STUDY OF CLADDING TOUGHNESS IN A PRESSURE VESSEL STEEL WATER REACTOR

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ABSTRACT

Toughness of cladding and pressure vessel steel were determined at different temperatures in order to appreciate the participation of cladding resistance against crack propagation. The toughness of cladding is comparable with typical results on austenitic welds. The test on covered CT specimens shows the possibility of having a relatively good prevision of the behaviour of a coated structure.

KEYWORDS

Cladding, pressure vessel steel, fracture mechanics.

INTRODUCTION

The purpose of this study is to obtain data which permits appreciation of the participation of cladding in resisting to the propagation of a surface crack in a pressure vessel steel.
For that, we have determined the toughness of cladding and pressure steel for temperatures in the lower part of the ductile to brittle transition curve, in order to examine the influence of cladding on the start of unstable crack propagation by cleavage with covered specimens having different cladding to base metal ratios. The use of the cold temperature simulates pessimistic condition due to irradiation embrittlement.

MATERIALS IDENTIFICATION

The cladding was deposited on A 508 cl 3 steel forging of 220 mm thickness. It was applied by automatic submerged arc welding with strip electrode. It was constitued by three layers, the first in 24 Cr - 12 Ni austenitic weld and the two others in 20 Cr - 10 Ni austenitic weld. After welding a stress relief treatment was carried out at 615°C during 7 h.

TOUGHNESS OF THE VESSEL STEEL

In order to determine K_{IC}, we have employed 2 T, CT specimens of 30 mm thickness. The tests were made at two temperatures, - 90°C and - 60°C. All specimens exhibited branched crack, therefore the toughness values were probably at the upper band of the dispersion.

The results are presented in table 1. At − 90°C there are on the lower shelf a toughness of 33 MPa$\sqrt{m}$ and at − 60°C there are in the transition zone a toughness of 110 MPa$\sqrt{m}$.

TABLE 1 Toughness of A 508 cl 3

Test temperature °C	a/W	P max N	K_{IC} MPa$\sqrt{m}$	J KN/m	K_j MPa$\sqrt{m}$
− 90	0.518	31 050	33	5.6	33.5
− 60	0.559	93 600	114	64.7	114
− 60	0.512	103 500	108	62.6	112
− 60	0.530	111 000	122		

TOUGHNESS OF THE CLADDING

The toughness of the cladding was determined with different kind of tests : dynamic Charpy V and precrack Charpy V testing, J-Δa resistance curve with static three points bending test.

The bend specimens have a section of 20 by 20 mm, including a cladding of 8 mm thickness. The precrack was made accross the ferritic section to the beginning of the austenitic weld. The J-Δa curves were determined at three temperatures (− 90°C, − 25°C and 20°C) by the interrupted loading method with multiple specimens. The results obtained show a low dispersion (Fig. 1) and an increase of J_{IC} and of the slope dJ/da with the increase of test temperature. For the characterisation of the toughness, we have adopted a value of J corresponding to a stable crack growth of 1 mm :

$$J_{\Delta a1} = J_{IC} + (dJ/da) \times 1$$

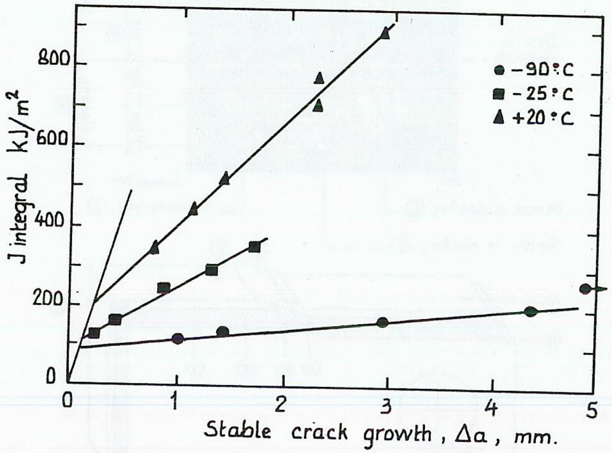
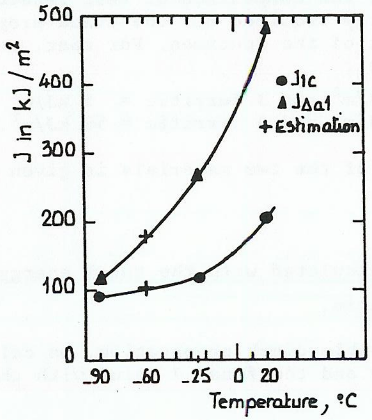


Fig. 1. J-Δa curves of cladding at differents temperatures

The interest of this value is to release a part of uncertainties of J_{IC} determination and take into account an important parameter, the slope value. The figure 2 shows the evolution of J_{IC} and $J_{\Delta a1}$ with the temperature. We observe an evolution of $J_{\Delta a1}$ more important but also more regular than J_{IC}. On the J_{IC} vs temperature curve, we have estimated the value for − 60°C required for other tests.

Now, if we compare $J_{\Delta a1}$ with Charpy V results (Fig. 3), a good correlation can be obtained by following expression

$$J_{\Delta a1}\ (kJ/m^2) = 9.1\ KCV\ (J/cm^2) - 64$$



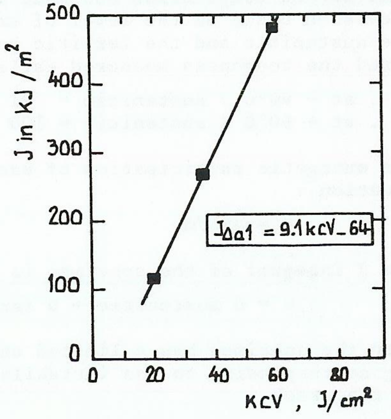


Fig. 2. Evolution of J_{IC} and $J_{\Delta a1}$ with temperature

Fig. 3. Correlation between J and the Charpy V energy

General results of toughness summarized in the table 2, show the evolution of toughness with temperature, which is most pronounced in the case of K_{jd} determined with precrack Charpy V.

TABLE 2 Toughness of Cladding

Test temperature °C	J_{IC} kJ/m²	dJ/da MPa	$J_{\Delta a1}$ kJ/m²	KCV J/cm²	K_{jd} MPa$\sqrt{m}$	K_j MPa$\sqrt{m}$
− 90	91	25	116	20	104	131
− 60	100*	80*	180*		115	
− 25	117	150	267	37	180	149
+ 20	212	268	480	60	237	200

* Estimation

TOUGHNESS OF COVERED SPECIMENS

We have employed covered 2 T, CT specimens of 25 and 40 mm thickness, with a cladding of 7 to 8 mm, in order to obtain different ratios of cladding to base metal. After precracking, specimens were broken at - 90°C and - 60°C. The computation of the stress intensity factor K was made in two ways, one directly by the maximum load of rupture and the other by the determination of integral J :

$$J = \frac{\alpha U}{B b}$$

with α correction coefficient of MERKLE and CORTTEN, and U total spent energy. This second computation was made for the comparison of test results with a prevision based on the level of energy required for the crack propagation in the austenitic and the ferritic part of the specimen. For that, we have considered the toughness measured earlier :

. at - 90°C J austenitic = 91 kJ/m^2 and J ferritic = 5 kJ/m^2
. at - 60°C J austenitic = 100 kJ/m^2 and J ferritic = 59 kJ/m^2.

The energetic participation of each of the two materials is given by the equation :

$$U = JBb/\alpha.$$

The J integral of the specimen is calculated with the total energy :

$$U = U \text{ austenitic} + U \text{ ferritic}.$$

When the specimen has a limited unstable crack propagation, we calculate the K_{IC} corresponding to the instability and the final J value with the new length of the crack.

The results are summarized in table 3. If we make comparison between experimental and calculated values of K_J, we notice a good agreement at - 90°C and at - 60°C for CT specimens of 25 mm thickness. With CT specimens of 40 mm thickness at - 60°C the experimental values are slighty lower, but in this case the fracture is more plane (Fig. 4) and the K_{IC} of the ferritic steel is probably a little lower than that with CT specimens of 25 mm thickness.

TABLE 3 Toughness of Covered Specimens

Total thick. mm	Cladding thick. mm	Temp. test °C	Maximal load daN	K_Q MPa$\sqrt{m}$	Measured values J_{IC} KN/m	Measured values K_j MPa$\sqrt{m}$	Austenite energy Joules	Ferrite energy Joules	Calculated values Jc kN/m	Calculated values Kc MPa$\sqrt{m}$
25	8.4	- 90	3 210* 6 390	38.5	39	86	15.5	1.7	34	80
25	8.2	- 60	7 380		68	117	16.2	6.3	72	120
25	8.2	- 60	8 280		99	141	16.1	6.6	72	120
40	7.3	- 60	9 300	91	40	94	13.9	30.5	66	115
40	6.7	- 60	4 290* 8 940	40 88	35	88	12.7	30.9	65	114

* Maximum load at the instability

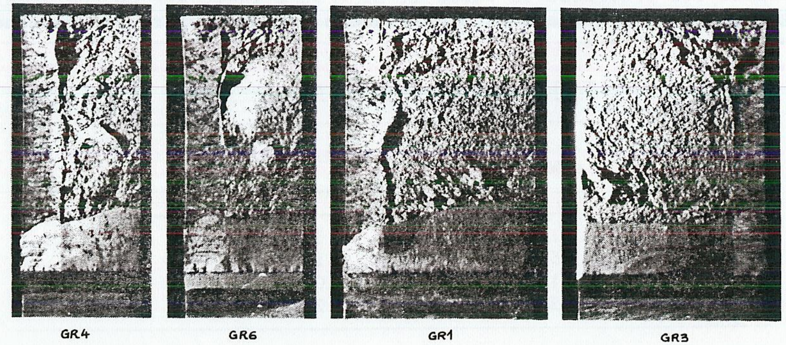


Fig. 4. Covered specimens tested at - 60°C

EXAMINATION OF COVERED SPECIMEN TESTED AT - 90°C

In order to have an idea of the mechanism of rupture we have made a detailed examination of the covered specimen of 25 mm thickness tested at - 90°C. A general view of the specimen (Fig. 5) shows the different zones and in particular, the unstable crack propagation in the ferritic zone and crack in martensite at the interface between austenitic and ferritic materials.

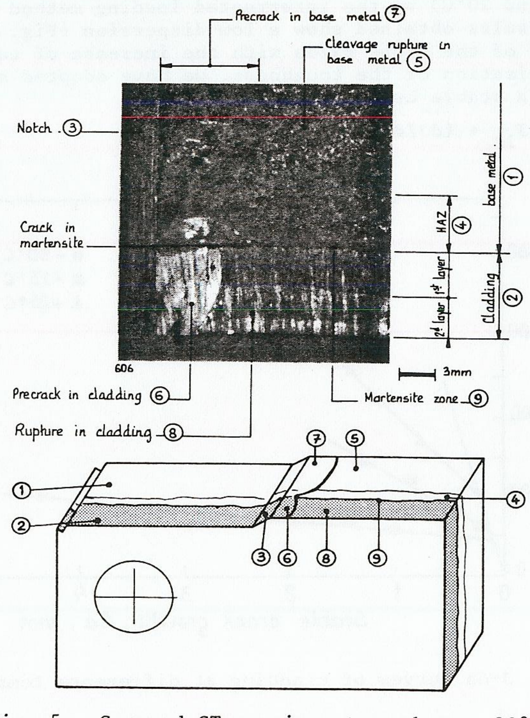
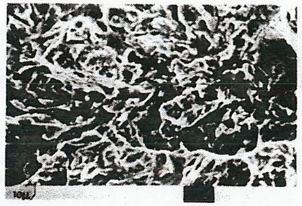
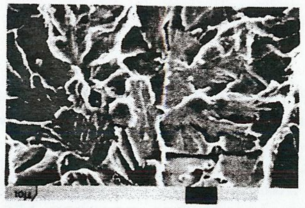


Fig. 5. Covered CT specimen tested at - 90°C

Optical microscopy examination show a heat affected zone of fine grains extending over 8 mm. This finer structure corresponds normally with a higher toughness. This is apparent for the heat affected zone and base metal appearances of rupture (Fig. 6).



a. EXAMINATION OF FRACTURE SURFACE OF HAZ



b. EXAMINATION OF FRACTURE SURFACE IN BASE METAL.

Fig. 6. Covered CT specimen
Evolution of fracture appearance
in the ferritic material

In the narrow martensitic zone, we observe cleavage in the plates of martensite (Fig. 7) and a crack at the interface. Examination of the cross section (Fig. 8) shows that the crack has a limited depth, 1 mm. The formation of this crack occurs during the rupture of the specimen since no crack was observed by destructive examination of regions not located at the vicinity of the fractured surfaces and observations conducted at higher test temperatures did not reveal the presence of such cracks. Residual stresses are suspected to contribute to the crack formation together with the loading stresses but the respective contribution were not evaluated.

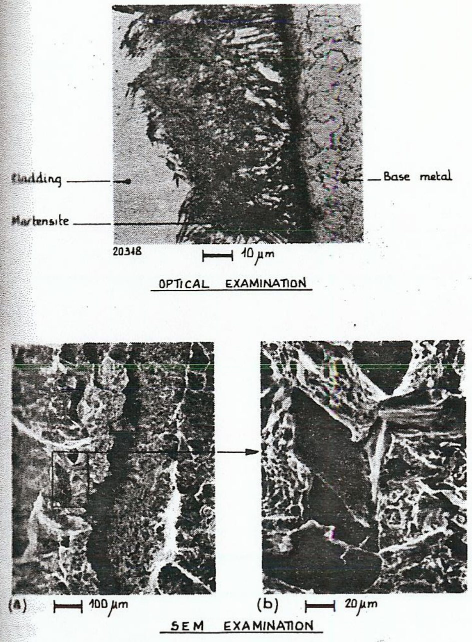


Fig. 7. Examination of the interface cladding-base metal

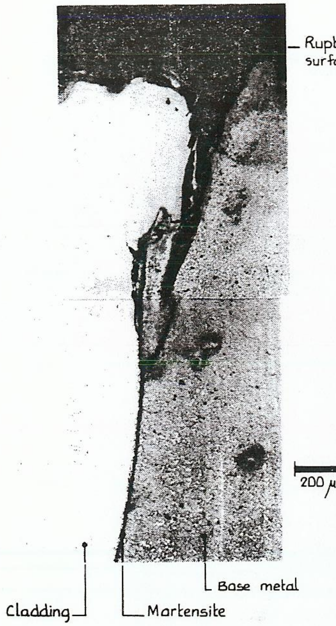


Fig. 8. Crack at the interface

CONCLUSION

This study allows us to draw out several conclusions :

- At the low temperature investigation, the toughness of the cladding is not very high, but comparable with other results of austenitic welding.
- The evolution of J_{1C} and the slope dJ/da with the temperature is important. A good correlation between $J_{\Delta a1}$ and Charpy V energy results, seems to be hold, however more data are needed to substantiate the proposed relation ship.
- The test on covered CT specimens shows the possibility of having a relatively good prevision of the behaviour of a covered structure, with the knowledge of the toughness of the components.
- In tests at low temperature (- 90°C), some cracks were observed at the interface between cladding and base metal, cracks were induced by the rupture of the specimen, but residual stresses are suspected to contribute to reach the critical conditions for crack formation at the interface.

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