350°C UTS (MPa)	YS (MPa)	A (%)	Z (%)
SS1	08X18H10T	556	272	54.0	67.8				—
SS2	08X18H10T	530	275	53.0	62.0				—
SS3	08X18H10T	580	330	51.0	64.0	535	250		—
SS4	08X18H10T	533	235	46.0	72.5				—
SS5	08X18H10T	550	280	42.0	61.0	530	226	38.0	60
SSM1	EA400/10Y	635	460	42.5	45.0				
SSM2	EA400/10Y	555	305	39.5	50.0				
SSM3	EA400/10Y	610	450	36.0	45.0				
SSM4	EA400/10Y	540	365	38.0	51.0				
SSM5	EA400/10T	685	470	40.0	49.0	510	390	37.0	50
SSM6	EA400/10T	536	355	42.0	59.0	413	236	31.0	50
SSM7	EA400/10T	637	416	42.6	60.8	542	385	38.0	60
SSM8	EA400/10T	625	410	41.5	50.5				
SSAM1	EA395/9	665	395	38.5	45.0	605	375	42.5	40
SSAM2	EA395/9	752	507	24.0	42.0	747	392		
SSAM3	EA395/9	630	480	28.5	47.5	500	370		
SSAM4	UTP-068HH	598	407	25.1	35.2	520	340		

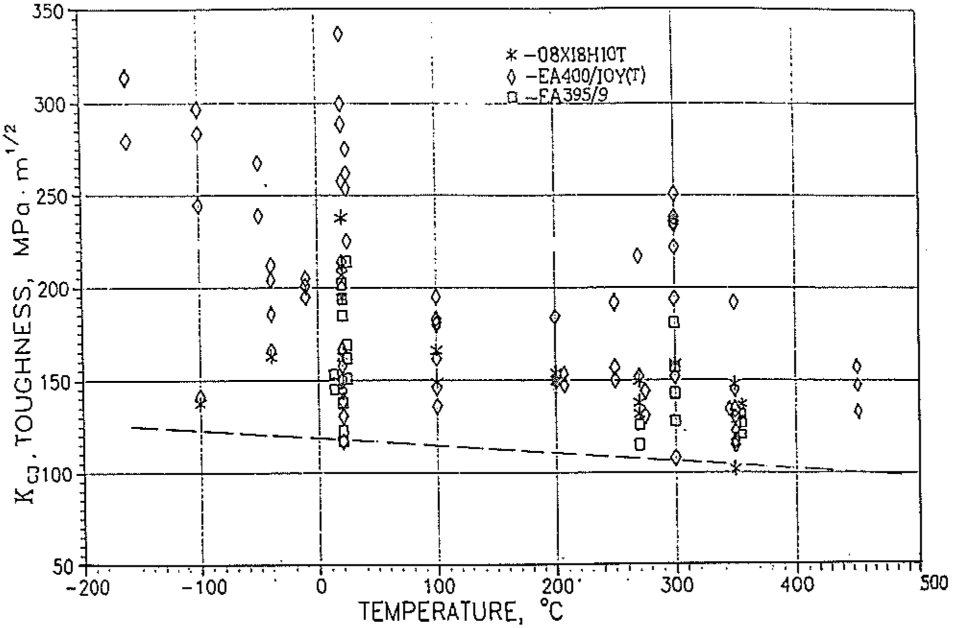

Fig.1. Fracture toughness test results of austenitic materials.

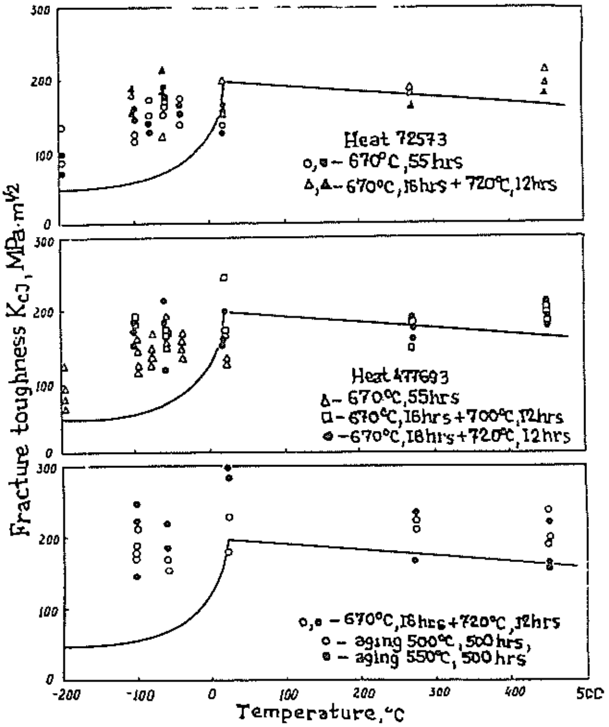

Fig.2. Fracture toughness temperature dependence for anticorrosive cladding Sv-04X20H10G2B strip, OF-10 flux.