POSTWELD INTERGRANULAR UNDERCLAD CRAKING : FORMATION MECHANISMS AND FRACTURE TOUGHNESS.

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Forged components of ferritic steel are protected by a welded austenitic stainless steel clad. Intergranular cracking can take place in the ferritic phase close to the ferritic austenitic interface. Sulphur segregations embrittle the grain boundaries which are cracked by residual and thermal stresses during the postweld heat treatment. The intergranular brittleness and fracture at low temperature is characterised by a lower toughness than for transgranular fracture. On the other hand, the crack ligament length ratio is small. The toughness transition temperature is decreased by the shallow crack effect.

INTRODUCTION

Large forged components are protected against corrosion by a welded austenitic clad, e.g. the vessel of pressurized water reactors (PWR). At the ferritic austenitic interface, intergranular underclad cracks can occur in the ferritic base metal during the postweld heat treatment. The cracks have to be taken into account in the safety assessment.

Crack characterisation has been previously presented, (1), (2), (3) and (4). Using a specific procedure (5), we reproduced real underclad cracks by welding a two layer coating on a thick testpiece with a 90mm tape width. The cracks in the ferritic material are located in zones with higher contents of impurities, the ghost lines which are situated perpendicular to the welding direction. In figure 1b, a ghost line cross section with an opened intergranular crack and in fig. 1c the crack extension perpendicular to this section are shown. On the scanning electron microscope (SEM) fracture surface observation (fig 1c), two kinds of intergranular facets can be distinguished: the inner central crack area with smooth facets (position 2) is surrounded by dimpled intergranular facets (positions 1 and 3).

Thermocouple temperature measurements under the fusion line show that the fracture zones are subjected to different temperature cycles, (4). When depositing the first layer, a coarse grained microstructure is generated in the HAZ. Depositing the second layer, the second fusion line is situated at the surface of the first layer. The coarse grained zone microstructure is refined. If the refinement remains incomplete, the final product still contains areas with a coarse grained

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microstructure. This can happen for partial juxtaposition of two neighbouring tapes. Coarse grained areas become potential intergranular underclad crack loactions (position 2 in figure 1c), when the postweld heat treatment is applied.

Two crucial questions arise: first, is there a maximum intergranular crack depth? And, second, what are the controlling parameters for intergranular underclad crack initiation? An attempt is made to propose a mechanism responsible for the intergranular formation based on different experimental results: impact tests in an Auger electron spectroscope (AES), SEM observations, hardness measurements, etc... After the mechanism proposal, we will then analyse the crack propagation potential by studying fracture toughness.

The underclad cracks in, e.g. pressure vessels, are small relative to the wall thickness (a/W=0.006). The crack propagation potential and/or the fracture is determined by the relative crack size superposed by the intergranular embrittlement. Therefore, we analysed both effects seperatly before discussing fracture toughness of an intergranular underclad crack, (6).

EXPERIMENTAL PROCEDURE

We tested a C-Mn-Ni-Mo steel widely used for nuclear constructions. It corresponds to the American standard A508 Cl3. In the AES observations the inner part of a steam generator tube sheet with a bainitic microstructure and a grain size of about 20 µm (before welding) has been analysed. For the fratcure mechanics tests, specimens have been taken out of a rolled product. Table 1 gives the chemical composition of the tube sheet which is similar to the rolled product composition.

TABLE 1- Chemical composition (Wt. Pct.), (7)

Element	C	Mo	Mn	Ni	Cr
weight %	0.175	0.49	1.42	0.72	0.22
Element	Si	Cu	Al	S	P
weigth%	0.23	0.06	0.035	0.010	0.006

Small specimen containing intergranular underclad cracks were opened in an Auger spectrometer under vaccum, (4). The Auger spectra of the fracture surface elements were normalized by the FeL3VV-703eV iron peak.

The mechanical characterisation of the intergranular underclad cracks has been done using a recently proposed model to take into account the loss of constraint at the crack tip (shallow crack effect), (6). Shallow cracked specimen toughness results were compared to those from CT specimen (a/W=0,5), (6). Intergranular fracture toughness data were measured with temper embrittled specimens containing a semi-elliptical fatigue crack; Analytical formula from Newman and Raju (9) allowed to calculate the stress intensity factor at the crack front. The toughness reduction due to the intergranular brittleness was evaluated by comparing the toughness results of 4 point bend specimens with different inter/ transgranular fracture ratios tested at a temperature of -196°C.

RESULTS

With the aim to analyse the intergranular underclad crack surfaces by AES, we opened cracks showing smooth and dimpled facets. The normalised sulphur peak height decreases from 0.8 to 0.3 when leaving the austenitic ferritic interface. 0.8 corresponds to central, smooth intergranular facets and 0.3 to dimpled ones, (7). When sputtering the fracture surface, segregations can be identified. The sulphur peak height decreases in an important manner in the first minutes before reaching nearly a constant level of about 0.2.

The shallow crack effect results were obtained from 16 specimens with crack ligament length ratios a/W between 0,02 to 0,15 in a temperature range from -196°C to -90°C .Fractographic examinations showed that, in most cases, fracture occured by cleavage, except in two specimens which contained a significant amount of intergranular facets in addition to the cleavage facets. These tests show a large scatter in the data and that the fracture toughness increases rapidly at a temperature above -150°C. The results on 19 CT type specimens carried out over the temperature range between -125°C and R.T. are reported in figure 2. Only 6 specimens fulfilled the conditions for valid K_{IC} measurements, (10). The test results show also a large scatter in the data. Furthermore the fracture toughness increases smoothly with temperature, especially above -80°C. At K_{IC}=100MPa$\times$m the shift is of the order of 60°C due to the shallow crack effect.

Fracture toughness reduction results due to intergranular brittleness at low temperature shows that the total difference is approximatively 10%.Two of the shallow crack specimens containing large amounts of intergranular fracture were broken at significant lower fracture toughness level than the rest, by transgranular fracture broken shallow crack specimens, fig. 2.

DISCUSSION

Mechanism of intergranular underclad formation. Intergranular underclad cracking is related to a tension residual stress state after welding, (12). In the coarse grained inner part, the segregated sulphur embrittles the grain boundary. A smooth intergranular fracture surface can be observed. When the postweld heat treatment is applied, the different dilatation behaviours (in the austenitic cladding and the ferritic base metal) and the temperature gradient increase the tension stress state until the grain boundary cohesion forces are exceeded.

When the crack is entering in the finer microstructure, the stresses are reduced but they remain high enough to allow further cracking. A combined mechanism of cavity coalescence (dimpled facets) and grain boundary embrittlement by sulphur controls the crack propagation. The intergranular underclad cracks formation is a two step process. The completly brittle intergranular fracture in the central crack area can be related to the postweld heat treatment beginning. The surrounding dimpled facet belt is formed in a second step.

The maximal crack depth is function of the first layer HAZ (determined by the welding energy), the ghost line brittleness and the MnS content. These variables determine the toughness transition temperature. High impurity contents favorise brittle intergranular fracture up to temperatures where one would expect a fracture controlled by the shallow crack effect.

.Fracture toughness. When specimens with intergranular underclad cracks are opened, only a small part is intergranular. The rest of the fracture surface is transgranular. Further cracking is transgranular due to the non by the welding operation affected microstructure. Only the crack ligament length ratio determines then the fracture conditions (the shallow crack effect). The fracture toughness can be expected to be higher than measured with CT specimen.

An example are forged components as pressure vessels where the material and the potential impurity zones are oriented parallel to the circonference. Here, radial propagating cracks are perpendicular to these brittle layers. The impurity zones will have only a minor impact because they are extremely short in the crack propagation direction. The shallow crack effect can become the major crack control factor.

CONCLUSIONS

1.) The intergranular underclad cracks are opened by both residual and thermal tension stresses. Embrittleing segregated sulphur allows crack initiation. Fracture with smooth intergranular facets takes place when the postweld heat treatment begins. In a second step, the crack propagates by coalescence of small intergranular cavities.

2.) The maximal observed crack depth is related to the by the welding operation coarsened microstructure. Crack propagation depends on the material orientation and, in particular, how potential segregation zones are situated relative to the cracking direction.

3.) The fracture toughness is increased by the shallow crack effect and decreased by the brittle intergranular fracture at low tempertures.

4.) Low toughness values for intergranular fracture must be considered, if the crack propagation can be parallel to potential impurity zones. If these zones are perpendicular, the shallow crack effect can become a major control factor.

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REFERENCES

(1) Faure, F., Bocquet, B., Boudot, R. and Zacharie, G., Colloque Int., Fontefraud, France, 1985.

(2) Kussmaul, K.,. Blind, D. and Ewald, J., Int. J. Pres. Ves.& Pip., 5, 1977, pp. 159-180.

(3) Shin, J. and McMahon, C.J., Acta metall., 32, 1984, pp. 1535-1552.

(4) Schnellhammer, W., Techn.-wiss. Ber., MPA Stuttgart, Heft 78-01, 1978.

(5) Piques, R., and Buisine,D., Journées d'automne SFMM Paris, 1992.

(6) Tigges, D., Piques, R. and Pineau, A., ICF10, Berlin, 1994, pp. 637-646.

(7) Tigges, D., Piques, R., Vignes, J.L. and Buisine, D., ICM7, Delft, 1995, pp. 279-280.

(8) ASTM 399, Annual Book of ASTM Standards, Section 3: Metals, Test Methods and analytical procedures, Vol. 3.01, ASTM, Philadelphia, 1992.

(9) Newman J.C. and Raju I.S., Eng. Frac. Mech., 15, No 1-2, 1981, pp 152-192.

(10) Chardes, J.C. and Masson, S.H., Internal Report HT/PV D564 MAT/T43, 1984.

(11) Tigges, D., Nocivité des defauts sous revêtement des cuves de réacteurs à eau sous pression, Thesis, Ecole des Mines de Paris, 1995.

(12) Bethmont, M. and Moinereau, D., Internal Report HTM 2/90,29A, HT46/90/NEQ1149A, 1990.

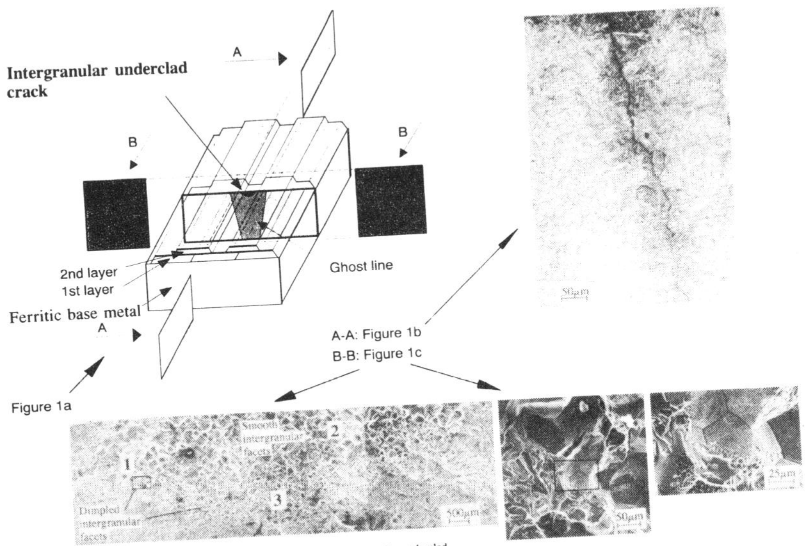

Figure 1: Intergranular underclad cracking: 1a) Orientation of the intergranular underclad cracks under the welded austenitic layer; 1b) Section of an intergranular underclad crack in a ghost line; 1c) Fracture surface of an intergranular underclad crack observed in a SEM.

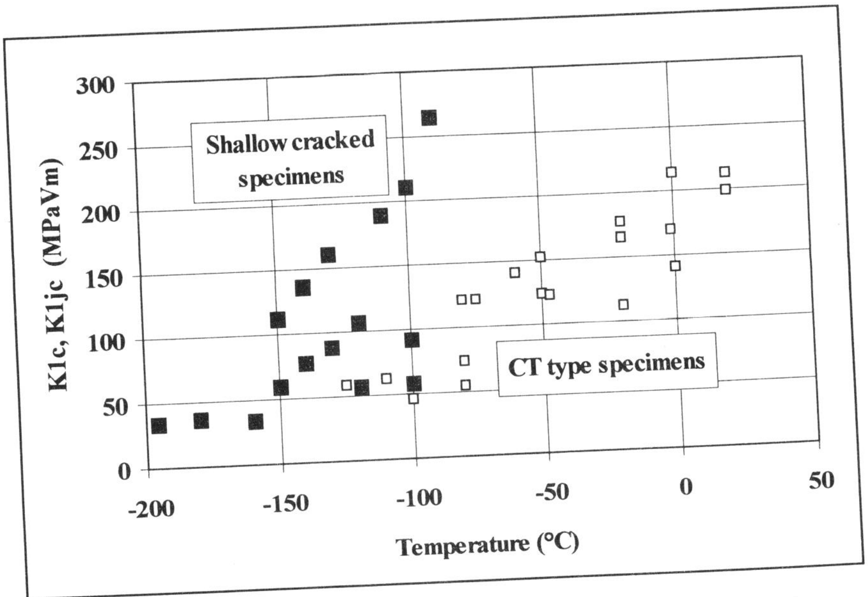

Figure 2 CT and shallow cracked specimens fracture toughness versus temperature.