Technical paper:

Metrological aspects of assessments of the quality of tubes used as fuel cladding and condenser tubes

In this article the author looks at the influence of metrology when assessing the quality of high-steel alloy and other alloy tubes and pipes in nuclear and conventional power plants.

Keywords: Corrosion, High-alloy steels, Nuclear power plants, Power plants, Quality

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Tubes made of high-alloy steels and other alloys are widely used in power plants where they operate at high pressures and temperatures and function under the influence of corrosive environments and radiation fluxes. As the operating conditions in such plants become ever-increasingly complex so also does the importance of improving the efficiency and the reliability of the tubes working in them. Their premature failure, for example, can cause significant economic losses, and sometimes may even lead to accidents. This is particularly the case with nuclear and steam power plants.

Improving the quality of the tubes used in nuclear and other power plants is of interest to both manufacturers and customers alike. At the same time the question also arises: "What quality levels are needed with what kind of tubes, not only now but also in the future to prevent failure during prolonged operation?" The answer to this is not simple because to date there has been no unambiguous interpretation of the causes of failure during the long-term use of tubes. The results that have been presented in numerous publications on this topic often have a hypothetical character. This is largely because of many complex, interacting factors.

Trying to find a solution to increasing the life expectancy of tubes in power plants is usually dealt with as a probability problem whereby the solution should ensure the maximum possible interchangeability of variables. The more the variables are interchangeable, the more reliable the results. When such an approach is used, however, special importance should be attached to the metrological assessment of the quality of the tubes.

Tubes made of zirconium alloys

The complexity and unique properties of the zirconium alloys that have been developed over the years have led to their use in ever broadening application areas. Actual evidence of this is shown by the fact that the US Patents Office currently has over 49,000 patents in its database that are directly or indirectly related to zirconium. Moreover, zirconium has come to occupy a leading position in terms of usage in the nuclear power industry. A review of several publications enables us to show that intensive developments have been made in this field aimed at the creation of structural materials that are able to increase the burn up of the nuclear fuel [1].

Many publications show that the current level of fuel burn is at a relatively low level, i.e. 5–8%, and is limited due to the failure of the zirconium cladding. The main goal of the numerous research and development studies in the literature is to double this figure. This could perhaps be achieved through the following activities:

- the creation of new zirconium alloys having a high corrosion and creep resistance;
- the development of special heat treatments to ensure the formation of a unique structure of zirconium alloys, which are resistant to corrosion;
- the development of technology for manufacturing zirconium cladding tubes with corrosion-resistant layers;
- the use of deformation and the heat treatment of tubes, to provide a tangential orientation of brittle zirconium hydrides, among others.

Over the past twenty years more than 800 patents have been registered, which in the author's judgment have higher corrosion resistances and improved mechanical properties. Their diversity can be grouped under the following criteria:

- binary alloys "Zr–Nb" and "Zr–Sn";
- ternary alloys "Zr–Bi–Mo" and "Zr–Bi–Sn";
- quaternary alloys "Zr–Bi–Mo–Nb";
- quandary alloys "Zr–Bi–Mo–Sn–Nb".

Most of these alloys have not found wide practical applications for two main reasons. Firstly, the increasing number of permitted elements greatly impair the transmission of thermal neutrons. Secondly, they came from a simplified representation considering that the main cause of the failure is the formation of corrosion pits.

A more comprehensive approach to solving the problem of the durability of fuel elements is provided by the program SCIP. It is performed by specialists from several countries. This program can be applied to complex scientific and application tasks. As such, in order to obtain reliable results, a high interchangeability of zirconium tubes for a number of parameters (including dimensional characteristics), should be arranged.

Boiler, condenser, feed and other types of tubes

The nomenclature of such tubes is comprehensive. They are used in thermal and nuclear power plants. Depending on the operating conditions, tubes of various sizes are used made of nonferrous metals, carbon and alloy steels, titanium alloys, and other materials. Requirements for their accuracy and their surface specifications are not high. However, their durability and ability to handle heat transfer is a problem. To date there is no ambiguity in the literature in dealing with this. There is, moreover, an opinion [4], that boiler tube failures are inevitable. There are twenty-two primary reasons for tube failures in a boiler. It is also noted, that knowledge about operating conditions and practical maintenance reduce tube failures. Reducing tube failure in boilers increases the lifetime of the boiler. There are also evidence that a single tube failure in a 500 MW requiring four days to repair can result in loss of more than one million US dollars, not even taking into consideration generation loss.

In Refs. [5–7] and in other publications on the topic of potential causes of failure, "fouling" of the inner surfaces of the tubes due to long-term operation is often highlighted. It is possible that the appearance of "fouling" can be explained by the fact that as water passes through areas of roughness on the inner surface of the tubes, local variations in the speed of the flow occur and that this generates turbulence, which will be associated with surface cavitation. The products produced by cavitation will be deposited inevitably on the inner surface of the tubes forming the "fouling" [8]. Some possibilities for increasing the performance characteristics of boiler tubes by improving their quality are considered in [9].

Reliability assessment of the geometric characteristics of the tubes

(a) Dimensional characteristics of the outer and inner diameters, and wall thicknesses

Numerous publications relating to the operational characteristics of tubes used in nuclear and thermal power lead us to conclude that their high durability depends largely on their interchangeability. At the same time standardized quality parameters and their estimates should be maximally harmonized with the causes of failures. Firstly, because of the operating conditions, they must be based on reliable estimates of the inner surface because this is generally the location of potential fractures.

In the current valid standards for the responsible use of tubes, primary tolerances have been stipulated for the sizes of the outer diameter and wall thickness. In some cases, they provide an assessment of the accuracy of the inner diameter. In order to accomplish this, ultrasonic testing is mainly used. The algorithm for such a control is relatively simple. It is produced by means of two diametrically opposite sensors believed to be placed on a line passing through the center of the inner surface. However, since this center is not defined by measuring wall thicknesses, significant errors may inevitably occur. This can further negatively affect the accuracy of the estimates of the internal diameters, determined from subtracting the measured values of the outer diameter from the two measured values of wall thicknesses. In this regard it can be argued, a priori, that

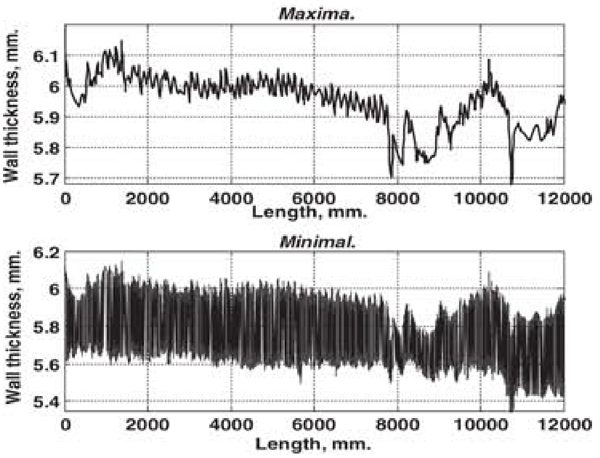


Fig. 1. The measured extreme values of the wall thickness of the tube 50,0 × 6,0 × 12000 mm at the output of the ultrasonic thickness gauge.

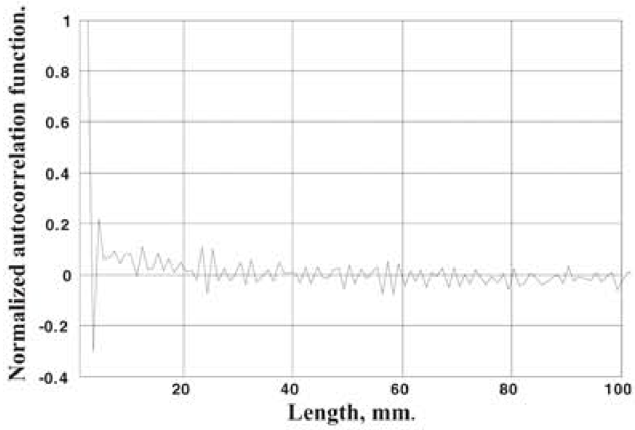


Fig. 2. The normalized autocorrelation function of the minimal values of the wall thickness on the tube 50,0 × 6,0 × 12000 mm at the output of the ultrasonic thickness gauge.

the results of such measurements of the internal diameter will be less accurate than the outside diameter.

Another cause of dimensional errors is the processing algorithm. The measurements are conducted at a frequency of 10 MHz. To reduce the amount of the measuring required only the extreme values within one revolution of the sensor relative to the tube surface are fixed. The procedure is illustrated in the below figures.

The results of the measurements before filtering are shown in Fig. 1. One can see that they contain a significant noise component. Evidence of this is shown by the autocorrelation function in Fig. 2. Its form suggests that the wall thickness and diameter measurements carried out by ultrasounding may have had significant metrology errors. Hereinafter the filtered results are displayed or recorded.

The character of such diagrams is shown in Fig. 3. From them we can conclude that the assessments undertaken in this way do not allow us to achieve a reliable assessment of the interchangeability of the tubes. In other words, all the tubes whose dimensions are within the specified tolerances, will be formally classified as the same, though in fact they differ significantly from each other. As such, conducting a multi-factor experiment to improve the durability of the tubes is not worthwhile.

(b) Assessment of the inner surface

Currently, in order to estimate the quality of the internal surface of tubes a well-known stylus method or profilograph-profilometer is used. With this it is necessary to satisfy a number of conditions. Firstly, the line of measurement must not run along but transverse to the prevailing surface deviations. This feature is associated with the topography of cold-rolled tubes, which is shown in Fig. 4. The deviation of the profile of the inner surface, measured in the transverse direction using a contact method with a discreteness of 2 microns, is shown in Fig. 5. Here, the Ra indexes differed by almost a factor of ten. It is known that when evaluating the state of the surface by means of the contact method it is necessary to preset the lengths of the measurements and the parameters of the filters beforehand. Performing such requirements with regard to the inner surface of the tubes can be problematic. From the metrological viewpoint, one cannot ignore the fact that the recommended settings are mostly of machined surfaces, which have stationarity in relatively short-time intervals and therefore differ fundamentally from those obtained by using plastic deformation.

It has been established that deviations in the cross-sections of cold-rolled tubes are approximately within the following limits: macro deviation ≤ 0.3 mm length of the perimeter of the internal perimeter and > 0.5 mm; micro deviations ≤ 0.3 mm [6].

Fig. 5 shows the components of the

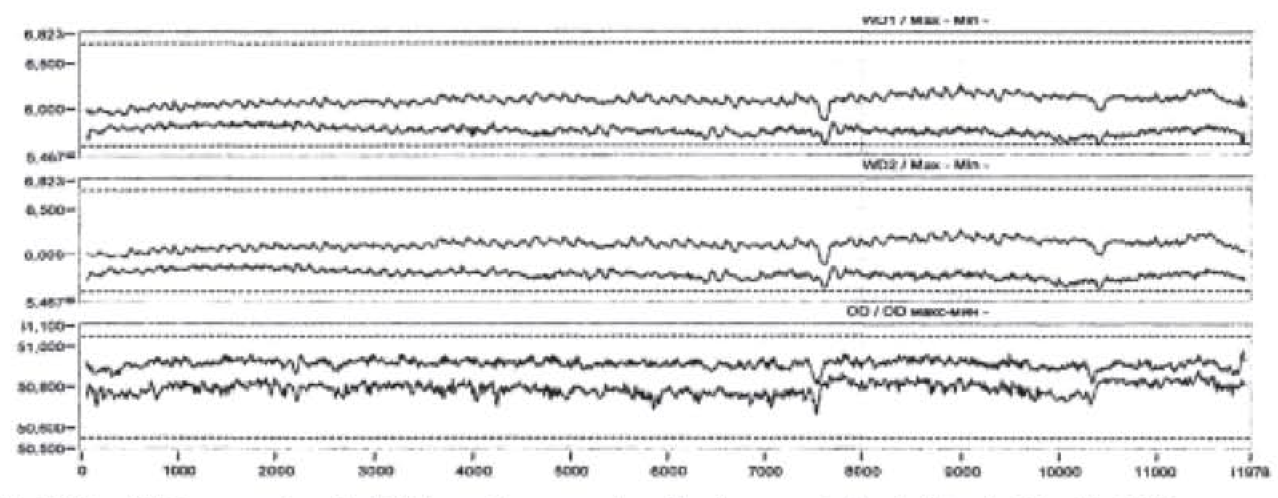


Fig. 3. WD1 and WD2 extreme values of wall thickness, OD extreme values of the diameter on the length of the tube 50,0 × 6,0 × 12000 mm.

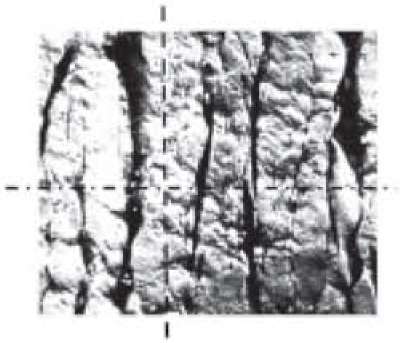


Fig. 4. The inner surface of cold-rolled tube, size 48 × 5 mm, stainless steel 304, magnification ×1000, dotted line - longitudinal direction of measurement; dash-dot line- transverse direction of measurement.

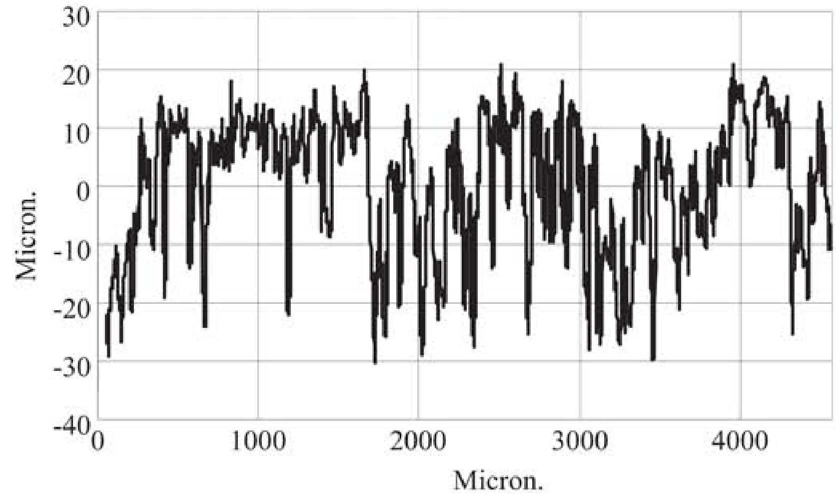


Fig. 5. Transversal profile record of the inner surface of the cold-rolled tube, size 25 × 1,65 mm, stainless steel 304. Ra as measured in the longitudinal direction is 1,5 microns, in the transverse direction is 14,8 microns.

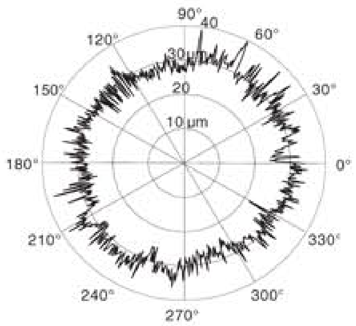


Fig. 6. The polar diagram of the cross-section of the inner surface, the tube 9,1 × 0,7 mm, Zr1Nb alloy.

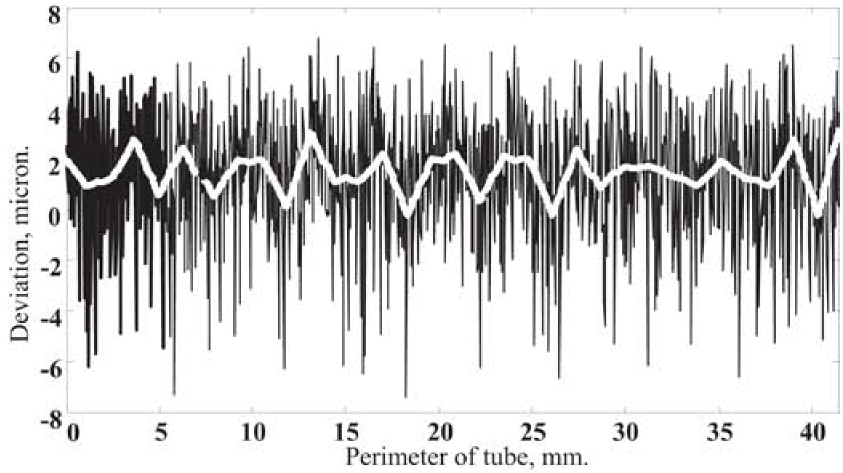
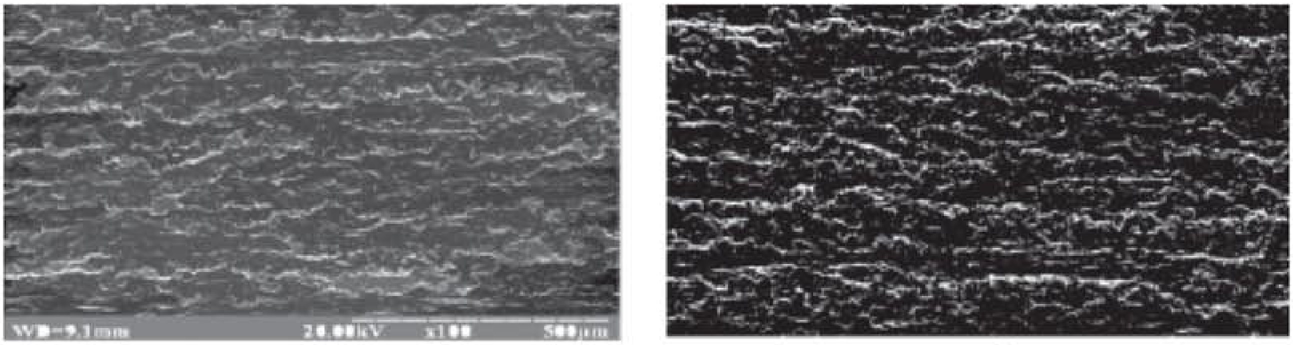


Fig. 7. The components of the cross-section deviations of internal surface, the tube 9,1 × 0,7 mm, Zr1Nb alloy: white line – macro deviation; black line – micro one.

deviations identified in these intervals. The macro-component, labeled in white, can be used to evaluate the stresses arising by changing the gap between the fuel cladding and the fuel pellets. Possible surface corrosion can be estimated with the help of micro-components. A technique was used for this task based on an assessment of the bearing surface [10]. The principles of this technique are shown on Figs. 8a and 8b. To do this, an image of the surface should be transformed into a binary image, and then the value of the supporting area should be determined. This is presented in Fig. 8 as white, longitudinal stripes. For this analysis, the total bearing area determined was relatively small, which led us to conclude that the analyzed surface had a low corrosion resistance.



a). b).

Fig. 8a. The raster image of internal surface of the tube 9,1 × 0,7 mm, Zr1Nb alloy; 8b. the binary image of the same one.

Summary

The durability of tubes used in nuclear and thermal power plants has remained a problem until now. The current estimates of the sizes and state of the surfaces tubes used, do not provide the desired accuracy. In order to address the problem of the increasing durability of power installations, the interchangeability of the tubes needs to be regarded as one of the basic characteristics.

Reference available on request