EVALUATION OF CRACKS FORMED DURING HEAT TREATMENT FOR STRESS RELIEF BY ACOUSTIC EMISSION

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SUMMARY

A new nondestructive testing (NDT) method—the acoustic emission analysis (AEA)—was applied to the problem of detecting undercladding cracks in reactor steel A508 Class II with overlay welds. This was made by measuring acoustic emission during the heat treatment for stress relief of clad blocks. The results of the AEA were compared with those of other NDT methods and micrographs.

It was found that AEA is a quite sensitive method for detecting cracks. The extent of crack formation can be qualitatively predicted by an acoustic emission parameter, the number of total emission counts during the heating period. By this method it is possible to classify the cracks roughly into different sizes. Especially a reasonable value of the acoustic emission parameter for industrial quality control can be given.

Due to the principles of the method, the AEA is able to follow crack formation during the whole heat treatment and to give detailed information of the kinetics of cracking in dependence of time and temperature: Undercladding cracks in reactor steel are not formed in the period of heating-up the blocks, but at the final temperature of the heat treatment. The velocity of crack formation in this stage gradually increases from zero to a maximum, which is reached after an incubation time of 2-4 hr at 600 °C, and decreases then continuously —also during further heat treatments. These results are in good correspondence to existing theories about the cause of undercladding cracks.

To study in more detail the mechanism of crack formation, acoustic emission was measured during creep tests of specimens, which had a similar heat treatment and structure as the coarse grained heat affected zone of the clad blocks. According to the AEA and to photographs, microcracks are already formed after times of less than 30% of rupture lifes. The rupture of the specimen is announced by an increase of acoustic emission activity, that means in this case a range of macroscopic crack formation, which takes nearly 7% of the total rupture life. It was found by acoustic emission analysis that crack propagation along a grain boundary cannot be spontaneous, but must proceed in steps.

1. Introduction

The detection of cracks under the austenitic cladding layer of reactor pressure vessels in 1970 has initiated extensive research work [1 - 3]. Geometry and size of these undercladding cracks (U.C.C.) were analysed in micrographs by removing the cladding layer.

U.C.C. are intercrystalline cracks formed during the heat treatment for stress relief. They appear under the junction of neighbouring bands of the submerged-arc overlay welds within the coarse-grained heat-affected zone of the base material A 508 Class II. As can be seen in Fig. 1, not single cracks but arrays of several cracks are found. The maximum crack length is around 15 mm, the maximum crack depth corresponds with the depth of the coarse-grained zone of 2.5 mm.

By means of conventional non-destructive testing methods U.C.C. cannot be detected. A special ultrasonic inspection method capable to indicate U.C.C. was recently developed by BAM (Bundesanstalt für Materialprüfung), Germany. The accuracy of the method was not yet proved systematically on natural U.C.C., but only on artificial defects. A main disadvantage is that the measurements are quite time-consuming. Therefore the method does not seem applicable to the evaluation of large areas, but rather to random inspection.

For the following reasons acoustic emission analysis (AEA) - a new non-destructive testing method - would be useful for the detection of U.C.C.:

- high sensitivity
- dynamic recording, that means the detection of the kinetics of cracking during the heat treatment for stress relief
- intergral inspection of a large area (≥ 20 m^2) by means of one pick-up

The method is based on the phenomenon that growing cracks, inner friction processes or plastic deformation will emit acoustic pulses whose frequency range extends far into the ultrasonic region. These acoustic pulses are measured by resonant piezoelectric transducers, which have resonant frequencies in the range of 50 to 500 kHz.

2. Application to Clad Blocks

2.1 Measuring Equipment

Fig. 2 shows a schematic view of the measuring equipment. A steel rod of 5 mm diameter and 500 mm length, extending outside the furnace without touching it, was welded to the clad block. The rod serves as a wave guide of the acoustic emission, which is recorded by a transducer of PZT (lead zirconium titanate) attached to the cold end of the rod. Metallic rods of aluminium and steel are quite useful as wave guides, since the damping losses are as low as 1 to 2 db/m. The actual acoustic emission equipment was an usual one to measure the so-called pulse rate [4], that is the number of ring-down oscillations of the transducer above a discriminator threshold level. The pulse rate was recorded by a printer and ratemeter and indicated by an acoustic monitor.

2.2 Experiments

Clad blocks of different chemical composition (Table 1), size and fabrication (Table 2) were available. All blocks were heated several times for stress relief. Temperature and heating time are summarised in Table 2.

Acoustic emission was recorded throughout the heat treatment. The results of AEA were compared with other inspection methods. After the heat treatment the ultrasonic method developed by BAM was applied. In addition, the austenitic cladding layer was removed at different spots, the surface was etched, and micrographs were taken.

In extensive preliminary experiments on unclad blocks the normal background noise during the heat treatment was investigated. By appropriate modifications it was possible to reduce the noise; the intensity of remaining noise was determined.

2.3 Results

During the heating-up period only background noise was recorded. But after reaching the final temperature near 600 °C additional characteristic acoustic emission was measured, which was clearly distinguished from the background. Fig. 3 shows a typical example. Sharp maxima of the pulse rate marked by arrows clearly indicate this acoustic emission (AE) against the background noise. As can be seen in Table 3, where the results of micrographs, ultrasonic inspection and AEA are compared, this acoustic emission corresponds to the formation of U.C.C. They were only found in micrographs when the characteristic maxima of the pulse rate, all similar to those of Fig. 3, were recorded.

As a parameter of the extent of crack formation the total emission count ΣJ was determined, the background noise being subtracted. As can be seen in Table 3 the total emission count measures the extent of crack formation in fair qualitative agreement with micrographs. If $\Sigma J \gtrsim 40 \cdot 10^5$ during the first heat treatment, U.C.C. are clearly be seen (crack length $\gtrsim 1$ mm); for $\Sigma J = 3 \cdot 10^5$ only small single microcracks were found (crack length ≈ 0.05 mm); and for $\Sigma J \lesssim 0.3 \cdot 10^5$, i.e. for values in the range of background levels, no U.C.C. were observed.

The ultrasonic inspection method, on the other hand, proved to be insensitive to small cracks. Only in one case (specimen No. 4/I) indications were recorded at three different spots where several large cracks were found in micrographs. But a single crack of 3.8 mm length and 1 mm depth in specimen 2 was not detected (Table 3).

AEA was found to give detailed information about the kinetics of crack formation:

a) At temperatures of 600 to 630 °C cracking does not start in the heating-up period, but shortly after reaching the final temperature. This agrees with the observation of Ref. [1] that U.C.C. appeared only after heat treatments at temperatures above 550 °C.

b) The formation of arrays of U.C.C. has a step function character. Each step takes a maximum time of 2 min; the intervals between them statistically scatter in the range of 5 to 60 min (Fig. 4).

c) The average pulse rate (see slope in Fig. 4), which proved to be a qualitative parameter of crack formation, rises from zero at the beginning of the annealing period to a maximum which appears within two to four hours at heating temperatures around 600 °C. During a second or further heat treatments the average pulse rate decreases continuously in the annealing period.

d) As can be seen from the total emission counts ΣJ in Table 3, the extent of crack formation is most pronounced during the first heat treatment and decreases with any further heat treatment.

2.4 Discussion

The investigations have shown that the total emission count is a proper parameter for a rough classification of the extent of crack formation. It appears that an application of AEA to industrial quality control would be useful to exclude U.C.C. above a minimum size. According to Table 3, a total emission count of $4 \cdot 10^6$ could be taken as a threshold level, that corresponds to a minimum crack length of 1 mm. This value would fit for relatively small blocks (Table 2). It should be the objective of further research to investigate whether similar values, characterising the extent of crack formation, can be given for larger industrial structures.

By means of AEA detailed experimental information about the kinetics of cracking is abtained, which helps understandig the fundamental question what internal processes finally cause the cracking. The fact that U.C.C. are formed mainly during the first heat treatment for stress relief can be understood if we consider that any crack will reduce the internal weld stresses and thus diminish the tendency to further cracking. It is more difficult to see why cracking reached a maximum only after a certain "incubation time" during the first annealing period, although the internal stresses should be most pronounced at the beginning of the annealing period. An explanation is provided by the theory of Ref. [3], which assumes that time- and temperature-dependent precipitation processes take place in the heat-affected coarse-grained zone. As a result of precipitation the strength of grain boundaries relative to the grains will be reduced and, in consequence of increased slip at the grain boundaries, finally intercrystalline microcracks will be formed.

3. Measurements During Creep Tests on Small Specimens with Course-Grained Structure

3.1 Experimental

By means of special heat treatments the coarse-grained structure of the heat-affected zone of clad blocks was simulated in small specimens. Creep tests were done and the kinetics of cracking were studied by means of AEA. The measuring equipment was similar to that of Fig. 2. In this case a flexible steel wire of 2 mm diameter was used as a wave guide, since bending was necessary because of the geometry of the furnace.

The creep tests were interrupted in some cases to study subcritical cracking in detail: The specimens were cooled down and torn at -196 °C.

The fracture surface were examined in a light and a scanning electron microscope.

3.2 Results and Discussion

The measurements of AE showed that subcritical cracking took place during the creep tests long before fracture, at times as early as 10 percent of the lifetime of the specimens. The results were examined by applying the above procedure and tearing the specimens at -196 °C. Fig. 5 shows a typical example of a creep test. A steep increase of the pulse rate near fracture marks a distinctive phase of macroscopic crack growth, which extends over 7 to 2 percent of the total lifetime. In Fig. 6 an intercrystalline crack formed in this stage of the creep test can be seen as a dark area indicating the presence of an oxide film.

High activity of AE was recorded long before the above phase of catastrophic failure (Fig. 5) had been reached. As was seen from fracture surfaces, this marks the beginning of the formation of small creep cracks with dark oxide films at the surface of the specimen or light microcracks without oxide films, which were statistically spread over the whole cross section. In consequence of the distinctive characteristics of AE both types of cracks were clearly distinguished.

Summing up it can be concluded that AEA proved to be a useful tool to study the kinetics of cracking in detail. Comparison of the number of individual burst signals with the number of cracked grain boundaries showed that crack growth along a single grain boundary cannot be spontaneous but must proceed in small steps. This agrees with small-scale pictures of the fracture surface made by a scanning electron microscope (Fig. 7).

References

[1] H. Cerjak, W. Debray; Proceedings of the VGB-Conference "Werkstoffe und Schweißtechnik im Kraftwerk", Düsseldorf, Germany, 1971, p. 23

[2] G. Bartholome, H. Dorner; 6th Annual Information Meeting of HSST-Program, Oak Ridge Nat.Lab., April 1972, paper No. 9

[3] A. Fuchs, K. Detert; First Intern. Conf. on Structural Mechanics in Reactor Technology, Berlin, September 1971, paper No. 5/4

[4] J. Eisenblätter; ingenieur digest Vol. 11 (1970) No. 10

Table 1: Chemical composition (wt %) of the base material

Charge No	C	Si	Mn	P	S	Cr	Mo	Ni	V	Cu	Al	Sn	Co
1	0.21	0.25	0.66	0.012	0.01	0.39	0.69	0.89	0.02	0.12	0.018	-	-
2	0.21	0.25	0.97	0.01	0.006	0.42	0.75	1.14	-	-	-	-	-
3	0.18	0.26	0.70	0.008	0.008	0.40	0.62	0.79	0.01	0.11	0.02	0.018	0.027

Table 2: Dimensions of the blocks and the conditions of welding and heat treatment

Block No.	Dimensions (mm)	Charge No.	Welding conditions	Temperature T (°C) and annealing time t (h)					
				1st heat treatment		2nd heat treatment		3rd heat treatment	
				T	t	T	t	T	t
1	100x230x130	1	normal conditions: heat of 120 000 joules/cm	600	5	600	13		
2	100x240x130	1	as No. 1	600	7.2	620	30		
3	100x240x130	1	as No. 1	600	7.5	605	10		
4	400x210x130	1	as No. 1	590-620 *)	15	-	-		
4/I	180x210x130	1	as No. 1	-	-	612	9		
4/II	180x210x130	1	as No. 1	-	-	626	46	600	12
5	190x250x110	2	preheating temp:60°C band speed:11cm/min power: 600 A/30V	590	56	600	23		
6	190x250x110	2	preheating temp:160°C band speed:9cm/min power: 700 A/30V	600	50	595	47		
7/1	220x230x150	3	as No. 1	600	10	620	10		
7/2	220x230x150	3	as No. 1	630	11	620	13		

*) Exceptionally a larger furnace was used, which could only be controlled in the given range

Table 3: Crack detection by different methods

Block No.	Ultrasonic inspection	Micrographs	Maximum crack length (mm)	AEA	Total emission count		
					1st heat treatment	2nd heat treatment	3rd heat treatment
1	no	no	-	no	-		
2	no	yes	3.8	yes	45	8	
3	no	yes	1	yes	110	0.2	
4 *)	-	yes	1	yes	40		
4/I *)	yes	yes	6	yes	-	15	
4/II *)	no	yes	0.5	yes	-	5	$\angle$ 0.3
5	no	no	-	no	$\leq$ 0.1	$\leq$ 0.1	
6	no	no	-	no	$\leq$ 0.1	$\leq$ 0.1	
7/1	no	no	-	no	$\leq$ 0.3	$\angle$ 0.3	
7/2	no	yes	0.05	yes	3	0.2	

*) Block No. 4 was divided after the first heat treatment into two parts 4/I and 4/II

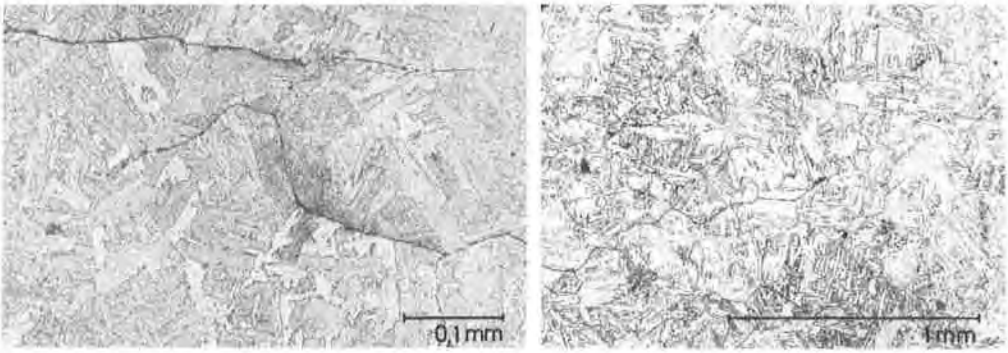


Fig. 1: Undercladding cracks in the coarse-grained zone of clad blocks of steel A 508 Class II

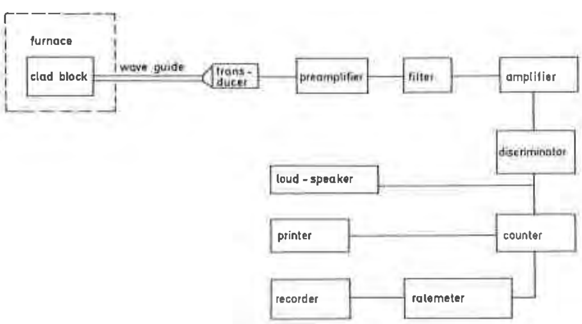


Fig. 2: Measurement equipment

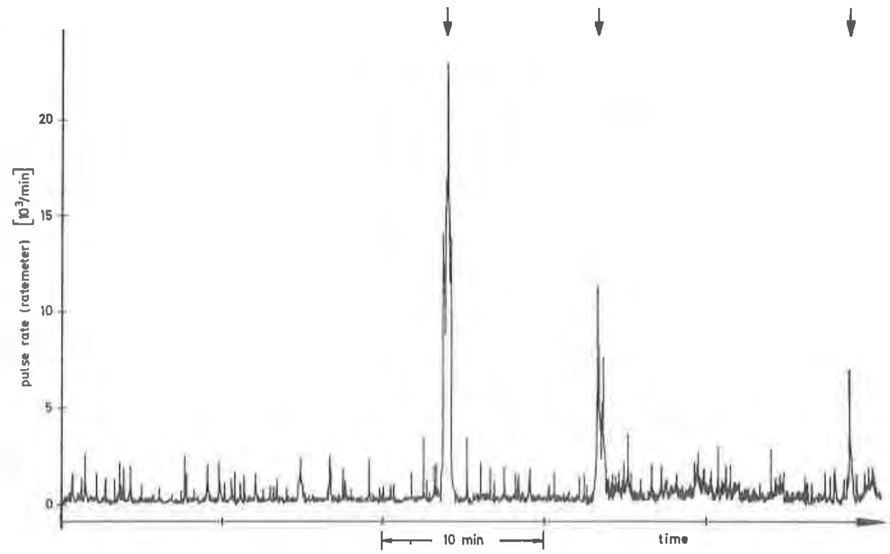


Fig. 3: Pulse rate (ratemeter) in the annealing period at 612 °C, block No. 4/I (2nd heat treatment)

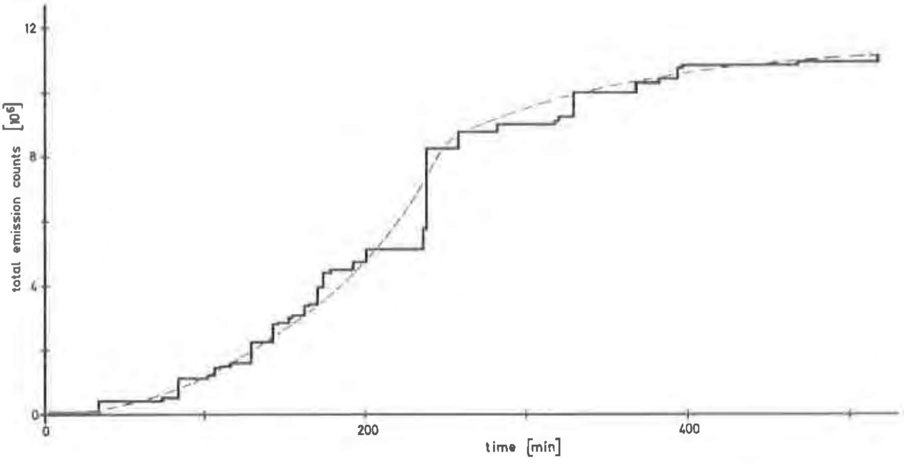


Fig. 4: Total emission count plotted against annealing time at 600 °C, block No. 3 (1st heat treatment)

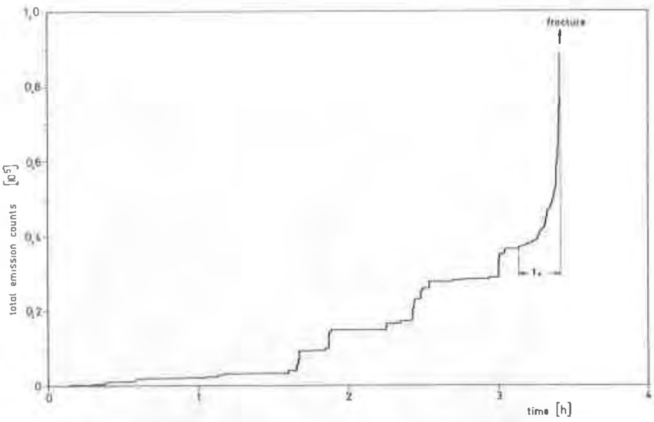


Fig. 5: Total emission count as a function of time during the creep test (temperature 600 °C, stress 220 N/mm²) of a specimen with coarse-grained structure

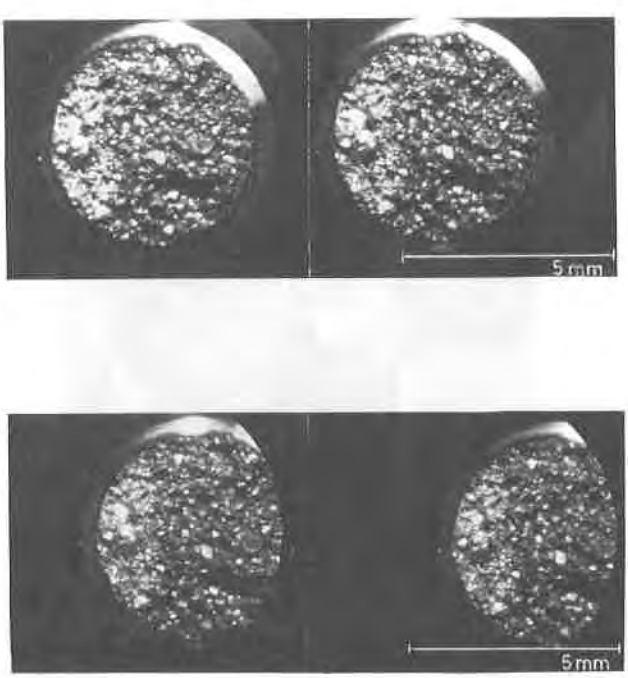
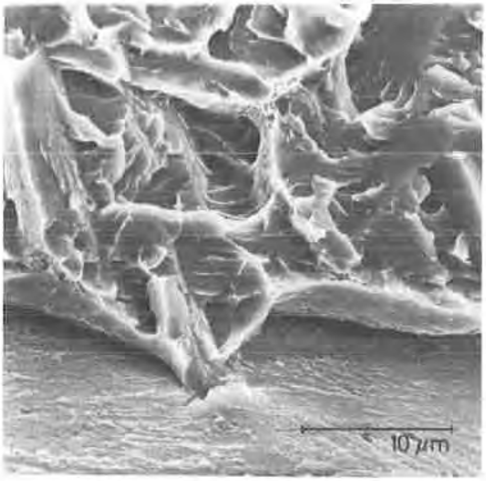


Fig. 6: Fracture surface of a specimen with a creep crack (dark area) which was torn at - 196 °C (light area)



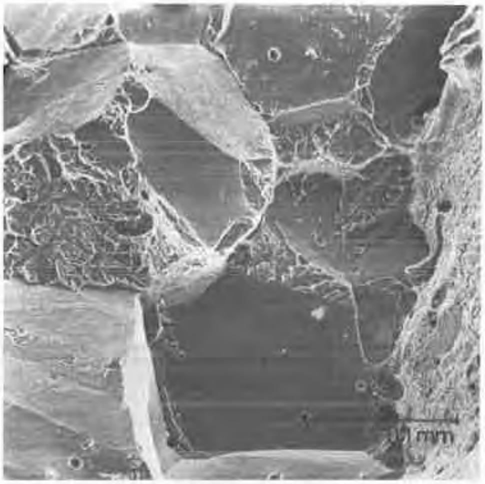


Fig. 7: Intercrystalline crack surface in the light area of Fig. 6