Non-destructive testing

ULTRASONIC DIAGNOSTICS OF SERVICE DEFECTS IN STRUCTURES OF OIL AND GAS INDUSTRY

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Results of diagnostics of petrochemical equipment conducted by specialists of the E.O. Paton Electric Welding Institute during the last 10 years were analyzed. The most characteristic regions of the apparatuses susceptible to service damage were determined, and methods for testing them by ultrasonic inspection were suggested. It is noted that the most frequent error in repair of welded joints on heat-resistant steels is their incomplete tempering in the zones of contact of elements made from different structural materials. Recommendations are proposed to select materials at replacement of equipment that exhausted its specified service life.

Keywords: *welded structures, service defect, diagnostics, low-temperature hydrogen delamination, crack, high-temperature cracking, heat treatment, medium impact, ultrasonic testing*

In connection with an abrupt increase of energy carrier prices and wear of the main equipment, a considerable part of enterprises of oil and gas industry are in need of technical re-equipment. Performance of reconstruction is associated primarily both with the need to reduce power inputs in manufacture of a particular type of product, and with increase of the depth of processing the used raw materials.

In view of the fact that a significant part of expensive equipment has been in operation for 20–30 years, only its stage-by-stage upgrading can be considered.

Hence the need for further use of part of processing equipment which has exhausted its specified service life, which, in its turn, requires development of more accurate means of non-destructive testing (NDT) and assessment of the possibility of its further operation.

Sufficiently advanced methods of ultrasonic (US) testing have been introduced over the recent years, which are based on analysis of the time of arrival of diffracted US waves reflected from sharp edges of internal defects. These methods, conditionally designated as TOFD, SAFT, tandem, etc. allow finding cracks, corrosion, hydrogen and other cracking which develop in service.

The main service conditions of welded structures usually include the contacting medium, loads, temperature, radiation and time of their aggregate effect.

Load influence is differentiated by duration of impact and rate of application (static, cyclic, dynamic, etc.). Loads may arise both from external impact and inherent deformations at structural transformations and non-uniform heating. In combination with the shape of welded joints and structural elements, complex local stresses are induced, which affect the strength and further performance of welded structures.

Distinction is made between the cyclic and dynamic nature of loading, which is also regarded as one of the most heavy-duty modes of welded structure operation. Many steels are sensitive to the rate of load application, particularly in the presence of stress raisers, which, in its turn, requires performance of heat treatment after welding and making more stringent requirements to norms of NDT of critical elements.

To ensure welded structure stability under the impact of high compressive forces, thickness of used metal and shape of structural elements have the main role. Temperature requirements are also significantly dependent on the material. For instance, ferrous metals are characterized by lower strength in the presence of stress raisers, which predetermines certain requirements to selection of metal, its heat treatment and to admissible defect dimensions.

A special situation arises in the region of high operating temperatures of equipment, where correct selection of the respective high-temperature steel is important. Otherwise it may lead to a change in the material strength and ductility, its structure, thermal embrittlement and fracture at long-term impact.

Medium influence on the structure is even more diverse. For instance, metal corrosion in combination with loads leads to corrosion cracking and fatigue. Temperature and load influence make the situation even more difficult.

Given below are the results of technical diagnostics of petrochemical industry equipment, conducted by PWI staff members over the last ten years.

In addition to acquisition of data on the characteristic defects and improvement of NDT procedures, also various aspects of possible degradation of service properties in structural materials and welded joints in corrosive media at normal and higher temperatures were studied.

Corrosion damage of petrochemical equipment (PCE) in petroleum processing is caused by its inevitable impurities [1]: sulphur-, chlorine-, oxygen-organic compounds, local water and products of their thermal decomposition. Corrosiveness of the formed components is determined both by raw material composition, and mode parameters of the technological processes in its processing (pressure, temperature, etc.). The following factors causing PCE failure, can be named:

- decomposition of sulphide compounds of oil and chlorides, leading to formation of corrosive components, such as hydrogen chloride and hydrogen sulphide;
- presence of water electrolytic media, promoting corrosion cracking, low-temperature hydrogen cracking, low-temperature hydrogen delamination and hydrogen embrittlement of steels;
- application of alkali agents promoting development of caustic brittleness of welded joints of ferrous metals;
- formation of hydrogen sulphide at high temperatures leading to acceleration of the corrosion processes;
- increase of cooling water aggressiveness;
- formation of acid compounds (naphthenic acid);
- presence of two-phase media, etc.

Considering the mobility of the corrosion media during petroleum processing, conditions are also in place for development of combined forms of corrosion failure (combination of pitting corrosion with corrosion cracking, intercrystalline stress corrosion cracking, etc.).

Many years of inspection of PCE, which operated in a broad range of temperatures, pressure, medium corrosiveness, content of H_2, H_2S, etc., allowed revealing a large number of cases of low-temperature lamellar-hydrogen damage of apparatus bodies, made from low-carbon and low-alloyed steels. Figure 1 shows a histogram of damage distribution by steel grades against the total number of studied cases. Figure 1 gives a good idea of the actual condition of the equipment on a qualitative level. Metal structures made from steels of 16GS and 09G2S grades show the highest susceptibility to low-temperature lamellar hydrogen delamination, unlike apparatuses made from steel 20 and St3sp (killed) grades.

Analysis of PCE technical condition shows that the difference in the degree of damageability is mainly related to peculiarities of structural texture of metal rolled stock [2] and diffusion processes running along the boundaries of non-metallic inclusion location [3, 4]. This is another confirmation of the need of both reconsidering the class of steels suitable for manufacture of PCE operating in hydrogen sulphide media, and applying US testing procedures based on recording the diffracted US vibrations.

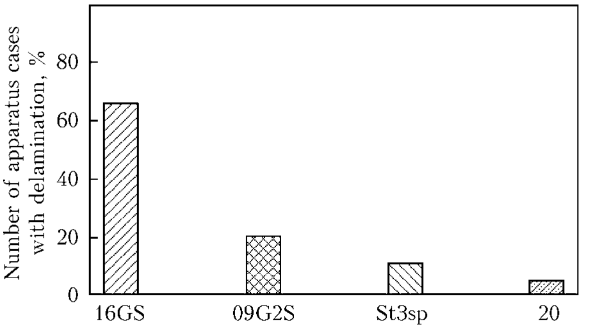

Figure 1. Fraction of apparatus cases in which corrosion damage was detected

A considerable number of cases was found in practice, when equipment manufactured from steels of 09G2S and 16GS grades without knowing more precisely the requirements to their categories, was rejected already after 2–4 years of service. For metal rolled stock with a pronounced zonal segregation occurring at depths equal to half or one third of sheet thickness, laminar cracking develops in the zone characterized by considerable anisotropy of strength properties in the thickness direction. This type of damage may differ by the rate of its propagation in the sheet plane, and can be of a stepped or plane nature. As damage accumulates, deformation of the thinner wall under the impact of internal pressure can be observed later on.

US inspection of metal rolled stock by P-Scan system showed that at increased sulphur content and more uniform distribution of sulphide inclusions by sheet thickness lamellar cracking mostly is of a stepped nature (Figure 2).

Lamellar hydrogen cracking in PCE made from low-alloyed steels 16GS, 09G2S and low-carbon steel St3sp5, affected gas absorbers, which had been in operation for more than 20 years at 30–50 °C temperatures in media containing 15 % water solution of monoetalomin (MEA), hydrocarbon gas, as well as H_2 and H_2S in different weight percent.

Figure 3 gives diffractograms of sections of scanning an absorber body from 09G2S steel 48 mm thick. The examined section was removed from the point of corrosive medium input. It is seen that the process of lamellar hydrogen cracking can be both of a plane and step-like nature, with predominant rate of propagation in the direction of rolled stock plane. Step-like nature of cracking in this case is determined by a considerable thickness of the segregation zone. Figure 4 shows the section of scanning the absorber body, located opposite the hydrogen-containing gas input (steel 16GS 28 mm thick). The Figure quite clearly shows two layers sub-

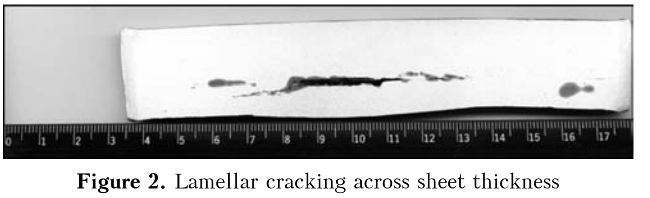

Figure 2. Lamellar cracking across sheet thickness

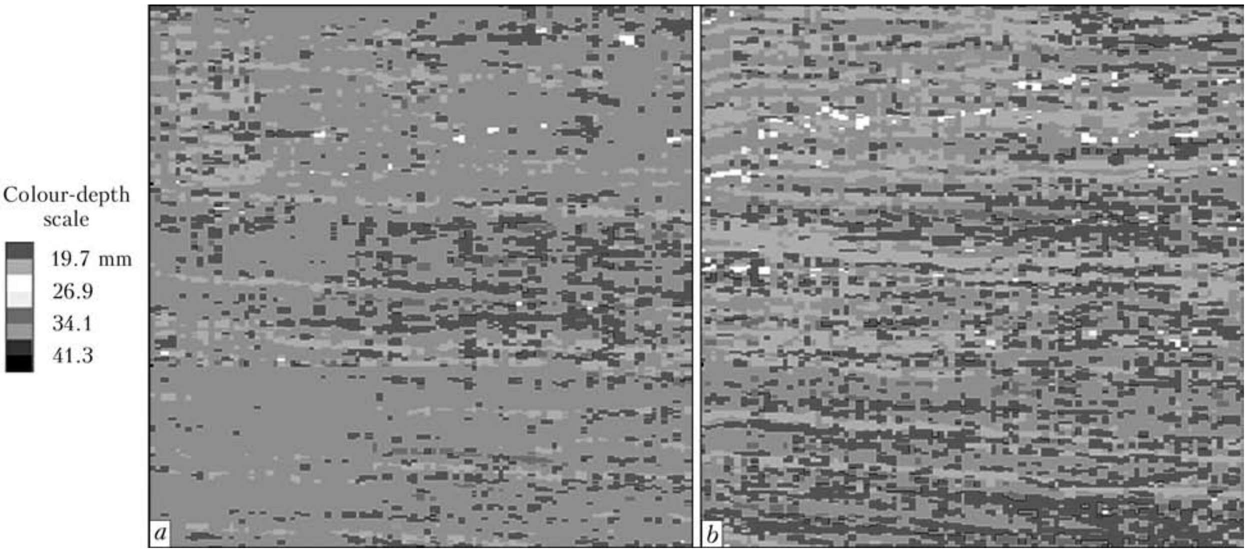

Figure 3. Monitoring of growth of discontinuities in the metal of absorber body from 09G2S steel of 48 mm thickness during one year of operation (reference section of 750 × 750 mm size): *a* — initial scanning; *b* — repeated scanning of the same section after one year

jected to lamellar hydrogen cracking, which are located at depth of 12–16 mm and 18.5–24.0 mm from the outer surface. Layer at the depth of 18.5–24.0 mm is at the final stage, which is indicated by step-like development of the process of cracking along the boundaries of developed discontinuities and visible plastic deformation of the thin wall under the impact of pressure of molised gas in the cavities. Layer at the depth of 12–16 mm is subjected to less intensive cracking. The latter is attributed to its shielding by the layer at the depth of 18.5–24.0 mm.

Section of scanning the body of an absorber made from steel St3sp5 12 mm thick has certain differences in the nature of lamellar cracking from those considered above. As is seen from Figure 5, the dimensions of discontinuities in the sheet plane are somewhat smaller than in Figures 3, 4, and step-like development of lamellar cracking comes to the inner surface.

In this case the predominant development of hydrogen cracking process occurs in the direction of sheet thickness. A similar cracking process is observed for steel 20, which is also associated with the features of structural texture of metal rolled stock and diffusion processes running along the boundaries of non-metallic inclusions.

During diagnostic inspection of PCE special attention was paid to zones subjected to the most intensive lamellar hydrogen cracking. These, first of all, are the region of input of hydrogen-containing products; sections along media interfaces; stagnation zones; regions of plastic deformations and residual stress zones.

In the region of hydrogen-containing product input, in addition to relatively high content of hydrogen, the impact of the flow (jet) is always present to varying degrees, which promotes diffusion saturation of metal in the contact region, and, as a consequence, leads to higher rates of development of lamellar cracking compared to other parts of the apparatus. As an example, Figure 6 gives ultrasonic evaluation of discontinuities in the section of the column body. The above section was located opposite the inlet for MEA water solution into the apparatus. Unlike other sections of the column, which also had lamellar damage in the metal, the region given in the Figure features a considerable intensity of hydrogen cracking development. As a rule, such regions are of a local nature, allowing their repair to be performed without column dismantling. In recent years cases of complete replacement of shells in product input zones have become more frequent in local petroleum processing enterprises, which except for a considerable increase of the cost of repair operations, does not in any way influence further performance of the equipment.

A quite frequent case is a combination of pitting corrosion with low-temperature hydrogen delamination of metal along the interface of media phase states. As a rule, such locations are in the lower parts of the

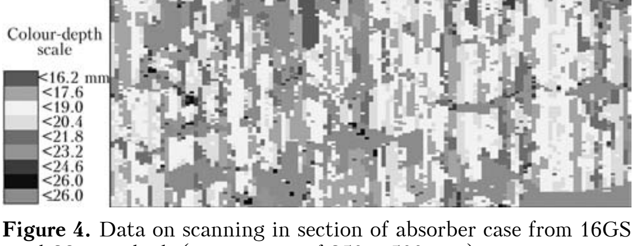

Figure 4. Data on scanning in section of absorber case from 16GS steel 28 mm thick (section size of 250 × 500 mm)

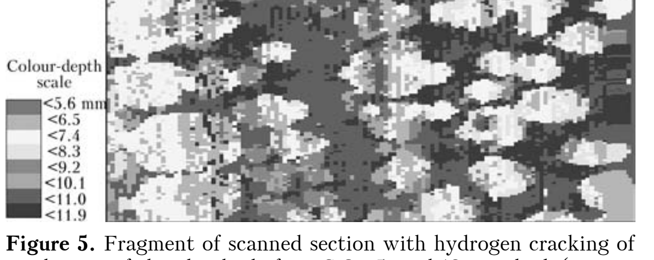

Figure 5. Fragment of scanned section with hydrogen cracking of an element of absorber body from St3sp5 steel 12 mm thick (section size of 250 × 250 mm)

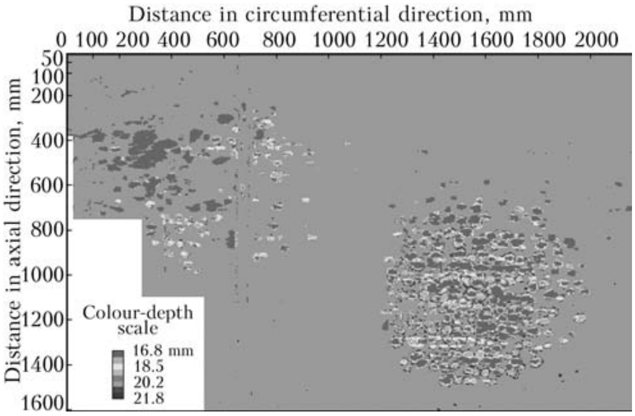

Figure 6. Data of scanning in the section of column body opposite to product input (MEA water solution) (section size of 1600 × × 2000 mm, metal thickness of 22 mm)

apparatus. In this case for separators and heat exchangers the main corrosion zone is located along the apparatus body generatrix on the level of fluctuation of media interfaces or in the wetting zones.

So, Figure 7 gives a combined form of corrosion damage of separator body in the stagnation region which forms because of the protruding nozzle.

Characteristic regions prone to possible intensive low-temperature lamellar cracking in hydrogen-containing media also include regions with residual stresses (for instance, zones of maximum plastic deformations in stamping of elliptical bottoms, locations of welding auxiliary elements to the body, etc.).

Influence of residual stresses in welded joints is rather clearly manifested in diagnostics of alkali tanks, made from steels of 16GS and 09G2S grades. In these apparatuses which are past their specified service life at temperatures above 50 °C and alkali concentration of not less than 10 %, central longitudinal cracks are periodically found in T-shaped welded joints of up to 10 mm and greater depth (in a number of cases cracks were observed in near-weld zones of field welds). When ordering this type of equipment, it is recommended to specify its high tempering.

As regards high-temperature hydrogen-sulphide corrosion, this type of damage is observed at service temperatures above 260 °C in transfer pipelines, furnace coils and heat exchangers connected to them, in the form of fine shallow wide pits connected to each other. In the pure form such a kind of corrosion fracture is rather easily detectable, however, the high propagation rate requires development of special approaches to its NDT. In the combined variant, this kind of corrosion damage is the most critical in connection with development of welded joint cracking in the points of fine linear porosity clusters and development of through-thickness cracks. Influence of residual stresses in these cases is particularly high. Despite the fact that practically all the power equipment is made from chromium-molybdenum steels requiring compulsory heat treatment after welding, it is not always possible to eliminate residual stresses completely. During this examination period, PWI experts found a considerable number of cases of welded joint cracking leading to emergency shutdown of critical power equipment and installations as a whole, because of development of through-thickness cracks and product leakage practically in all the petroleum-processing plants of Ukraine. So, Figure 8 gives a section of the weld with a developed crack one year after performance of repair work in power heat exchanger.

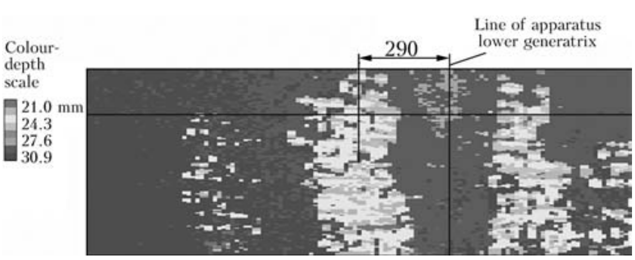

Figure 7. Data on scanning metal with corrosion damage in stagnation zone of separator 32 mm thick from steel 16GS (section size of 500 × 1750 mm)

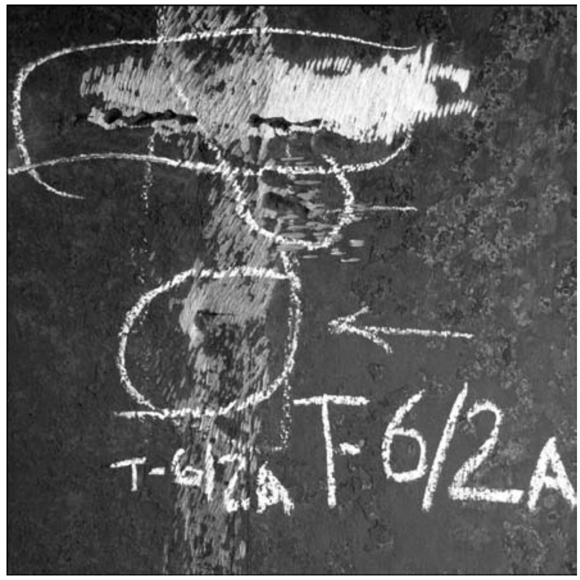

Figure 8. High-temperature cracking of weld of heat-exchanger from 12KhM steel in repair welding zone

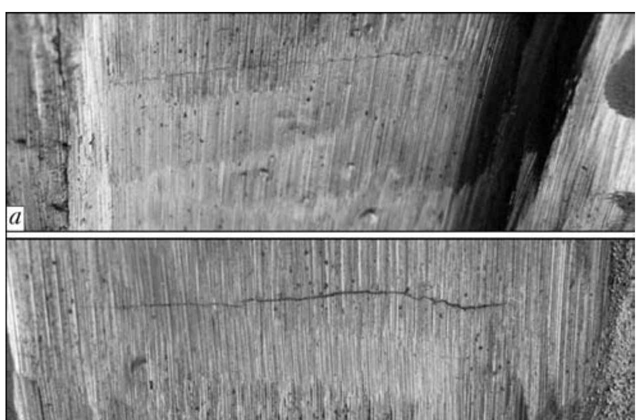

Figure 9. High-temperature cracking of circumferential welds in zone of joint of flange (steel 15Kh5MU) to heat exchanger shell (12KhM) of various thickness: *a* — weld joining heat exchanger shell to bottom of 35 mm thickness; *b* — weld in the zone of joint of 45 mm thickness shell to flange

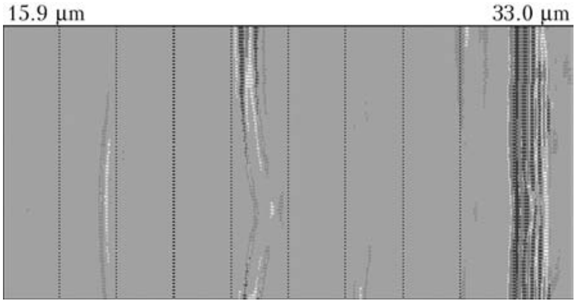

Figure 10. Example of TOFD measurement of a crack in a welded joint which initiated through cracking of facing cladding layer

The most characteristic elements, subjected to such damage, are sections of welded joints in the locations of welding branchpipes, elements of transfer pipelines and heat exchanger shells to flanges. In most of the cases appearance of defects in these joints is related to incomplete tempering of the welded joint because of the difference of joined element materials (Figure 9).

In heat-exchanger equipment the length of such defects is usually not greater than weld width because of the presence of residual compressive stresses in the HAZ metal, restraining their development in this direction. Such limitations are absent in the thickness direction, which is what leads to appearance of through-thickness «short» cracks.

For transfer pipelines such cracking usually occurs along the line of fusion of flange to pipe weld. In this case, bending stresses due to thermal expansion of the pipeline have a quite significant role, which is what leads to partial or complete rupture.

Intercrystalline cracking of protective facing welds and the main cladding layer of the equipment, made from a bimetal, also is a quite frequent phenomenon in petrochemical production. On the other hand, while the depth of intercrystalline cracking of the cladding layer of bimetal is usually limited by cladding thickness due to the presence of a thin martensite interlayer on the boundary of transition to alloyed metal, in facing welds it largely depends on correct selection of welding consumables and welding technology. Several cases were recorded when such violations resulted in extended cracks of a length greater than half of the section [5]. As an example Figure 10 gives the result of measurement of the depth of such a crack using TOFD method. It should be noted that US technology allows a sufficiently accurate (with 1–2 mm error) measurement of crack dimensions, the information about which is required for assessment of tested facility performance. In regular practice of diagnostic examinations crack dimensions are evaluated by cutting out, which involves a number of technological difficulties. It should be noted that application of TOFD method in structures with a clad surface has a number of special features, so that specialists conducting the measurements are required to have certain qualifications and experience. A higher susceptibility of 10Kh18N10T steel to this type of damage unlike 08Kh13 steel should be noted.

Fatigue fracture, except for tanks, is a quite rare phenomenon in petrochemistry. On the other hand, in a number of enterprises a growth of process cracks was registered in welded joints of supporting parts and coverplates with their propagation into the main body of coke chambers under the impact of thermal cyclic stresses and vibrations.

As regards brittle fractures, practically all the cases occurred after performance of repair-reconditionning operations at incomplete removal of the defect with its subsequent remelting. In most of the cases brittle fracture was caused by strain ageing and hydrogenation of metal ahead of the front of incompletely removed defect. Over the recent years such fractures occurred in repair of vacuum columns in several enterprises of Ukraine and Russia.

CONCLUSIONS

1. Characteristic PCE zones the most prone to damage in service were analyzed. Recommendations are proposed on requirements to selection of structural materials for PCE manufacture and repair, allowing lowering the risk of equipment service damage.

2. An advantage of ultrasonic computerized systems of monitoring the growth of service defects in PCE diagnostics is shown.

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