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ASSESSMENT OF MATERIAL DAMAGE OF BOILER DOWN-PIPES

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The results of damage examination of boiler down-pipes (type OR/32) are presented. The investigation program included: static tension test, determination of fracture toughness, hardness measurement and metallographic examination. It was found that material of worked down-pipes in the vicinity of knees has been damaged and thus these down-pipes must have been removed from service. Taking into account the results of hardness measurement of specimens made of virgin down-pipe knee it has been found that the virgin down-pipes are not fit to be put into service either.

1. Introduction

Structural components of power plants operate not only under loading at high or elevated temperature. Periodical power demands as well as routine repairs result in periodical changes of loading and temperature. These are the reasons for the increase of material damage development rate in structural components. Safety margin of structural components is affected by both manufacturing process and proper selection of material. A faulty manufacturing process can be the cause of initial material damage. If this effect is neglected, failure can occur.

In the present paper the results of damage examination of down-pipes of 102mm diameter and 5mm wall thickness made of K18 steel (designation according to Polish Standards) are presented. These down-pipes were cut out of a failed boiler (type OR/32) in one of Polish power plants. The failure took place at the convex portion of the pipe bend (knee).

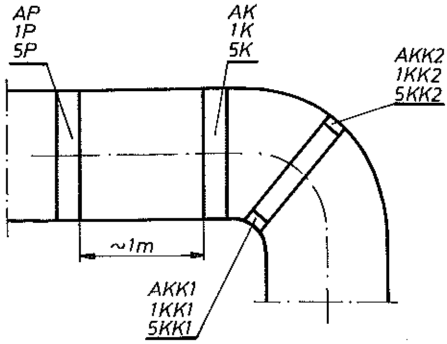

Fig. 1. Portion of down-pipe used in examination.

The examination was carried out on specimens made of rectilinear portions of down-pipes which were cut out of places shown in Fig.1. The investigation program included:

static tension test at room temperature,

determination of fracture toughness,

hardness measurement,

metallographic examination.

Two down-pipes that had worked during the period of 56749 h (designated 1 and 5) and a virgin one (designated A) were used in the investigation. Additional designation was also used. The specimens that were cut out from the portion in the vicinity of the pipe bend (knee) were denoted K while those cut out of the down-pipe portion located further from the knee were denoted P. The specimens that were cut out of the convex portion of the knee were denoted $KK2$ while those cut out on the concave side were denoted $KK1$. Designations of specimens in dependence on their locations are shown in Fig.1.

2. Static tension test

The plane specimens with parallel side surface were used in the investigation. The specimens were made in accordance with Polish Standards (PN-80/H-04314). The static tension tests were performed according to Polish Standards (PN-80/H-04310) using the Instron testing machine supplied with an integrator.

Table 1. Mean values of obtained results and their 95% confidence ranges.

Specimen designation	R_e [MPa]	R_m [MPa]	A_5 [%]	W_s [J/cm^3]	D_w
AP	354±21	503±17	29±3	209±27	0.00
AK	347±17	496±14	27±3	196± 9	0.06
$1P$	330±15	496±13	28±1	175±23	0.16
$1K$	345±15	474±18	20±4	131±30	0.37
$5P$	335±18	460±29	24±4	146±26	0.30
$5K$	366±28	472±18	19±3	126±10	0.40

In papers [1, 2] a new material damage parameter was proposed. The relative value of the difference of specific strain work has been assumed to be the damage parameter:

$$D_w = \frac{W_{0s} - W_s}{W_{0s}}, \tag{2.1}$$

where W_{0s} – specific strain work required for breaking a specimen made of virgin material, W_s – specific strain work required for breaking damaged specimen, W_{0s} and W_s are determined from the static tension test at room temperature. For virgin material $D_w = 0$, while for damaged one $D_w = 1$. This suggestion was experimentally confirmed for various heat resistant steels in uniaxial and plane stress states [2–4]. Six series of specimens (designation AP, AK, $1P$, $1K$, $5P$, $5K$ – Fig.1) were examined. Each series contained five specimens. Yield point (R_e), ultimate tensile strength (R_m), unit elongation (A_5) and specific strain work (W_s) were determined during examination. Mean values of the obtained results as well as their 95% confidence ranges are listed in Table 1.

It was assumed that material of specimens made of virgin down-pipe (designation AP) is undamaged ($W_s = W_{0s}$), so, for these specimens $D_w = 0$. Mean values of damage parameter D_w calculated from Eq.(2.1) are also listed in Table 1.

3. Determination of fracture toughness

Six series of specimens (designation AP, AK, $1P$, $1K$, $5P$, $5K$) cut out of the same places as for static tension tests were examined.

Each series contained three specimens. The fracture toughness has been determined according to ASTM E992-84 because wall pipe thickness was smaller than 8mm. The notched specimens were examined using Instron testing machine. To determine fracture beginning the electric potential method has been applied. A schematic plot of the force as a function

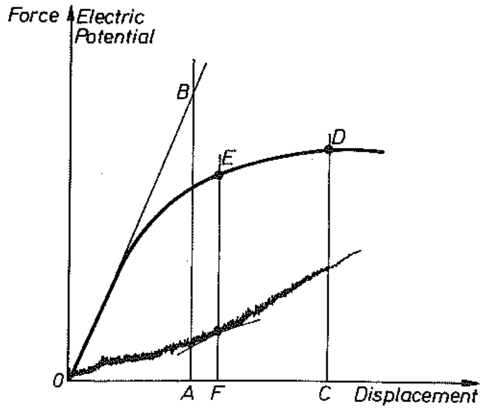

Fig. 2 . Plot of specimen bending and electric potential change.

of the specimen displacement is shown in Fig.2. The areas under force-displacement curves have been determined using a planimeter: A_s – area $OABO$ (for linear elastic range) and $A_{\max}$ – area $OAFCDEO$ (to maximum force) as can be seen in Fig.2. The schematic plot of electric potential as a function of the specimen displacement is also shown in Fig.2. The electric potential plot shown in Fig.2 can be approximately represented by two straight lines with different slopes. The intersection point E of these lines determines the most probable fracture beginning. The point being known, the value A_p – area $OAFEO$ can be determined.

Fracture toughness $K-EE$ accorrding to ASTM E992-84 can be determined (using equivalent energy method) from the following equation

(3.1) $$K-EE=\frac{P_{\max}S}{BW^{3/2}}\cdot f(\frac{a}{W}),$$

where

(3.2) $$P_{\max}=P_B\sqrt{\frac{A_{\max}}{A_S}},$$

Table 2. Mean values of fracture toughness and their standard deviations.

Specimen designation	Fracture toughness with standard deviations	
	$K-EE$	$K-EE_p$
AP	189±23	134±11
AK	155±23	118±15
$1P$	151±11	114±10
$1K$	134±9	98±20
$5P$	138±11	99±9
$5K$*	149±1	101±18

* Only two specimens were examined

(3.3)

$$f\left(\frac{a}{W}\right)=\frac{3\left(\frac{a}{W}\right)^{1/2}\left[1.99-\left(\frac{a}{W}\right)\left(1-\frac{a}{W}\right)\left(2.15-3.39\frac{a}{W}+2.7\frac{a^2}{W^2}\right)\right]}{2\left(1+2\frac{a}{W}\right)\left(1-\frac{a}{W}\right)^{3/2}}.$$

B – specimen thickness, S – distance between supports, a – notch depth, P_B – force corresponding to point B in Fig.2, W – test piece width.

If force $P_{\max}$ is substituted by P_p, fracture toughness $K-EE_p$ will be determined. Value P_p can be determined from the following equation

$$P_p = P_B\sqrt{\frac{A_p}{A_s}}, \tag{3.4}$$

Mean values of the obtained results are listed in Table 2.

4. Hardness measurement

Hardness measurement was carried out on longitudinal sections of specimens using Vickers method according to Polish Standards (PN-78/H-04360). Six series of specimens (designation AP, AK, $1P$, $1K$, $5P$, $5K$) cut out of the same places as for static tension tests were examined as well as the specimens cut out pipe knees (designation $AKK1$, $AKK2$, $1KK1$, $1KK2$, $5KK1$, $5KK2$). Hardness measurement of the specimens made of failed down pipe (designation $AM3$ and

Table 3. Mean values of hardness with 95% confidence ranges.

Specimen designation	HV
AP	162±1
AK	164±3
$1P$	183±8
$1K$	189±4
$5P$	181±4
$5K$	178±8
$AKK1$	217±7
$AKK2$	215±5
$1KK1$	213±6
$1KK2$	220±7
$5KK1$	217±7
$5KK2$	218±9
$AM3$	242±8
$AM4$	240±5

$AM4$) was also performed. Mean values of the obtained results (each calculated from five measurements) with 95% confidence range are listed in Table 3.

5. Metallographic examination

Metallographic examination was carried out on longitudinal and cross-sections of all the specimens using scanning electron microscope and light microscope. The specimen designations as well as places where the specimens were cut out from, are provided in Fig.1. Non-metallic inclusions were found on unetched sections of the specimens. The main form of these inclusions were uniformly arranged plastic silicates as well as sulphide and oxide inclusions.

Visible irregularities on external surfaces of down-pipes were found for used as well as for virgin down-pipes. The dimensions of these irregularities were similar for both types of down-pipes and they came up to 0.25mm. External surfaces of down-pipes were covered with annealing scale layers and corrosion products whose thickness reached 0.5mm. Visible irregularities were also found on internal surfaces of down-pipes. However, non-metallic layers accumulated on internal surfaces were different for both used and virgin down-pipes. Internal surfaces of virgin down-pipes were covered with annealing scale layers and corrosion products while for used down-pipes a tight intermediate layers have been observed between pipe surfaces and annealing scale layers. This intermediate layers of 0.1mm maximum thickness were formed as a result of interaction between steam and steel surface of down-pipes. Annealing scale layers on internal surfaces of down-pipes were covered with dust sediment. The different types of layers formed in service on internal surface of down-pipe are shown in Fig.3. The results obtained for specimens

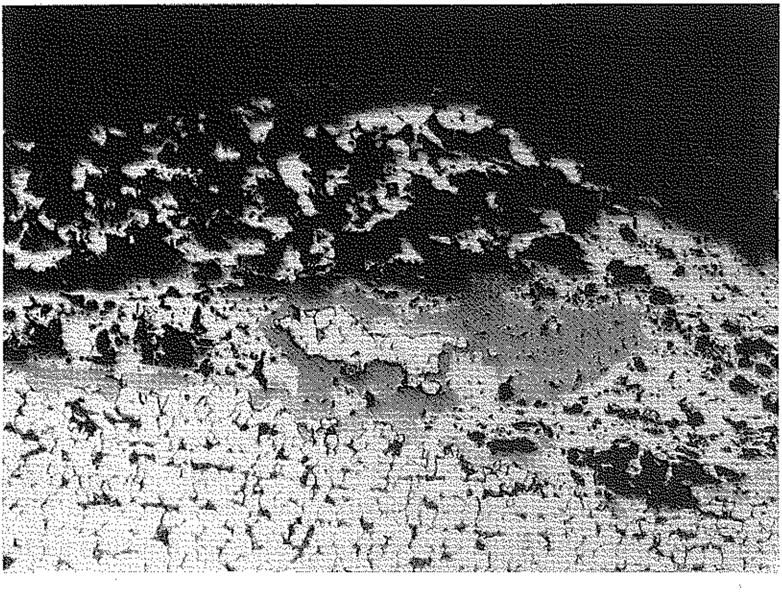

Fig. 3. Different types of layers. Internal surface of used down-pipe. Magn. 200x.

made of the portion of failed down-pipe were similar to those obtained for unfailed used down-pipes except for some cracks in the vicinity of fracture (Fig.4). Lack of sedimental and corrosion products inside these cracks shows that observed cracks can be considered due to failure.

The comparison of chemical composition of the tested steel with Polish Standards (PN-75/H-84024) allowed us to confirm the type of steel. It was K18 steel. Fine-grained and banded ferritic-perlitic structure has

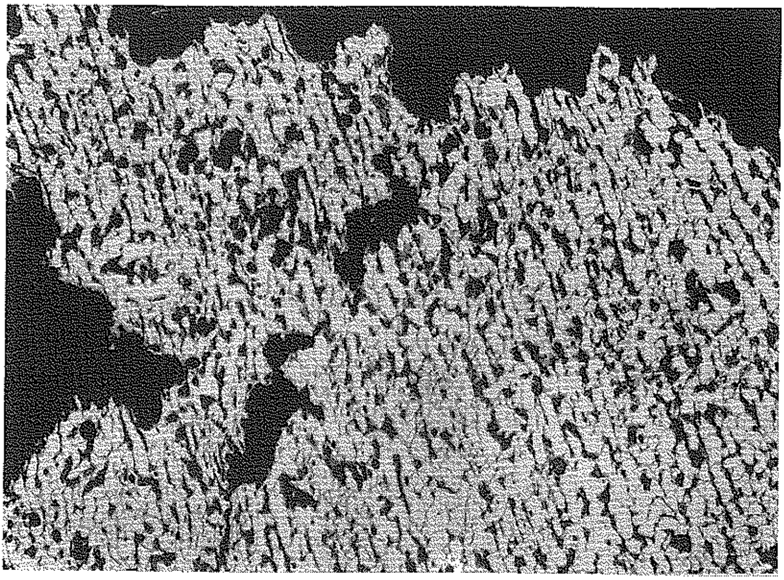

Fig. 4. Cracks in the vicinity of fracture. Failed down-pipe. Magn. 200x.

been observed during metallographic examination.

Fractography was carried out on the fracture surfaces of specimens which were broken during tension test. Essential differences between the specimens made of virgin and used down-pipes have been observed. Coincidence between fracture type and the value of damage parameter D_w obtained during tension tests has been found. The greater the value of damage parameter D_w, the greater the share of intercrystalline fracture. Ductile transcrystalline fracture has been observed for ruptured specimens made of virgin down-pipe while for specimens made of used down-pipes a mixed fracture (ductile transcrystalline and cleavage intercrystalline) has been found.

6. Analysis of the results

The mechanical properties of K18 steel according to Polish Standards (PN-74/H-74252) are the following: $R_e \geq 255$MPa, $R_m = 440-540$MPa, $A_5 \geq 21\%$. Comparison of these values with the values of corresponding properties obtained from experiments (Table 1) showed that only unit elongation (A_5) for specimens designated $1K$ and $5K$ was smaller than that required by Polish Standards. The other values of mechanical properties are in good agreement with Polish Standard demands. The damage parameter D_w for specimens designated $1K$ and $5K$ is also higher than for the other specimens and exceeds 35%. It means that the material of used down-pipes in the vicinity of knees has been damaged to a high extent. Thus these down-pipes must have been removed from service. This statement has been confirmed by fracture toughness examination.

No information on maximum hardness of down-pipe material can be found in Polish Standards. The maximum values of down-pipe hardness can be found in the Standards of other countries e.g. ČSN 412022 (173 HV), GOST 8731-74 (166 HV), ASTM A 210-69 (150 HV) for steels similar to $K18$ type. Assuming the maximum values of hardness according to ČSN 412022 or GOST 8731-71 it was concluded that only hardness of rectilinear portions of virgin down-pipe are smaller than those required by the mentioned Standards. In view of the results of hardness measurement of specimens made of virgin down-pipe knee also virgin down-pipe is not fit for service. Hardness of specimens made of virgin down-pipe knee is similar to that obtained for specimens made of down-pipe knees after having been in service during 56749 hours. It was probably caused by uncorrect process of pipe bending. Proper heat treatment after pipe bending would probably improve the material state. The results of preliminary experiments confirmed this supposition. The 18% decrease of hardness was found after stress-relief annealing while 30% – after normalization.

References

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Streszczenie

OCENA USZKODZENIA MATERIAŁU KOTŁOWYCH RUR OPADOWYCH

Przedstawiono wyniki badań rur opadowych kotła typu OR/32, który uległ awarii. Program badań obejmował statyczną próbę rozciągania, określenie odporności na pękanie, pomiary twardości i badania metalograficzne. Stwierdzono, że materiał rur eksploatowanych został uszkodzony w tak dużym stopniu, że nie nadają się one do dalszego użytkowania. Biorąc pod uwagę pomiary twardości można stwierdzić, że także rury nieeksploatowane nie nadają się do użytkowania z powodu niewłaściwego procesu ich gięcia.

Резюме

ОЦЕНКА ПОВРЕЖДЕНИЯ МАТЕРИАЛА КОТЕЛЬНЫХ ОПУСКНЫХ ТРУБ

Представлены результаты исследований опускных труб котла типа OR/32, который потерпел аварию. Програма исследований охватывает статическое испитание растяжения, определение стойкости на разрушение, измерения твердости и металлографические исследования. Констатировано, что материал эксплуатированных труб был поврежден в так большой степени, что они не пригодны для дальнейшей эксплуатации. Имея в виду измерения твердости, можно констатировать, что также неэксплуатированные трубы не годятся к эксплыатанции из-за неправильного процесса их изгиба.

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