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Zirconium Alloy Mechanical State and its Evolution during Deformation

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A series of tests have been run for Zr alloy tubes in a strain-stressed and structural state worked by cold rolling. It has been shown that the information obtained can be used for predicting alloys' reserve of ductility, for evaluating the level of internal stresses built up and for detecting the incipient nuclei of fracture in the material. Suggested are methods of checking as based on the results of the study that afford a significant improvement in the product quality.

1 Introduction

The fuel elements of modern nuclear reactors are critical parts; their reliability in service is in many respects dependent on the strength and structural uniformity of the materials used for their manufacture (Langford, 1970). Materials of this sort are usually selected with due regard to the kinetics of nuclear reactions. These are precipitation-hardened zirconium-base alloys containing Nb in amounts of 1 - 2.5%. Moreover, Fe, Sn and O are used as alloying additions for a range of materials; they cause precipitation of intermetallic compounds and oxides microparticulates with resultant precipitation hardening of the material (Nikulina and Markelov, 1990). Zirconium is noted for a transition that occurs at 1085 K from the low-temperature hexagonal close-packed α-phase to the high-temperature body-centered-cubic β-phase.

Such a singular package of properties hampers significantly the processes of plastic deformation in Zr alloys, especially when the material sustains high levels of strain, e.g. during the manufacture of tubes for the fuel elements of nuclear reactors by helical rolling. During pipe production, cracking of the pipe billets is likely to occur; therefore, it is imperative that on-line monitoring of the material's reserve of ductility should be run after each stage of the process of cold rolling of the pipe billets to a finished size. The conventional tests using special specimens fabricated for the purpose appear to be too expensive and insufficiently informative. Therefore, in order to evaluate the tolerable level of strain that a Zr alloy billet is capable of sustaining without cracking, it has been suggested to use the method of speckle interferometry (Jones and Wykes, 1983). The technique has been specially adapted to the analysis of strain fields and to the nondestructive control of materials in a planar stressed state (Panin et al., 1993).

2 Strain Localization and the Mechanical Properties of Zirconium Tubes

In the first series of the runs, the concentration and localization of strain was determined in specimens cut out of round billets in the different stages of pipe manufacture. It is known that the application of the above method allows to determine the components of the plastic distortion tensor, i.e., the local elongation ε_{xx}, the shear ε_{xy} and the rotation ω_z (with the axis x directed along the extension axis), for all the points of a deformed specimen or a loaded part and to follow the evolution of the same with time. A typical picture of this kind is presented in Figure 1. In this work as well as elsewhere (Zuev at al., 1997; Zuev and Danilov, 1997) it can be seen that in the process of deformation, a concurrent localisation of strain takes place in the specimen under deformation, which is characteristic for practically all the stages of plastic flow from the yield point to fracture.

Plastic deformation has a distinguishing feature, viz. a nonuniformity of the flow, which is characterized firstly by a localisation of strain and secondly by a difference in the amplitudes of the components of the plastic distortion tensor obtained for the various nuclei of strain localisation. Provided the strain stresses sustained by the material are equal, the greater amplitudes obviously correspond to those zones of the material in which it exhibits maximum deformability at a given amount of stresses. If a specimen is cut out along the pipe axis, its initial part has a greater reserve of ductility (see Figure 1). This observation is supported by the lower value of hardness obtained for the respective points. The reason for this inhomogeneity has to do with the fact that in the preliminary stage of pipe manufacture, the material sustains a different amount of plastic strain at every cross-section of the pipe, with the value of deformation hardening being correspondingly different. Thus, the use of the method of speckle interferometry allows to reveal nonuniformities in the distribution of plastic deformation zones, which is an indirect indication of the material's reserve of ductility and of its ability to deform without fracture in the process.

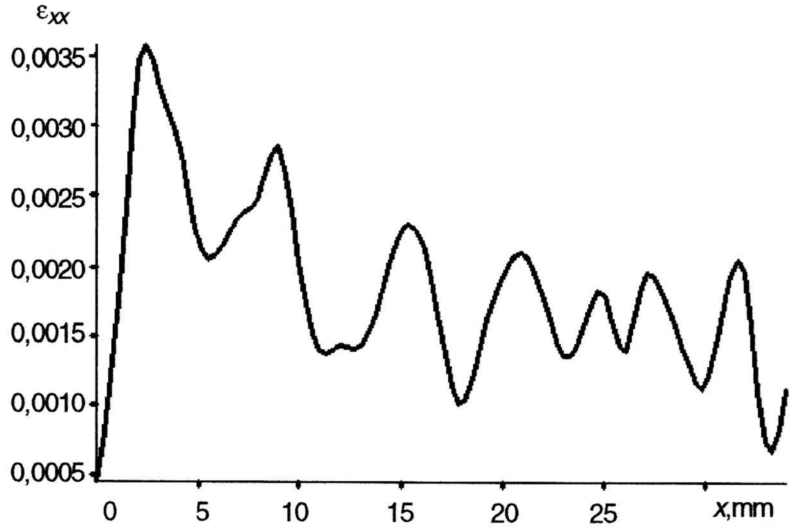

Figure 1. The distribution of the local elongations along the length of a Zr specimen cut out of a tube manufactured by cold rolling.

Further developments involved direct testing of tube billets with the aid of the above experimental technique following each stage of the pipe manufacture, which precluded fracture caused by cutting out special specimens. In this instance, the billets tested were loaded by internal pressure. It was found that in those billets zones of strain localisation could be also revealed and the alloy's reserve ductility could be assessed. Of great interest is the detection of incipient nuclei of fracture that are not detectable by other methods. It has been found that in the specimen under extension, the emergence of the maximum of the components of the plastic distortion tensor that are localised in a certain site by Panin at al. (1993) is observed long before the formation of necking detectable by visual inspection takes place (see Figure 2). This is an early warning indicative of low reserve of ductility which necessitates rejection of the billet or semifinished item tested.

Use of the above methods to check the status of alloys in the different stages of pipe manufacture for nuclear reactor fuel elements has permitted optimization of the process of pipe manufacture and upgrading of the product quality to afford pipes whose physico-mechanical properties are found to be uniform over the entire length. In order to relieve the internal stresses built up in the pipe billets after each stage of working by pressure and to attain optimum grain orientation in finished items, the most cost-effective and time-saving annealing schedule has been selected.

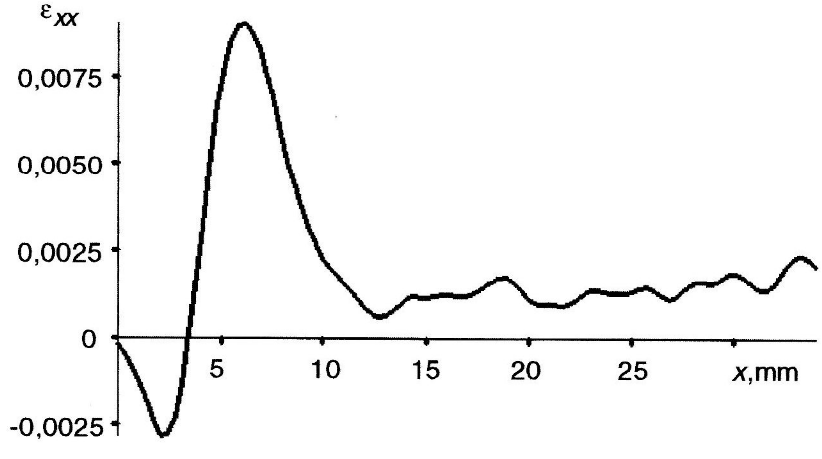

Figure 2. The distribution of local elongations along the length of a Zr alloy specimen as observed prior to fracture

3 Measurement of Internal Stresses from Ultrasonic Velocity

Zirconium alloy billets worked by cold rolling undergo plastic deformation at low temperatures; therefore, high amounts of internal stresses are built up in semifinished items. Such a situation is liable to be critical since it might bring about premature fracture of the material. The conventional method for monitoring the amount of internal stresses is the X-ray testing; however, it is hardly feasible in actual practice. This generated a need for the development of an indirect method for evaluating the amount of internal stresses from ultrasonic velocity. It is known (Muraviev at al., 1996) that the velocity at which ultrasonics having a frequency of about 1 MHz travels in a solid is a magnitude sensitive to any changes, however small, that are caused in the material's properties by hardening, cold work hardening, fatigue of metal, etc.

Under such conditions, a change in the ultrasonic velocity generally does not exceed $3 \cdot 10^{-2}$; however, with the aid of, e.g., the method of autocirculation of sound impulses, the same value can be measured to an accuracy of 10^{-3} or better, which will suffice for the purpose. If the amount of stresses created in an object is measured by the X-ray testing method and the velocity at which ultrasonics travels in the same with the aid of special instruments, the two values would be found to reveal a close correlation (see Fig. 3), with high-level stresses corresponding to low ultrasound velocity and vice versa. The physical reasons for such a correspondence are considered by Muraviev at al. (1996). A method for nondestructive testing of tubes and round billets manufactured from *Zr* alloy and facilities designed for the purpose as based on the above principle have been developed, which permits rejection of semifinished items that do not meet the requirements for quality.

4 Optical Television Method for Testing the Quality of Zirconium Tube Surface

Of utmost importance is testing the quality of the surface of Zr alloy tubes intended for nuclear reactor fuel elements. However, the routine visual checks are not sufficiently reliable. To eliminate this drawback and to run more severe checks of product quality as necessitated by the more stringent requirements for the safety of nuclear reactors performance, a special-purpose optical television instrument has been developed. It is designed for on-line monitoring of the tube surface in order to detect possible flaws in the surface structure. The software developed for that purpose allows to compare the television image of a portion of the tube surface containing a defect with a set of images of standard defects stored in the computer memory. The instrument based on this principle performs digital processing of the image and displays the data obtained on the type, dimensions and position of the surface defect.

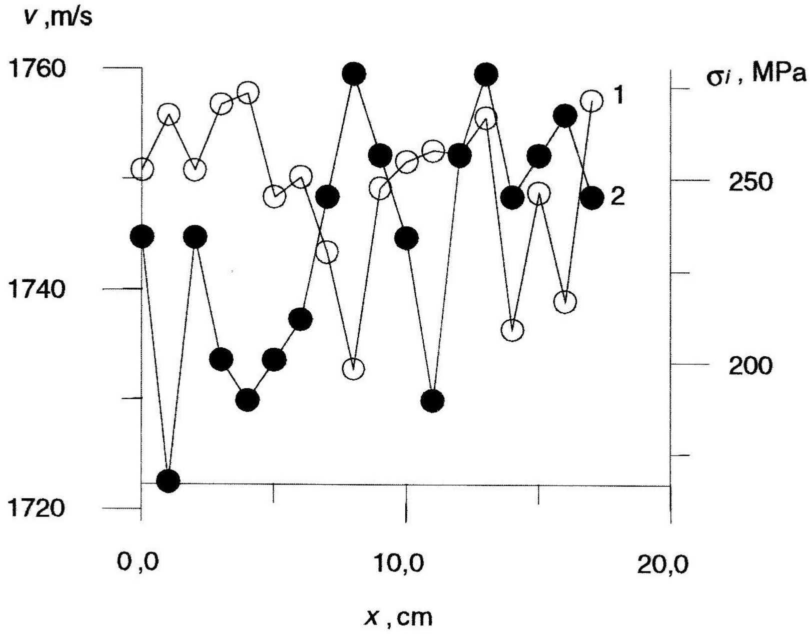

Figure 3. The correlation established between ultrasonic velocity and the internal stresses built up in a Zr alloy tube manufactured by cold rolling.
1. Ultrasonic velocity; 2. Internal stresses

Using the above method, sufficiently reliable final tests of the quality of Zr alloy pipes designed for nuclear reactor fuel elements are run at the Chepetsk mechanical plant, which affords a significant improvement in the quality of the same.

5 Conclusions

Checks of the ductility margin of alloys performed for semifinished items after each production stage as well as for finished products, detection of incipient nuclei of fracture and assessment of the level of internal stresses both in the billets and in the finished items afford a significant improvement in the quality of the pipes intended for nuclear reactor fuel elements and consequently, in the safety margin of nuclear reactor performance. The methods developed in the pursuit of these goals can be used for testing other products manufactured by rolling, forging or stamping.

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