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ACOUSTIC EMISSION DURING CRACK PROPAGATION IN NUCLEAR RPV STEELS

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Abstract. The main goal of this work is to determine the parameters of the AE signals registered with a PC-controlled automated AE-system SCOP-8 during initiation and propagation stages of fracture in three differently aged reactor RPV steels. Two types of steel, namely 15Kh2MFA and 15Kh2MFA-A were investigated. The following parameters of the acoustic emission signal were evaluated for analysis: amplitude, rise time, spectral characteristics, wavelet coefficients etc. The initial stages of crack growth are characterized with the acoustic emission signals of moderate amplitudes and short duration. With expansion of the crack the flow of acoustic data contains both low-amplitude and high-amplitude signals. The collected data could be used for the quantitative evaluation of the crack growth and thus transferred to the design of the acoustic emission system for structural health monitoring of nuclear RPVs.

Keywords: fracture, acoustic emission, reactor pressure vessel steel, crack growth, stress intensity factor.

1. Introduction

Ferritic Cr-Mo steels modified with vanadium have been widely and successfully used as reactor pressure vessel (RPV) materials both in chemical and in nuclear power industries. These steels exhibit high mechanical strength combined with outstanding elasticity and fracture toughness. Moreover, they also demonstrate high levels of workability, hardenability and weldability, which are so important in manufacturing large size and thick walled vessels [1]. As to the in-service properties, this group of steels has demonstrated relatively high durability under high-temperature high-pressure conditions even under the influence of strong irradiation fluxes, thus becoming a major candidate for nuclear RPV applications. All Ukrainian nuclear PRVs were made of Cr-Mo-V steels [2].

However, even such good materials suffer degradation during prolonged synergetic influence of thermo-mechanical fatigue and irradiation [1–3]. Since most nuclear reactors in Ukraine have been in operation for more than 20 years and are coming close to their engineering design lifetime (30 years), one of the most urgent needs is to inspect the RPVs regarding their degree of ageing and possibility to extend their lifetime. In fact, two nuclear RPVs in Ukraine exhibit embrittlement of their weldments and one RPV is showing degradation of the base metal [4], confirming the need for effective detection and evaluation of the degree of degradation and, consequently, the integrity and safety level of all nuclear RPVs.

Among the methods of nondestructive testing, which seems permissible not only for inspection of RPV's integrity during its manufacturing stage, but also during operation, is acoustic emission method. It has been known for several decades and, probably, is indebted to its major development to the nuclear power industry where it was extensively studied regarding monitoring of nuclear RPVs' integrity back in 1970-1980s [5-7]. At that time, implementation of this method into such a heavily legislated industry as nuclear power was not successful for several reasons: relatively low intensity of acoustic emission signals generated in plastic materials of the RPVs, significant level of cavitation noise generated by the water moving within the first circulation loop, and an unfortunate spectral dependency of attenuation of elastic waves with frequency. The listed issues all together caused the metrological aspect (related to the quantitative evaluation of the flaw size in a RPV) to become a significant problem that had to wait for another implementation trial at times when the electronic industry, materials science and theoretical fracture mechanics show the adequate solutions for the quantitative evaluation of damage.

Actually, in 1980-1990s a significant progress in the mentioned areas was demonstrated [8] and acoustic emission method sounded as a premiere candidate for monitoring structural integrity of nuclear RPVs even in the belt zones of the highest irradiation. The metallurgical aspects of nuclear RPV materials' degradation had been outlined and the correlations had been established between the parameters of the growing flaw in a thick-walled RPV material and the parameters of the acoustic signals generated during the incremental growth of such a flaw [9-11].

After two disasters at Chornobyl and Fukushima nuclear plants, the need for a significant expansion of the arsenal of nondestructive methods able to monitor integrity of principal components of nuclear power plants became strongly manifested. All the safety regulations have been reevaluated – the process that coincides with the efforts to extend the lifetime of the existing nuclear power plants. In this light, any effort to implement additional diagnostic tools for the working nuclear RPVs is of major importance. Acoustic emission method has been enjoying significant improvements on the part of instrumentation owing to the developments in programmable microprocessors and high performance integrated circuits. Besides, the fundamentals of quantitative acoustic emission and even the legislative grounds have been significantly moved forward [12-13]. In our opinion, the major demand today is accumulation of the reliable acoustic emission data that would enable quantitative nondestructive monitoring of structural integrity of the Ukrainian RPVs and serial manufacturing of the acoustic emission systems for such purposes. As a prototype for the latter is a wireless telecommunication system that is currently being developed at Karpenko Physical Mechanical Institute of the National Academy of Sciences of Ukraine.

The main goal of this work is to determine the parameters of the AE signals registered with a PC-controlled automated AE-system SCOP-8 during initiation and propagation stages of fracture in three differently aged reactor RPV steels.

Table 1
The required chemical compositions of the studied RPV steel

Grade, document	Element, % wt.									
	C	Si	Mn	Cr	Ni	Mo	V	S	P	Cu
15Kh2MFA TU 108-131-75/86	0,13-0,18	0,17-0,37	0,3-0,6	2,5-3,0	0,4 max	0,6-0,8	0,25-0,35	0,015 max	0,012 max	0,10 max
15Kh2MFA-A TU 02.02.014-89	0,13-0,18	0,17-0,37	0,3-0,6	2,5-3,0	0,4 max	0,6-0,8	0,25-0,35	0,007 max	0,007 max	0,07 max

2. Experimental approach

The samples were manufactured from two types of steel, namely 15Kh2MFA and 15Kh2MFA-A, both in two different conditions: i) as received and ii) after being embrittled during an ageing procedure. The chemistries of the studied materials were supposedly within the required compositions, which are listed in Table. 1.

There were manufactured three groups of samples with the following histories:

1 – samples made out of 15Kh2MΦA in as received condition with subsequent ageing in air for 25 years. This
material has structural strength level 60 (designated KP-60) – corresponds to $\sigma_{0,2} \geq 60$ kg/mm^2 (590 MPa);

2 – samples made out of 15Kh2MΦA in heat treated condition with subsequent ageing in air for 25 years. Heat treatment was supposed to cause artificial ageing which is equivalent to 40 years of in-service embrittlement. This material has structural strength level 100 (designated KP-100) – corresponds to $\sigma_{0,2} \geq$ 100 kg/mm^2 (980 MPa); and

3 – samples made out of 15Kh2MΦA-A in as received condition with subsequent ageing in air for 10 years.

Notched fracture toughness samples with rectangular cross-section 10?20 mm were machined from the source material followed by fatigue precracking according to the known ASTM standard procedure [14]. Each precracked sample was placed into a loading device with an acoustically coupled piezoceramic sensor. The sensor was electrically connected to an acoustic emission system SCOP-8 through preamplifier.

Three-point bending of the precracked samples was conducted employing the central indenter moving with a speed of about 20 ?m/s. Simultaneously, during loading, the acoustic emission signals were recorded with an automated acoustic emission system, which recorded also crack opening displacement, deflection and load of the indenter. The relationship between the acoustic emission data and the load deflection curve was determined and analyzed.

The following parameters of the acoustic emission signal were evaluated for analysis: amplitude, rise time, spectral characteristics, wavelet coefficients etc. The moments when acoustic signals exceeded a settled threshold limit were treated as crack growing events [15]. The post-bending quick fracture of the samples (Fig. 1) confirmed that the recorded signals were generated by the incremental growth of a crack. Backward calculations of the accumulated acoustic emission data and their comparison with load-deflection curve enabled quantitative evaluation of the growing crack with acoustic emission system.

As was found previously [15], the acoustic emission signals appear much sooner then the crack growth becomes optically visible. In soft materials, a plasticized process zone ahead of the crack tip is being formed before an incremental expansion of a macrocrack takes place. Even at this stage some acoustic emission activity is detectable, which probably originates from microcracking of secondary phases, like carbides or sulfides. The propagation of a macrocrack was ascribed to the moments of qualitative change in the intensity of acoustic signals, as reflected on a load-deflection diagram (Fig. 2).

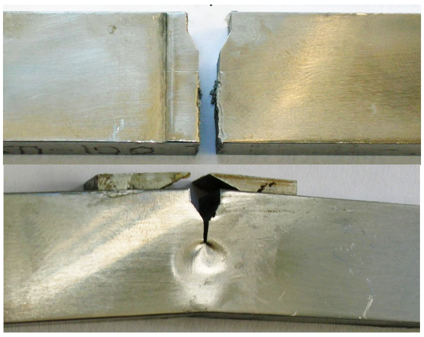

Fig. 1. Brittle fracture of the sample from group I (upper) and plastic deformation of the sample from group III (lower).

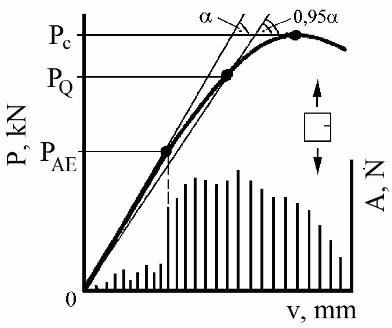

Fig. 2. Intensity change of the acoustic emission signals at point P_{AE} as a criterion for the macrocrack propagation.

As could be easily traced, the load level P_{AE} is significantly smaller than P_Q determined according to the standard, and so is a corresponding stress intensity factor K_{IAE} compared to K_{IC}. It has to be noted, that the value detected from the acoustic emission activity does not depend on the sample thickness, the loading mode and temperature, thus making the obtained value of K_{IAE} more credible than K_{IC} [15-16].

3. Results and discussion

The results obtained during this series of experiments on all three groups of samples revealed that the macrocrack begins to grow at loads P_{AE}, significantly lower than P_Q, which are obtained from the load-displacement diagram according to the standard procedure for the quasi-brittle fracture and plane strain condition. The corresponding values of stress intensity factors are given in Table 2. The initial stages of crack growth are characterized with the acoustic emission signals of moderate amplitudes and short duration. With expansion of the crack the flow of acoustic data contains both low-amplitude and high-amplitude signals. As the load approaches P_Q the relative number of high-amplitude signals is growing until the final fracture of the sample.

The early acoustic emission signals appeared soon after the loading started and their intensity was comparable to the background noise of the system SCOP-8 (Fig. 3a). Their maximum amplitudes, if looked closer (Fig. 3b), hardly exceeded 0,1–0,2 mV. The value of stress intensity factor K_I during the appearance of acoustic emission signals was for the first group of the order of $K_I \approx$ 2–3 MPa·m$^{1/2}$, for the second – $K_I \approx$ 3–4 MPa·m$^{1/2}$, and for the third – $K_I \approx$ 4–5 MPa·m$^{1/2}$. We have to note here that the amplitudes of the early acoustic emission signals from group III were the strongest, of the order of 0,5 mV. As the load increased, the signals were generated more frequently and their amplitudes gradually increased. When approaching point P_Q on the load-displacement diagram the amplitudes often reached 0,2–0,3 mV (for the group III – 0,5–0,7 mV). Beyond this point the amplitudes could have grown to several mV (Fig. 3, *c*).

Table 2

Critical stress intensity factors determined by the standard procedure and from the acoustic emission data

Group of samples	K_{IAE}	K_{IQ}	K_{IC}	K_C
	MPa·m$^{1/2}$			
1	27,93	88,35	88,35	132,28
2	29,26	82,96	82,96	134,79
3*	15,81	39,68	__	58,54

- plane strain condition is not provided

Further on the acoustic signals contained a mixture of the low-amplitude (fraction of 1 mV) and high-amplitude (few mV) signals, which suggests at least two different fracture mechanisms. It is possible that the high-amplitude signals were generated by the incremental growth of a macrocrack, while the plastic flow in the process zone resulted in low-amplitude signals. Such a stepwise mechanism involving two different mechanisms continued till the quick fracture of the sample.

Thus, the specific acoustic emission data has been obtained for the three differently aged groups of nuclear RPV steels. Such laboratory data is an invaluable for the future implementation of the acoustic emission method for structural health monitoring of nuclear RPVs. Besides the presented quantitative acoustic emission evaluation of the growing crack, there is also a need to gain the attenuation data since the elastic waves lose their intensity during their propagation through the material.

Attenuation coefficient was studied for these materials, using a rod 50 mm in diameter and 3 m long. The exponential approximation of the wave attenuation resulted in the value of attenuation coefficient δ = 0,45...0,52 m^{-1}.

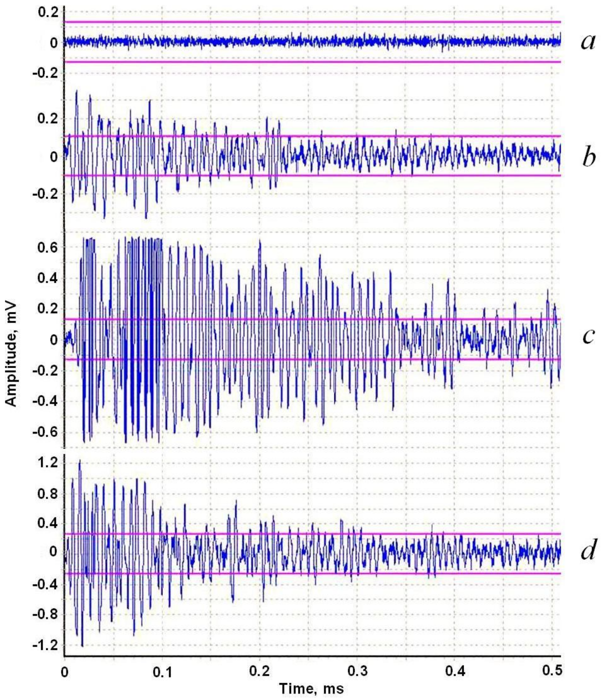

Fig. 3. Acoustograms recorded by the AE system SCOP-8 during experimental studies: *a* – background noise of the system; *b* – typical early signal for the samples representative of the group I and II; *c* – typical acoustic signal in the vicinity of P_{AE} (fig. 2); *d* – representative acoustic signals when the load approaches P_Q (fig. 2).

4. Conclusion

The preliminary study has been conducted that employed registration and analysis of the acoustic emission signals generated during initiation and propagation of fracture in nuclear RPV steels with different microstructural conditions due to different ageing scenarios. The laboratory study that employed acoustic emission system SCOP-8 revealed that the critical stress intensity factor determined with acoustic emission data is significantly smaller than that determined by the standard fracture toughness approach. The collected data, which also includes the attenuation coefficients for the nuclear RPV steels could be used for the quantitative evaluation of the crack growth and thus transferred to the design of the acoustic emission system for structural health monitoring of nuclear RPVs.

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