Probabilistic Distribution of Structure Integrity Characteristics of Materials for Russian PWR Reactors

Boris Timofeev, Tatiana Chemaenko and Georgy Karzov

CRISM "Prometey", Russia

ABSTRACT

In this paper the statistical distribution of mechanical properties and structural integrity characteristics (low cycle fatigue, fatigue crack growth rate and fracture toughness) of base metal and weldments for reactor pressure vessels VVER-440 and VVER-1000, produced in Izhor plant, are presented. To determine the service reliability of a pressure vessel weld and to resolve problems dealing with the operating capacity of a structure containing defects, the information related to their effect on structure performance under various load conditions is necessary. However in this paper the distribution of defects in reactor vessel detected by the application of various non-destructive techniques is not given.

INTRODUCTION

The erection of nuclear power plants (NPPs) in densely populated districts makes a demand on the prediction of their safety. In principle, the aim is to determine probabilistic serviceability indexes of the whole NPP equipment (mechanical, electric, thermal, etc.) since the refusals of separate elements influence (in a definite way) the operating conditions. In this research we consider the elements operating under pressure (piping, vessels). A most obvious and perspective approach in safety prediction of pressure vessels consists in the solution of problems of the kinetics of flaws development in NPP structure elements considering the statistic scattering of data on their initial sizes and material mechanical properties. The solution of the problems stated permits to determine the probability of various failures by the realization of operation regimes. It gives a possibility to reveal most weak spots in the serviceability provision of pressure vessels and piping.

To assess the reliability of pressure vessels and the probability of their large scale or local failure it is very important to take into consideration the current distribution of flaws sizes in structure. It should be noted that a set of statistical data on flaws distribution on full scale specimens is quite problematical. First of all the efficiency of various NDT systems depends on the type and sizes of flaws, structure wall thickness, device type. Therefore, in the analysis of statistic data of flaws sizes, revealed by NDT, it is necessary to make corrections of the errors of inspection systems.

Besides, in the determination of probabilistic indexes of equipment serviceability the properties distribution of materials and their welded joints and first of all the distribution of structure integrity characteristics responsible for the failure process are also of a great
importance. Nevertheless the deterministic analysis is still used mostly for the estimation of reliability of NPP equipment in our country. At the same time nowadays the probabilistic safety assessment starts to be applied more often. It is necessary to know (for realization of this approach) the statistical distribution of mechanical properties and structure integrity characteristics of basic materials (from which was manufactured this equipment) and their weldments and also manufacture quality and service conditions. It is this problem which has been considered in the present report in respect of the accumulated experience in VVER-440 and VVER-1000 reactor pressure vessel production.

1. DISTRIBUTION OF MECHANICAL PROPERTIES

Originally, the data analysis with statistic methods for pressure vessels was carried out at Izhora plant. When the collection of data was completed the information was obtained, in all, for 27 pressure vessels of the type VVER-440 reactor and 10 pressure vessels of VVER-1000 reactor. The source of information was the data on properties examination of samples, used for the production of pressure vessel components as well as on the examination of welded samples, manufactured according to the standard technology with welding materials, applied to weld pressure vessel components. Thus, the obtained information is reliable from a position of the estimation of production processing, quality and characteristics of materials applied for native nuclear power plants.

The initial information on VVER-440 and VVER-1000 reactor pressure vessel properties was treated using mathematical statistics methods. The basic mechanical properties (UTS, YS, A, Z) were analyzed at 20 and 350°C, impact strength (KCV) at 20°C; it was also analyzed DBTT (Tko) and the content of P and Cu. Their concentration influences greatly the tendency to embrittlement under irradiation, and from a position of structure material strength estimation their amount is of a decisive importance.

For each specified parameter on the empirical distribution of the frequencies of the parameter value appearance it was selected a theoretical law of probability distribution. By this, as possible theoretical laws, the Weibull probability law, the normal and logarithmic-normal laws were taken. The verification of the agreement of theoretical and empirical distribution was carried out with the Pirson, Komogorov and χ² criteria for the confidence level 95%. The best agreement was observed by normal distribution for all parameters stated, and it agrees with other reference results. For most samples on the stated confidence level the normal law can be accepted as the approximation of the experimental data obtained. The normal law can also be accepted for the rest parameters considering the stated above factors, though for actual samples this hypothesis was confirmed with the probability below that, which was accepted. The results of the statistical analysis in the form of differential and integral curves are given in Figs.1 and 2 with regard for data in [1]. To compare real values with the required level specified in drawings and technological documentation, the figures also show the corresponding normative values.

Production processings of pressure vessel components have some peculiarities. From one detail to the other the weight of ingots, sample thickness, plastic metal working and heat treatment are varying. Accordingly, the details must differ in metal composition and properties. By considering the earlier obtained data [2] the statistical analysis of mechanical properties was carried out on the following groups of samples: flange, nozzle zone shells, shells of a smooth part of pressure vessel and bottom. The samples were united in groups on the indications of the likeness of thickness design and technology. The latter, in particular, was the reason to classify shells and bottoms in separate groups.
inspite of the likeness of thickness and covers, because in contrast to shell samples the samples for bottom and covers are forged from the ingot wholly without core removement and besides, bottoms and covers are subjected additionally to one more operation - attended by plastic deformation - stamping. The statistical analysis results of the variation of each component properties in the form of integral curves of probability are given in [2].

2. DISTRIBUTION OF STRUCTURE INTEGRITY CHARACTERISTICS

The estimation of reliability and safe loading conditions of nuclear power equipment, in the main, cannot base on the deterministic values of material characteristics, reflecting its fracture resistance at three main stages of this process (fatigue crack nucleation, stable crack propagation and brittle fracture) on the accepted at present criteria, used in engineering practice, but must take into account a possible dispersion of properties and composition on this type of steel (weld metal). To provide a high reliability of equipment and connected with it the operation safety the probabilistic methods of strength and service life calculation are more widely used at present, which are based on material characteristics, obtained with either degree of confidence. The accumulated scope of experimental data on fracture resistance for pressure vessel materials permits to carry out the statistical analysis and determine these characteristics at each stage of fracture process in the probabilistic aspects in order to obtain a trustworthy initial information for reliability prediction of power plant engineering structures.

The stated characteristics for each type of material must take into consideration intra- and interheat dispersion of properties. Below, in the next three sections we have analyzed the experimental data on low cycle fatigue resistance, fatigue crack propagation resistance and brittle fracture resistance of pressure vessel of high temperature steels of the types 15X2MFA and 15X2HMFA and also their welds with regard for dispersion. The experimental material for the statistical treatment was on the whole obtained by the author. For structures, operating under conditions of cyclic loading, induced by the variation of operating pressure and temperature, it is necessary, in the first place, to determine material resistance to fatigue damage.

2.1. Low Cycle Fatigue

Below, the statistical analysis is presented of fracture resistance under low cycle fatigue loading conditions of 15X2MFA steel on experimental data and calculation relations, constructed considering the dispersion of material mechanical characteristics. Originally, the statistical analysis of data on low cycle fatigue crack nucleation was carried out for one heat of 15X2MFA steel in order to determine intra-heat dispersion. The mechanical properties of this material, determined by short-term statistic tests, varied within the following limits: UTS = 619-745 MPa, YS=484-656 MPa, A=18.7-26%, Z=70.4-78.6%. The specimens, manufactured from this material, were tested under three levels of deformation - 2.02; 0.86; 0.395% on the scheme of rigid symmetric loading "tension-compression" at room temperature. At each deformation level 20 specimens were tested with net section 10x30 mm and 30 specimens with net section 4x12 mm, besides, two large scale specimens with net section 40x120 mm by the amplitudes of total deformation. In the process of testing the number of cycles was fixed to fatigue crack appearance and number of cycles to a complete rupture of a specimen. The obtained experimental results (Fig.3) show a good agreement of average values of lifetime on the moment of fatigue crack appearance for specimens of various sizes [3].
2.2. Fatigue Crack Growth Rate

In the last ten years a great number of investigations have been carried out on the estimation of fatigue crack growth rate in various materials. It is not accidental, as the problem of service life increase of the main structures was always highly actual. For some large scale structures the requirements to service life increased, for a comparatively short time, by 5-10 times (the requirements to safety remained). It is natural to suppose, that it is hardly possible to meet such requirements on account of new structural and technological solutions. Due to technological measures the service life can be increased not more, than by 2-3 times but not in all types of equipment, because in some branches of industry the service life, in a large measure was exhausted. The transition to operation on technical state will permit on the average to increase sharply service life without safety reduction, but it is associated with labor-consuming studies of fatigue crack development laws. In aircraft industry this problem is paid a special attention, and fatigue crack growth rate is determined not only in materials, but also in real structures. As to the investigation of crack propagation laws, this problem is considered, as a rule, in a statistical aspect. A set of studies are known, in which the process of fatigue crack propagation is discussed on the base of the probabilistic models of fracture.

As applied to nuclear power equipment fatigue crack growth rate was studied for a set of materials and their welded joints. At present a large scope of experimental data has been accumulated, which permits to give proposals on the consideration of crack growth rate in strength calculations for reactor pressure vessels. However, in the statistical aspect for materials, used in nuclear power engineering, this problem has been studied insufficiently. There are some investigations, in which crack growth rate was studied in zones of structural concentration of stresses, including high temperature pressure vessel steel of the type 15X2HMFA.

The experimental results on the determination of fatigue crack growth rate in high temperature 15X2MFA steel and its welded joints, produced by submerged arc welding with the type Sv-10XMFT wire under AH-42 flux were presented in detail in Ref. [4]. By this, for base metal the resistance to fatigue crack propagation was evaluated both for one steel heat and coinciding inter-heat dispersion of chemical composition and mechanical properties of semi-products, used to manufacture specimens.

2.3. Brittle Fracture Resistance

The main criteria, determining material brittle fracture resistance are the ductile brittle transition temperature $T_{K0}$ and fracture toughness, characterized by the critical value of the stress intensity factor $K_{IC}$, between which, as it was shown in [5] there exists a certain correlation. The first characteristic stated is usually determined during inspection acceptance of various types of semi-products, from which NPP equipment elements are manufactured, and on inspection samples from weldments, manufactured with the same welding materials, by the same welders and in the same regimes, that were applied for finished products. By this, it must meet the requirements of the corresponding specifications and standards. The critical transition temperature of material as its main characteristic was used in power engineering at the end of seventies. Nowadays some experience has been accumulated for its determination both for base metal and welds.

The critical transition temperature $T_{K0}$ is used as calculated characteristic. In the first case, $T_{K0}$ is used to confirm semi-product quality at this stage of technological process, i.e. to verify if the requirements of corresponding specifications and GOST are met. If these requirements are not met ($T_{K0}$ values are higher than those specified by TY and GOST), then a semi-product is additionally heat treated or rejected. Its application permits
to determine the permissible loading condition of the power equipment element considering the variation of this characteristic in the process of operation and to determine structure service life. The calculation of brittle fracture resistance includes the determination of ΔT shift and the curve of permissible stresses in the period of operation as well as the comparison of this dependence with the curve of actual stresses. The trend of the curve of permissible stresses is determined by the other criterion - material fracture toughness.

Below the estimation of fracture toughness dispersion of RPV materials is carried out. By constructing temperature dependencies of the critical value of the stress intensity factor $K_{IC}$ of these materials the test results of specimens of various dimensions were analyzed statistically. Their use is permitted by the available normative and technical documentation, as under conditions of the maximum constraint of strains at the crack tip (plane strain) specimens of various dimensions give identical results. However, within the developed range of plastic strain (in incorrect area) the specimens of large dimensions give, accordingly, higher values of the critical stress intensity factor. In the temperature range from -40 to 20°C the data were partially incorrect as far as by the statistical analysis the values $K_{IC}$, obtained by testing not only large-scale specimens but also those having sections 60x60 and 30x30 mm were used.

The fracture toughness of pressure vessels of high temperature steels was estimated considering the intra- and inter-heat dispersion of composition and properties of these materials. For the type 15X2MFA steel the intra-heat dispersion of $K_{IC}$ values was determined by testing 13 specimens of the dimension 50x100x450 mm on three point bend at the temperature -40°C. Thus, for Cr-Mo-V steel the fracture toughness dispersion under the same conditions of the experiment and on one heat was determined for steel plate. The critical stress intensity factor $K_{IC}$ by static loading was determined for the types 15X2MFA and 15X2HMFA steels on 7 heats of each material, which were produced on the standard technology for VVER reactor pressure vessels and in its chemical composition and mechanical properties met the specification requirements.

The statistical analysis of $K$ values for weld metal, produced by submerged arc welding with the type Sv-10XMFT and Sv-08XGHMTA wires, was carried out on the test results of not less, than 5 welds, manufactured with various welding materials. On the base of the obtained experimental data on temperature dependencies of fracture toughness of heat resistant pressure vessel steels and their welded joints it is possible to analyze the character of $K_{IC}$ values distribution (with regard for inter-heat dispersion) at various test temperatures.

Basing on the results of the statistical treatment of all materials investigated the temperature dependencies of fracture toughness were constructed using the parameter of fracture probability. In Fig.4 these dependencies of high temperature pressure vessel steels and their welds are given in the form of curves, corresponding to an equal fracture probability from 1 to 99%. Comparing the presented data it can be noted, that the temperature dependence of $K_{IC}$, constructed on 1% fracture probability, for 15X2MFA steel is located below than that for 15X2HMFA steel. This difference is especially evident in brittle region at the temperatures below -70°C, where on $K_{IC}$ value the materials differ from each other by 1.5 times. The stated difference is, apparently, associated with a favorable influence of nickel on brittle fracture resistance of high temperature pressure vessel steel in the absence of neutron fluence attack. It is known that for the type 15X2HMFA steel the low level of fracture toughness temperature dependence shelf decreases appreciably. In the temperature range above -30°C the difference of temperature dependencies of fracture toughness of 15X2MFA and 15X2HMFA steels is
practically not observed. The dispersion value of the critical stress intensity factor is approximately identical with values of both types of reactor steels at the same temperatures. The temperature dependencies of $K_{IC}$ for the type 15X2MFA steel and its weld, produced by submerged arc welding with the type Sv-10XMFT wire, corresponding to 1% probability, practically, coincide within the whole range from -190 to -20°C; it is not observed for the type 15X2HMFA steel and its weld, produced by submerged arc welding with Sv-08XGHMTA wire. The dispersion of $K_{IC}$ values for weld metal is slightly less than for the corresponding base metal, which, apparently, may be explained only by smaller sizes of samples in the first case (five lots of welding materials against 7 steel heats). However, the low bounds of fracture toughness temperature dependencies, corresponding to 1% fracture probability, reflect reliably in this case the properties of the corresponding materials.

REFERENCES

Fig. 1. The results of statistical probabilistic analysis of data about chemical composition and mechanical properties of VVER-440 shells.

Fig. 2. The results of statistical probabilistic analysis of data about chemical composition and mechanical properties of VVER-1000 shells.
Fig. 3. Life time distribution curves for 15X2MFA steel.

Fig. 4. Fracture toughness temperature dependences of RPV materials on the parameter of fracture probability.