DOI 10.1007/s11003-017-9991-z

Materials Science, Vol. 52, No. 4, January, 2017 (Ukrainian Original Vol. 52, No. 4, July–August, 2016)

DETERMINATION OF THE DEGREE OF DEGRADATION OF STEELS OF STEAM PIPELINES ACCORDING TO THEIR IMPACT TOUGHNESS ON SPECIMENS WITH DIFFERENT GEOMETRIES OF NOTCHES

H. V. Krechkovs'ka[1] **and O. Z. Student**[1,2]

UDC 620.17

We analyze the characteristics of impact toughness KCU and KCV of 15Kh1M1F and 12Kh1MF heat-resistant steels by using Menage and Charpy specimens, respectively, taken from the straight sections of the steam pipelines of a thermal power plant, their welded joints, and different zones of the bends. We reveal the specific features of their behavior depending on the period of operation and the number of shutdowns of the units. It is shown that, as a result of the in-service degradation of the metal, the KCU/KCV ratio significantly increases due to a more intense reduction of the crack-growth resistance as compared with the crack initiation resistance.

Keywords: heat-resistant steels, long-term service, degradation, brittle-fracture resistance, impact toughness.

The currently working branch standards regulate the resistance of structural materials of power-generating installation to brittle fracture mainly according to their impact toughness KCU measured on Menage specimens with a notch radius of 1 mm [1, 2]. However, in recent years, the researchers often prefer to use the Charpy specimens characterized by a sharper stress concentrator (with a notch radius of 0.25 mm) whose impact toughness KCV is lower than KCU. However, despite the correspondence of the values of KCU of heat-resistant steels to routine requirements, the corresponding values of KCV are often unsatisfactory [3]. This difference is explained by the separation of the total fracture energy of specimens into the energies of crack initiation and crack propagation. The fraction of the energy of crack initiation is lower for specimens with sharp notch. Therefore, by using the specimens with different geometries, it is possible to separate the effects of various factors on different stages of the fracture process.

Among these factors, we can mention, in particular, the degradation of steels as a result of their long-term operation manifested, first of all, by the decrease in the brittle-fracture resistance. In [4], the method of separation of the total fracture energy into parts corresponding to the stages of crack initiation and crack propagation was used for the determination of the fracture toughness KCV. It was discovered that the influence of the in-service degradation of steels of gas mains on the decrease in crack-growth resistance is more pronounced. This was explained by the development of dispersed damage in the material [5, 6] and the influence of hydrogen absorbed by the metal in the course of electrochemical reaction of humid gases with the inner surface of the pipe on the analyzed process [7].

For heat-resistant steels, it is necessary to take into account the fact that the long-term high-temperature operation leads to the formation of pores [8] and cracks [9, 10]. Therefore, the evaluation of brittle-fracture resistance

[1] Karpenko Physicomechanical Institute, Ukrainian National Academy of Sciences, Lviv, Ukraine.

[2] Corresponding author; e-mail: student@ipm.lviv.ua.

Translated from Fizyko-Khimichna Mekhanika Materialiv, Vol. 52, No. 4, pp. 106–110, July–August, 2016. Original article submitted March 10, 2016.

 1068-820X/17/5204–0566

should be preferably performed on specimens with sharp concentrators. Thus, in particular, the higher sensitivity to the in-service degradation of steels of steam pipelines of thermal power plants was established in [3] for the Charpy specimens (as compared with the Menage specimens). In what follows, we compare the results of testing for impact toughness of heat-resistant steels of steam pipelines in the initial state and after operation obtained for specimens with different geometries of the notches.

Object and Method of Investigations

We estimated the influence of the long-term operation of the metal of three structural parts of steam pipelines of a thermal power plant [welded joints, rectilinear sections (RS), and bends] on the impact toughness with regard for the duration of operation τ_{op} and the number of shutdowns of the technological process N. Moreover, we analyzed the data for 15Kh1M1F steel and its welded joints in the intact state (from the pipes of stock and repair welded joints) and after $\sim 2 \cdot 10^5$ h of the operation. For the same duration of operation, the base metal (BM) was characterized by different numbers of shutdowns of the technological process (501 and 576). The properties of the metal from different zones of welded joint were estimated for larger numbers of shutdowns. In addition, we analyzed the brittle-fracture resistance of 12Kh1MF steel from the rectilinear sections and various zones of bends after $\sim 2.7 \cdot 10^5$ h of operation.

The impact toughness of the metal was determined according to the requirements of GOST 9454-78 [11] on a pendulum hammer of the IO-5003 type. We analyzed the values obtained according to the results of testing of the Menage and Charpy specimens. The anisotropy of the characteristics of 15Kh1M1F steel from rectilinear sections of the pipe was estimated on specimens with axial $(L-R)$, tangential $(C-L)$, and radial $(R-C)$ orientations cut out from the central part of the cross section of the pipe. The impact toughness of the metal of heat-affected zone (HAZ) and the metal of the weld (WM) was determined on specimens with axial $(L-R)$ orientation. The gradient of characteristics of 12Kh1MF steel on different levels across the thickness of the wall in bends of the pipe was found on specimens with tangential $(C-L)$ orientation cut out from rectilinear sections and stretched (SZ), compressed (CZ), and neutral zones (NZ) of the bends of steam pipelines.

Results and Their Analysis

The influence of various factors on the brittle-fracture resistance of steels and their welded joints was estimated, on the one hand, according to the values of KCU (Tables 1 and 2) and, on the other hand, according to the ratio $\alpha = KCU/KCV$ (Figs. 1 and 2). Thus, in particular, independently of the geometry of the notch, the impact toughness of the specimens made of 15Kh1M1F steel for all analyzed orientations is definitely lower for a larger number of shutdowns of units in the course of operation, which corresponds to the intensification of the process of degradation of the metal under these conditions. However, if we consider the ratio α (which increases), then it becomes clear that the fraction of energy losses for the propagation of the fracture decreases (Fig. 1a). In this case, for the intact steel, the indicated ratio varies from 1.20 to 1.38 (depending on the orientation of specimens). At the same time, after $\sim 2 \cdot 10^5$ h of operation, this ratio increased and attained its maximum value equal to 2.53 after 576 shutdowns of the technological process for the specimens with radial orientation. In other words, the energy losses in the stage of propagation of fracture decrease almost twice. In addition, we note that the coefficient α determined according to the characteristics measured on the specimens with radial orientation reproduces the changes in the state of the metal in the process of operation with the maximum possible sensitivity.

Table 1. Impact Toughness of the Heat-Resistant 15Kh1M1F Steel of Steam Pipelines of Thermal Power Plant in the Intact State and after $\sim 2 \cdot 10^5$ h of Operation

Number of shutdowns of the units	Intact state			501	576			Orientation of specimens
Zone of assessment	BM	HAZ	WM	BM	BM	HAZ	WM	
KCU, MJ/m^2	2.02	2.3	3.25	0.81	0.64	0.5	0.7	Axial
	1.73	–	–	0.63	0.38	–	–	Radial
	1.45	–	–	0.38	0.23	–	–	Tangential
KCV, MJ/m^2	1.68	1.77	2.6	0.65	0.48	0.26	0.4	Axial
	1.25	–	–	0.42	0.15	–	–	Radial
	1.05	–	–	0.24	0.12	–	–	Tangential

Table 2. Impact Toughness of 12Kh1MF Steel from Various Zones of the Bends after Operation for $\sim 2 \cdot 10^5$ h in Steam Pipelines of Thermal Power Plants Determined on Specimens with Tangential Orientation

Bending zone	RS			SZ			CZ			NZ		
Location of specimens in the cross section of the pipe	OS	CCS	IS	OS	CCS	IS	OS	CCS	IS	OS	CCS	IS
KCU, MJ/m^2	1.65	1.75	1.87	0.25	0.65	1.13	1.34	1.45	1.59	1.45	1.57	1.79
KCV, MJ/m^2	1.12	1.25	1.28	0.1	0.3	0.56	0.58	0.69	0.81	0.89	1.08	1.08

Comments: OS is the outer surface of the pipe, CCS is the center of its cross section, and IS is the inner surface.

We compared the values of KCU and KCV measured on specimens with axial orientation for the metal of welded joint of 15Kh1M1F steel (Table 1 and Fig. 1b). Independently of the geometry of the notch in the intact specimens, the highest fracture resistance was exhibited by the weld metal, which can be regarded as an indication of the high quality of the applied technology of welding. The coefficient α varied within the range 1.2–1.3 for all zones of the intact welded joint (Fig. 1b). However, for the metal after operation, both characteristics of impact toughness are noticeably decreased even for the specimens with axial orientation whose susceptibility to degradation is minimum (Table 1). Moreover, after operation, the resistance of the metal of the weld (for which the value of KCV in the intact state was maximum) to the propagation of fracture became lower than for the base metal.

By analyzing the changes in α, we made the conclusion that the main contribution to the decrease in the brittle-fracture resistance is made by the drop of energy of crack propagation, especially for the metal of the heat-

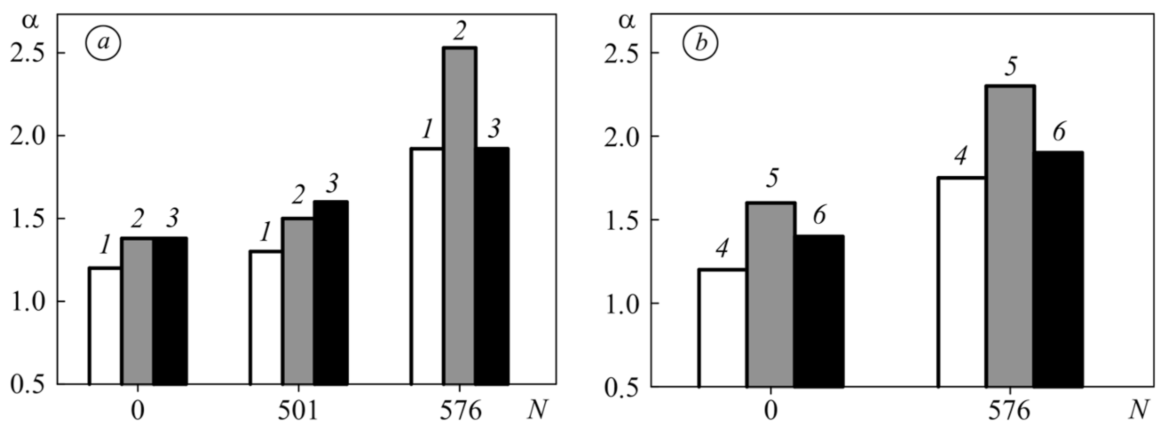

Fig. 1. Values of the coefficient α for different numbers of shutdowns of the units N for $\sim 2 \cdot 10^5$ h of operation of 15Kh1M1F steel (a) and its welded joint (b) in steam pipelines of thermal power plants with regard for the orientation of the specimens [(a): (1) axial; (2) radial; (3) tangential] and the differences between the zones of welded joints [(b): (4) base metal; (5) heat-affected zone; (6) weld metal] obtained for the specimens with axial orientation.

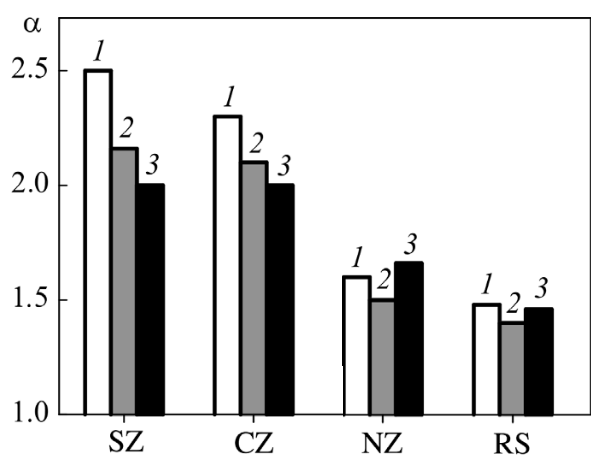

Fig. 2. Coefficient α for different zones of the bends of 12Kh1MF steel after operation for $\sim 2.7 \cdot 10^5$ h in the steam pipelines of thermal power plants with regard for the location of tangential specimens across the thickness of the pipe wall [(1, 3) near the outer and inner surfaces of the pipe and (2) in the central part of its cross section).

affected zone and the metal of the weld (Fig. 1b). Thus, for the welded joints, we also confirmed a significant increase in α in the degraded metal caused by the more intense decrease in the crack-growth resistance.

The analysis of the results of testing for impact toughness of the specimens with tangential orientation taken from different zones of the bends of a steam pipeline made of 12Kh1MF steel shows that, in the vicinity of the outer surface of the pipe, the values of *KCU* and *KCV* are minimum independently of the analyzed zone of the bend (Table 2). This is explained by the creep defects formed in the surface layers of the pipe with typical orientation along its axis. Since the number of defects of this kind is larger in the stretched zone of the bend (due to more favorable conditions for creep as compared with the other zones), the resistance of the metal of this zone to fracture turned out to be minimum.

We also recorded an almost invariable value of the coefficient $\alpha \approx 1.5$ for the metal of the neutral zone and rectilinear sections of the bend practically in the entire cross section of the pipe wall (Fig. 2). At the same time, in the metal of the stretched and compressed zones (especially near the outer surface of the pipe), the values of this coefficient became as high as 2.5 and 2.3, respectively. Thus, in analyzing the bend after operation, we also revealed a similar trend of increase in the coefficient α caused by the operation of the metal.

At present, there are no standard specifications concerning the determination of the values of KCV via the known values of KCU. In [12], the empirical formula $KCU = 1.25KCV$ was used for the materials of ammonia pipelines. This formula satisfactorily describes the data obtained for the intact steels of steam pipelines and their welded joints (the coefficient α varies from 1.2–1.3 for the axial specimens of the base metal, the heat-affected zone, and the metal of the weld to 1.38 for the radial and tangential specimens).

We also note that KCU is regulated for steels in the intact state. At the same time, the values of KCV are more sensitive to the in-service degradation. Therefore, it is necessary to be able to recalculate (at least approximately) one value via the other (experimentally obtained) value. The presented data enable us to do this with regard for the following two aspects:

First, the coefficient α strongly depends on the orientation of the specimens and takes the highest value for the radial specimens (under certain conditions, it may become equal to 2.5). Under the same conditions for specimens with axial and tangential orientations, we get the values equal to 1.33 and 1.92, respectively. Therefore, in order to get the maximum sensitivity to changes in the state of the metal in the course of operation, one should prefer the use of radial or tangential specimens.

Second, the coefficient α is higher after a more intense degradation of a metal, which was demonstrated by an example of 15Kh1M1F steel for various zones of welded joints after the maximum number of shutdowns of the units of thermal power plants. In the last case, we used the specimens with the axial orientation. Here, the coefficient α for the metal of the heat-affected zone increased after operation to 1.92 and, for the metal of the weld, to 1.75. At the same time, in the intact state, its values insignificantly differ from the values typical of the base metal.

On the basis of the results of analysis of both characteristics of brittle-fracture resistance, we recommend to use the much higher values of the coefficient α than for the intact metal (within the range 2.0–2.5) for the evaluation of KCV of the metal after operation (according to the experimentally determined value of KCU).

CONCLUSIONS

The characteristics of impact toughness KCU and KCV for heat-resistant steels determined on Menage and Charpy specimens reveal the same trend to decrease in the course of their long-term operation. However, the resistance to fracture caused by V-like stress concentrators decreases more intensely, than for the U-notches. Quantitatively, this observation is characterized by the coefficient $\alpha = KCU/KCV$ varying for the metal after operation within the range 1.5–2.5 as compared with the range 1.2–1.4 for the intact metal. The values of this coefficient increase with the intensification of the in-service degradation of the metal for the radial and tangential specimens.

REFERENCES

1. GOST 5520-79. *Rolled Sheet of Carbon, Low-Alloy, and Alloyed Steels for Boilers and Vessels Operating under Pressure. Specifications* [in Russian], Izd. Standartov, Moscow (1979).
2. SOU-N MPE 40.1.17.401:2004. *Normative Act. Manual. Monitoring of the Metal and Extension of the Service Life of the Main Elements of Boilers, Turbines, and Pipelines of Thermal Power Plants. Typical Instruction* [in Ukrainian], GRIFRE OEP, Kiev (2005).
3. O. Z. Student, H. V. Krechkovs'ka, A. D. Markov, "Influence of thermal changes in a high-temperature hydrogen-containing medium on the degradation of 15Kh1M1F steel of steam pipelines of thermal power plants," *Nauk. Notat.*, Issue 42, 296–304 (2013).

4. G. Gabetta, H. M. Nykyforchyn, E. Lunarska, P. P. Zonta, O. T. Tsyrulnyk, K. Nikiforov, M. I. Hredil', D. Yu. Petryna, and T. Vuherer, "In-service degradation of trunk gas pipeline Kh52 steel," *Fiz.-Khim. Mekh. Mater.,* **44**, No. 1, 88–99 (2008); ***English translation**: Mater. Sci.,* **44**, No. 1, 104–119 (2008).
5. E. I. Kryzhanivs'kyi and H. M. Nykyforchyn, "Specific features of the hydrogen-induced corrosion degradation of steels of gas and oil pipelines and oil storage reservoirs," *Fiz.-Khim. Mekh. Mater.,* **47**, No. 2, 11–20 (2011); ***English translation**: Mater. Sci.,* **47**, No. 2, 127–136 (2011).
6. H. M. Nykyforchyn, K.-J. Kurzydlowski, and E. Lunarska, "Hydrogen degradation of steels in long-term service conditions," in: S. Shipilov, R. Jones, J.-M. Olive, and R. Rebak (editors), *Environmentally Induced Cracking of Materials. Prediction, Industrial Developments, and Evaluations,* Vol. 2, Elsevier, Amsterdam (2007), pp. 349–362.
7. O. T. Tsyrul'nyk, Z. V. Slobodyan, O. I. Zvirko, M. I. Hredil', and N. M. Nykyforchyn, "Influence of the operation of Kh52 steel on corrosion processes in a model solution of gas condensate," *Fiz.-Khim. Mekh. Mater.,* **44**, No. 5, 29–37 (2008); ***English translation**: Mater. Sci.,* **44**, No. 5, 619–629 (2008).
8. D. Milanović, V. Šijaćki-Źeravćić, A. Marković, and M. Radović, "Assessment of the residual life of a pipeline bend by metallographic measurements of cavitation damage—determination of the A-parameter," *Fiz.-Khim. Mekh. Mater.,* **30**, No. 5, 65–72 (1994); ***English translation**: Mater. Sci.,* **30**, No. 5, 589–597 (1995).
9. H. M. Nykyforchyn, O. Z. Student, H. V. Krechkovs'ka, and A. D. Markov. "Evaluation of the influence of shutdowns of a technological process on changes in the in-service state of the metal of main steam pipelines of thermal power plants," *Fiz.-Khim. Mekh. Mater.,* **46**, No. 2, 42–54 (2010); ***English translation**: Mater. Sci.,* **46**, No. 2, 177–189 (2010).
10. H. V. Krechkovs'ka, "Fractographic signs of the mechanisms of transportation of hydrogen in structural steels," *Fiz.-Khim. Mekh. Mater.,* **51**, No. 4, 67–70 (2015); ***English translation**: Mater. Sci.,* **51**, No. 4, 509–513 (2016).
11. GOST 9454-78. *Metals. A Method of Testing for Impact Bending at Low, Room, and High Temperatures* [in Russian], Izd. Standartov, Moscow (1978).
12. V. D. Myndyuk, M. O. Karpash, A. V. Yavors'kyi, I. V. Rybits'kyi, and E. R. Dotsenko, "Experience of estimation of the degradation of materials of the pipes of ammonia pipelines according to the results of nondestructive testing of their mechanical characteristics," *Tekh. Diagnost. Nerazrush. Kontr.,* No. 2, 30–35 (2012).