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# Low cycle fatigue of materials in nuclear industry

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## 1. Introduction

By operation the NPP equipment and piping are subjected to the influence of elevated temperatures under constant and variable loads. This may result in initiation and propagation of fatigue damages and accumulation of one-side strains. The other region of equipment is characterized by increased stresses, caused by concentration. Namely, in these areas the level of acting stresses is more than the value of yield strength. For example, such areas in reactor pressure vessel are [1]:

- nozzle shells, where the theoretical stress factor $\alpha_\sigma$= 1.5 - 2.9;
- area between nozzle shell and flange, where $\alpha_\sigma$= 1.2 - 1.4;
- area between shell and bottom, where $\alpha_\sigma$=1.6 - 1.7;
- straight and bend holes in head of RPV, where $\alpha_\sigma$= 1.8 - 3.4.
- threaded part of the flange, where $\alpha_\sigma$ = 3.3 - 5.0.

In areas of stress concentration the fatigue damage accumulation is possible which may result in the nucleation of fatigue cracks and metal embrittlement as a result of the action of variable loads [2, 3]. A spectrum of cyclic loads effecting NPP equipment in the process of operation is different. Together with the action of low frequency loads of high level the vibration loads with a low level of stresses, (their number may reach $10^7$ cycles during the operation period) also take place. The above mentioned factors lead to the necessity of studying fatigue strength of materials. In the present paper we consider only the behavior of materials, which is widely applied for NPP with Russian light water reactors, by low cycle fatigue.

These investigations were performed during 25 years (in period 1966 - 1991) in low cycle fatigue laboratory of Kaunas Polytechnic Institute (leader – Prof. M. Daunys) in accordance with contracts by Central Research Institute of Structural Materials "Prometey". The experimental results were used in Russian Code (chapter "Assessment of Cyclic Strength"). Lower we present summarized experimental results which are the foundation of low cycle fatigue data base for materials of nuclear engineering. The primary results were presented earlier in numerous articles, collections and books.

## 2. Investigated materials

Different materials (steels and welds) are used for equipment and pipe-lines of NPP with the above stated types of reactors. Besides the operating conditions of this equipment are also different and certainly they are reflected in mechanical properties of materials. The applied materials and operating conditions for the equipment and pipe-lines are presented in Table 1.

Table 1

Main sizes, operation parameters and materials for NPP equipment

| NPP with type of reactor | Part of NPP equipment | Primary circuit | | | Operating parameters | |
|---|---|---|---|---|---|---|
| | | Size, mm | Base metal | Weld | Pressure, MPa | Temperature, °C |
| WWER-440 | Reactor | ∅3840x140 | 15Cr2MoVA | Sv-10CrMoVTi | 12.2 | 265-295 |
| | Steam generator | ∅3260x120 | 22K | Sv-08A | 5.7 | 273 |
| | Primary circuit | ∅560x32 | 08Cr18Ni10Ti | EA-400/10Y | 12.2 | 265-295 |
| WWER-1000 | Reactor | ∅4535x190 | 15Cr2NiMoVA | Sv-08CrMnNiMoTi | 15.7 | 290-320 |
| | Steam generator | ∅4290x145 | 10MnNi2MoVA with cladding | Sv-10MnNiMoA | 6.3 | 279 |
| | Primary circuit | ∅960x55 | 10MnNi2MoVA with cladding | PT-30 | 15.7 | 290-320 |
| | Steam line | ∅630x25 | 16MnSi | YONI-13/55 | 6.4 | 287 |
| | Pipe-line of feed water | ∅159x6 | 08Cr18Ni10Ti | EA-400/10Y | 5.7 | 180 |
| RBMK-1000 | Separator | ∅2300x105 | 22K with cladding | Sv-08A | 7.6 | 260-275 |
| | Pressure header | ∅1040x70 | 22K with cladding | Sv-08A | 8.5 | 260-275 |
| | Suction header | ∅1020x70 | 22K with cladding | Sv-08A | 7.6 | 260-275 |
| | Primary circuit | Pressure piping ∅828x38 | 22K with cladding | YONII-13/55 | 8.5 | 260-275 |
| | Pipe-line of feed water | ∅426x24 | 20 | YONII-13/45 | 5.7 | 170-190 |
| | Downcomers | ∅325x16 | 08Cr18Ni10Ti | EA-400/10Y | 7.6 | 270-290 |

The main requirement for all materials, used for these types of equipment, is the high level of stability of properties during operation. To provide this requirement in accordance with item 7.6.3 of “Rules of arrangement and safe operation of equipment and piping of NPP”, PNAE G-7-008-89 [4] the inspection of mechanical properties in the equipment is carried out using destructive and non-destructive techniques. This procedure shall be performed after 100000 hrs of operation for NPP with water-cooled and water-moderated reactors (WWER) and water-graphite reactors (RBMK). This order of assessment of actual properties of material in the process of operation is foreseen in the regulations of NPP work for the purpose of safety provision. The values of mechanical properties of NPP materials during the whole design lifetime should meet definite requirements, which are presented in Table 2 In accordance with “Strength Calculations Norms” [5].

Table 2

Requirements of mechanical properties for NPP equipment materials

| Base material | Part of welded joint | At 20°C | | | | At 350°C | | | | $T_{KO}$ °C |
|---|---|---|---|---|---|---|---|---|---|---|
| | | $\sigma_u$ MPa | $\sigma_y$ MPa | A % | Z % | $\sigma_u$ MPa | $\sigma_y$ MPa | A % | Z % | |
| 15Cr2MoVA | Base metal | 540 | 432 | 14 | 50 | 461 | 395 | 14 | 50 | 0 |
| | SAW Sv-10CrMoVTi | 539 | 392 | 14 | 50 | 490 | 373 | 12 | 45 | +40 |
| 15Cr2NiMoVA | Base metal | 549 | 441 | 15 | 55 | 491 | 395 | 12 | 45 | -12 |
| | SAW Sv08CrMnNiMoTi | 539 | 422 | 15 | 55 | 490 | 392 | 14 | 50 | 0 |
| 10MnNi2MoVA | Base metal | 540 | 343 | 16 | 55 | 491 | 294 | 15 | 55 | +15 |
| | SAW Sv10MnNiMo | 539 | 343 | 16 | 55 | 490 | 294 | 14 | 50 | +10 |
| | MAW PT-30 electrode | 539 | 343 | 16 | 55 | 490 | 294 | 14 | 50 | 0 |
| 20 | Base metal | 402 | 216 | 21 | 40 | 353 | 157 | 17 | 42 | +20 |
| | MAW YONII-13/45 | 353 | 216 | 20 | 55 | 314 | 176 | 20 | 55 | +20 |
| 22K | Base metal | 430 | 215 | 18 | 40 | 392 | 177 | 18 | 40 | +40 |
| | SAW Sv-08A | 353 | 196 | 20 | 55 | 314 | 176 | 13 | 50 | 0 |
| | MAW YONII-13/45 | 353 | 216 | 20 | 55 | 314 | 176 | 20 | 55 | +20 |
| | YONII-13/55 | 431 | 255 | 20 | 50 | 372 | 216 | 18 | 50 | +30 |
| 08Cr18Ni10Ti | Base metal | 510 | 216 | 35 | 55 | 412 | 177 | 26 | 51 | - |
| | MAW EA-400/10Y | 539 | 343 | 18 | 30 | 431 | 294 | - | - | - |

## 3. Fatigue test procedure

The properties of all materials presented in Table 2 under cyclic elastic-plastic deformation were determined by axial tension-compression testing of cylindrical specimens (with gauge length diameter 10 mm) by symmetric cycle of control amplitude of strain (ratio of strain is -1). The waveform was sine, test temperatures at tests in air – 20°C and 350°C. Besides the specimens from base metal (only 15Cr2MoVA steel) with a plane gauge length (cross section – 4x12 mm, 10x30 mm and 40x120 mm) were investigated by the strain amplitudes equal to 2%, 0.86% and 0.4% and room temperature. A symmetric cycle of strain control was selected as most universal because in this case the tensile and compressive strains are manifested in the same way. The loading with tension-compression was accepted due to the similar distribution of stresses across the specimen section. The number of cycles to failure was 100 - 10000 cycles (only on separate specimens number of failure cycles exceeded $10^4$). A greater number of tests were carried out in air with the frequency of cycles 0.33 - 0.53 Hz and automatic recording of stress-strain diagramed. In this case the moment of fatigue crack appearance was registered on a visible decrease of stresses on this type cyclic diagram’s. When testing cylindrical specimens in aqueous medium for power water reactor (PWR) at next conditions: hydrogen potential pH7, content of oxygen $[O_2] < 10$ ppb) and temperature 270°C by the variation of loading frequency from 0.0085 to 0.167 Hz. These tests were performed only for the specimens of one heat RPV steels (15Cr2MoVA and 15Cr2NiMoVA) and also one hear of SG steel type 10GN2MoVA.

## 4. Experimental results and discussion

The experimental data are given in Figs. 1 and 2 as separate dots for each steel heat and respectively for each welded sample. The array of experimental data for 15Cr2MoVA steel at 20°C (362 dots, 9 heats) is given in Fig. 1. This array was subjected to statistical treatment with the use of the equation

$$lg\, N = B + B_1\, lg\, \varepsilon_a$$

for the construction of root-mean-square dependence corresponding to 50% probability for the given array and confidence interval corresponding to the given truth (95%) of random lifetime value ($N$). The values of constants in the above given equation were $B$= 2.8919 and $B_1$ = -2.3151. The obtained data array with the consideration of margin coefficient on strain amplitude $n_\sigma$= 2 and $n_N$= 10 became the base for the construction of reference calculated fatigue curve for low alloyed steels in the first editorship "Strength Calculation Norms…". In Fig.1 this curve is presented as a 1 line. The same dependence is used as calculated dependence by the cyclic strength assessment of nuclear power equipment made from 15Cr2MoVA steel and in acting Norms PNAE G-7-002-86 [5].

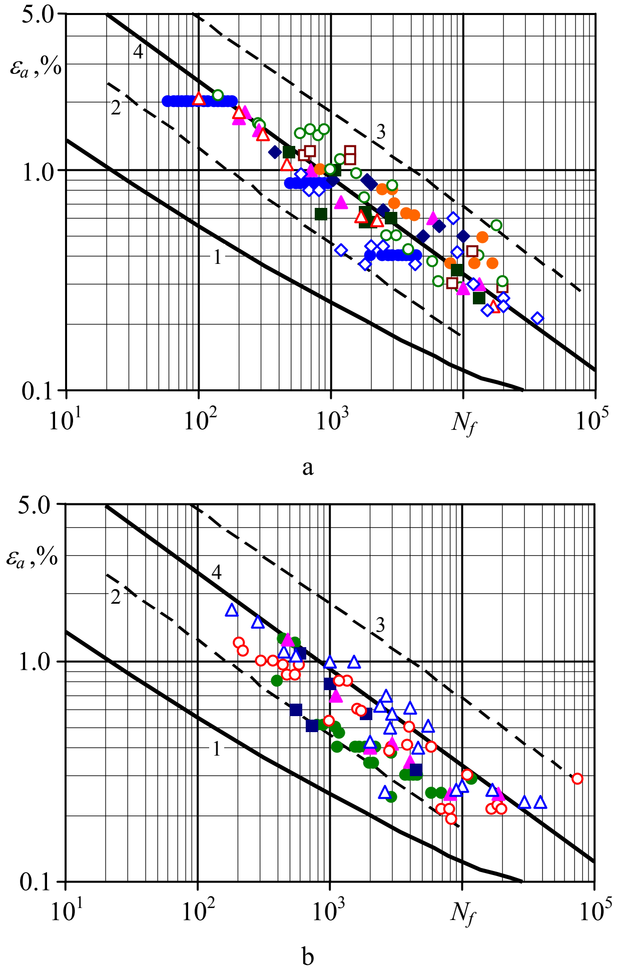



Fig. 1 Low cycle fatigue of 15Cr2MoVA steel: a – at 20°C temperature (9 heats); b – at 350°C temperature (5 heats). Dots – experimental data for different heats of steel; *1* – reference curve [5] for low alloyed steel; *2* and *3* – data falling outside the 5 and 95% tolerance bounds for steel at 20°C; *4* – mean square dependence for the scatter band for steel at 20°C

Later in this report the root-mean-square dependence corresponding to 50% failure probability and boundaries of 95% confidence interval will be used for the comparison of failure resistance characteristics by low cycle loading of all the materials investigated.

The experimental results for data array for pure 15Cr2MoVA-A steel, obtained for three heats at 20°C the scatter of lifetime values by the given strain amplitude is somewhat less and the root-mean-square dependence for 15Cr2MoVA steel in reality may also describe these data. For welds produced using submerged arc welding (SAW) under flux with the type Sv-10CrMoVTi wire the data array at room temperature, obtained on the representative number of welded samples (six) in the investigation [6] somewhat differs from the initial array on the base of which the comparison is carried out. All experimental dots (Fig. 2) are located below the root-mean-square dependence, and for three welded samples the dots are even beyond the boundary of lower envelope of experimental data for base metal - 15Cr2MoVA steel. The presented results confirm that for weld metal the low cycle fatigue resistance is lower than for base metal. Relying on this fact the value of the coefficient of cyclic strain reduction for welded joints of 15Cr2MoVA steel, produced using SAW under flux such reduction is not noted in the first editorship of "Strength Calculation Norms" [5]. All experimental dots for array at room temperature (71 dots, 3 welded samples) are located within the limits of 95% confidence interval. By this for the weld metal of two samples the dots are located below the root-mean-square dependence, and for the third sample (wire heat –70538) are mainly above.

Let us consider more attentively the results of experiments at 350°C in comparison with the scatter band obtained in Fig.1, b. As can be seen in this figure for 15Cr2MoVA steel mainly all experimental data at elevated temperature are located between the root-mean-square dependence and lower envelope at 20°C. This demonstrates some reduction of low cycle fatigue resistance by such increase of test temperature. At the same time the experi-

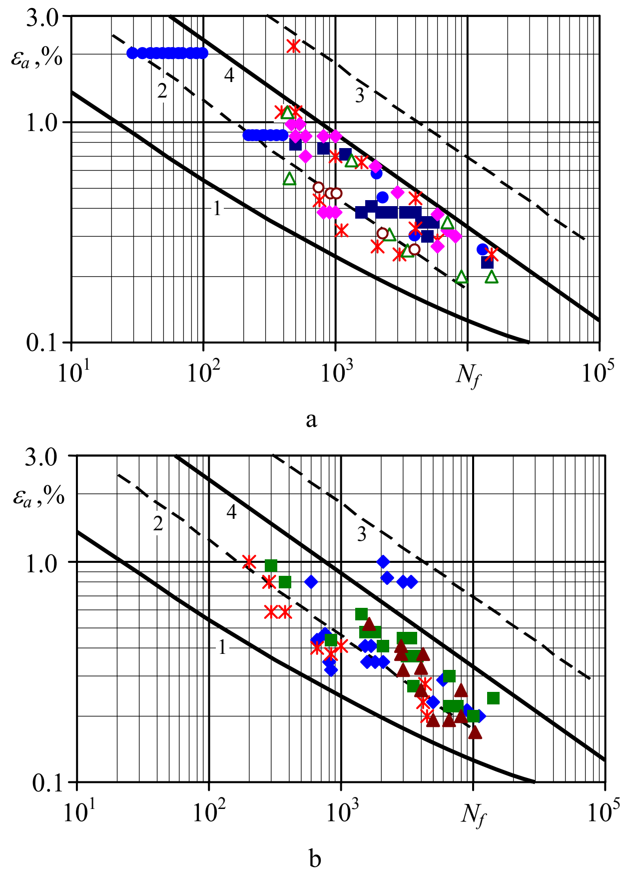



Fig. 2 Low cycle fatigue of 15Cr2MoVA steel welds, produced by SAW using Sv-10CrMoVTi wire: a– at 20°C temperature (6 heats of welding wire); b – at 350°C temperature (4 heats of welding wire). Dots– experimental data for different weld metal; *1* – reference curve [5] for low alloyed steel; *2* and *3* – data falling outside the 5 and 95% tolerance bounds for base metal at 20°C; *4* – mean square dependence for base metal at 20°C (see Fig. 1)

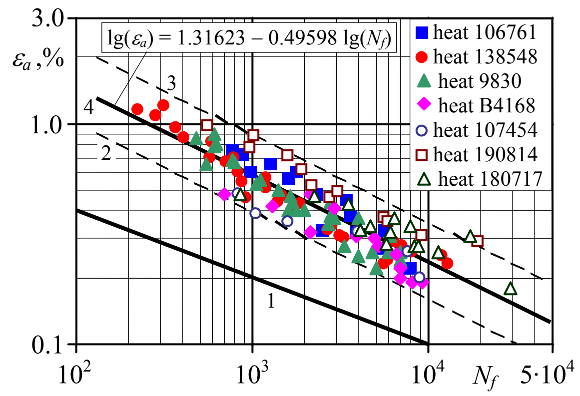
mental dots as a rule are not beyond the boundary of lower envelope of data array. This location is confirmed to a greater degree for pure 15Cr2MoVA-A steel and this is conveniently illustrated by the experimental results.

What concerns welds (see the data presented in Fig. 2, b) the increase of test temperature from 20 to 350°C leads to the reduction of low cycle fatigue resistance of these welds. Even for metal of welds produced using SAW under flux with Sv-10CrMoVTi-A wire some experimental dots for all three tested welds are beyond the boundary of lower envelope curve for the base metal. In this connection we consider advisable to use the reduction coefficients according to Table 5.8 of PNAE G-7-002-86 in the cyclic strength assessment of welded joints of equipment from 15Cr2MoVA and 15Cr2MoVA-A steels [5].

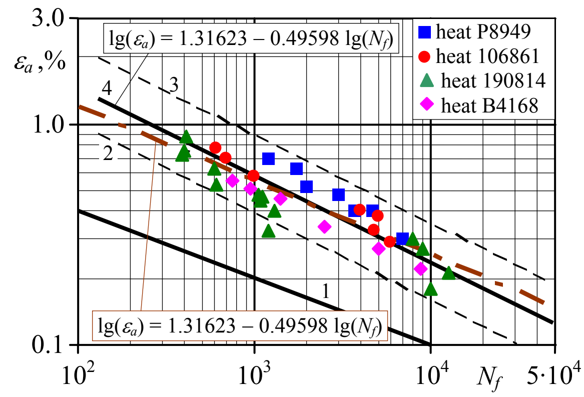
In reference to this type of heat-resistant steel we can see:

- at the stage of fatigue crack nucleation within the range of temperatures typical for operating WWER-440 reactors has a high stability of fracture resistance by low cycle loading (the total number of cycles is within the limits $10^2$ - $10^5$) not only during their design service life (30 years) but also by its extension by 15 years;
- low cycle fatigue resistance of equipment made from 15Cr2MoVA steel practically does not depend on the content of harmful impurities (sulphur, phosphorus, etc) in it at the stage of fatigue crack nucleation;
- the increase of test temperature (up to 350°C) and water medium (coolant of the primary circuit) have some influence on failure resistance at the stage of fatigue crack nucleation of this steel, however in practice do not result in the change of lower (95%) boundary of scatter band of experimental data, obtained on the representative number of 15Cr2MoVA steel heats at room temperature;
- low cycle fatigue resistance of metal of welds produced by SAW using Sv-10CrMoVTi wire under AN-42 flux is lower than that of base metal. On the basis of obtained results it was determined the value of cyclic strength conditions of WWER-440 RPV that type 15Cr2MoVA steel reduction coefficient is equal to $\varphi_s = 0.8$ for the above stated welded joints of 15Cr2MoVA steel.

The experimental results for data array for 15Cr2NiMoVA steel are presented in Fig. 3. Steel of Cr-Ni-Mo-V composition is used at manufacture for VVER-1000 reactor pressure vessel. Usually all shells of RPV [7] are produced from the forgings of different thickness (from 192 mm to 450 mm). The mechanical properties of these

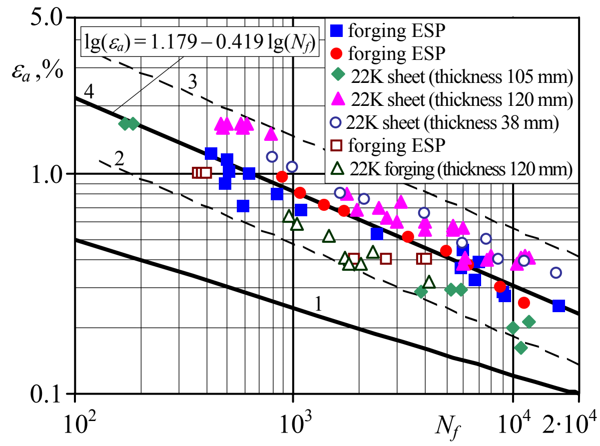



a

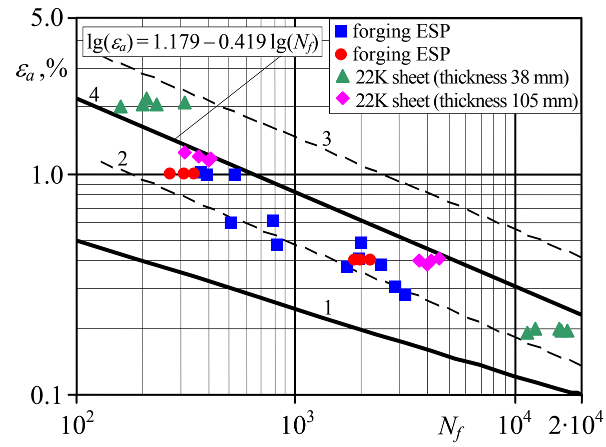



b

Fig. 3 Low cycle fatigue of 15Cr2NiMoVA steel: a – at 20°C temperature (7 heats); b–at 350°C temperature (4 heats). Dots – experimental data for different heats of steel; *1* – reference curve [5] for low alloyed steel; *2* and *3* – data falling outside the 5 and 95% tolerance bounds for steel at 20°C; *4* – mean square dependence for the scatter band for steel at 20°C




a




b

Fig. 4 Low cycle fatigue of 10G2NiMoVA steel: a – at 20°C temperature (7 heats); b–at 350°C temperature (4 heats). Dots–experimental data for different heats of steel; *1* – reference curve [5] for low alloyed steel; *2* and *3* – data falling outside the 5 and 95% tolerance bounds for steel at 20°C; *4* – mean square dependence for the scatter band for steel at 20°C shells are distinguished. Consequently the low cycle fatigue resistance can be various and it is necessary to test the metal of these forging on cyclic strength. As you can see all experimental dots for 7 heats of this steel are conducive to the narrow scatter band (Fig. 3, a). Lower 95% tolerance bounds for steel of this composition at 20°C is located on relation to the Reference curve [5] for low alloyed steel and take into account the safety factors $n_N = 10$ and $n_\sigma = 2$. Mean square dependence for the scatter band for Cr-Ni-Mo-V steel at 20°C and 350°C practically coincide (Fig. 3, b). The curve plotted on the base of experimental data and corresponding to 50%probability is located above Reference curve, which was constructed without consideration of margin factor [8].

Investigations of low cycle fatigue of 10G2NiMoVA steel at 20°C were carried out on 7 heats and at 350°C – on 5 heats. Experimental data are presented in Fig. 4 and were received for semiproducts which used at manufacture of steam generators PGV-1000 and main circulating circuit of NPP with WWER-1000 reactors. As the semiproducts used sheets and forging which melted in open-hearth furnace and electroslag remelting. The various method of production effects on standard mechanical properties at static loading and also on cyclic characteristics including low cycle fatigue. The experimental data are presented in Fig. 4, a at 20°C and Fig. 4, b at 350°C [8].

Experimental tests on low cycle fatigue of 08Cr18Ni10Ti steel at 20°C were performed on 6 heats and at 350°C – on 3 heats. In total we received 134 experimental points for base metal in the room temperature and 43 points in elevated temperature. The experimental results are presented in Fig. 5. These results show that the greater part of experimental points obtained at 350°C lies within the scatter band of data for 20°C. Hence, an increase in the temperature within the limits mentioned above does not affect the breaking strength under cyclic loading in the elasto-plastic region [9].

Experimental results of low cycle fatigue tests for low carbon steel of grade 22K are shown in Fig. 6. Here data of 22K steel after various procedures (melting in open-hearth furnace, electro-slag and vacuum-arc remelting) is presented. These data were received for forging, sheet rolling and a pipe at room and elevated temperatures. The thickness of semiproducts is changed from 38 to 120 mm. All experimental points are located in a fairly narrow scatter band and, therefore, can be referred to a single general population. This fact enabled us to construct a mean-square relation (solid line 4) and bound areas of the 95% confidence interval (dashed lines 2 and 3) for the entire array of experimental data. The mean-square relation is described

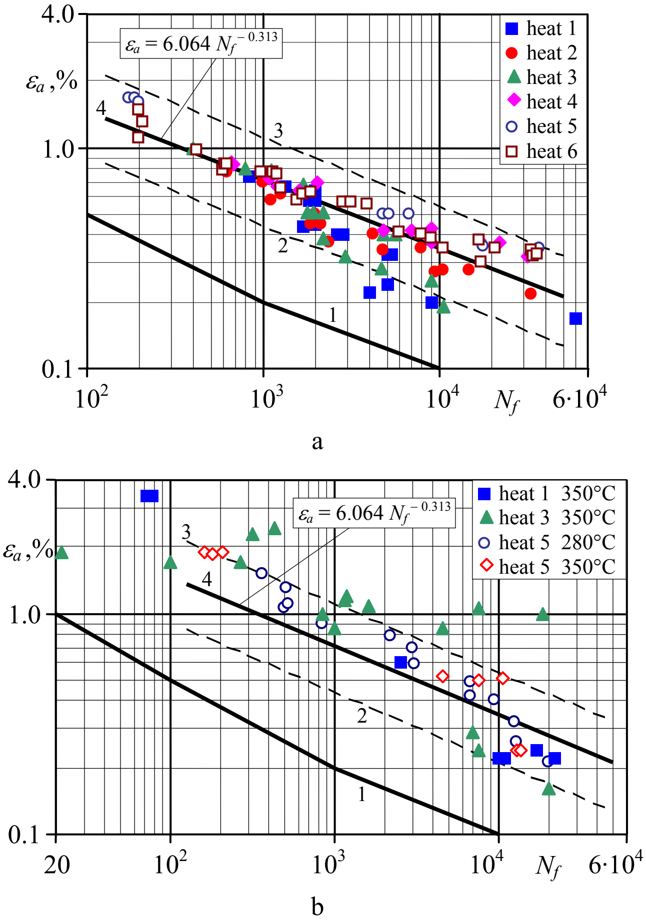



Fig. 5 Low cycle fatigue of 08Cr18Ni10Ti steel: a – at 20°C temperature (6 heats); b–at 350°C temperature (3 heats). Dots–experimental data for different heats of steel; *1* – reference curve [5] for low alloyed steel; *2* and 3 – data falling outside the 5 and 95% tolerance bounds for steel at 20°C; *4* – mean square dependence for the scatter band for steel at 20°C

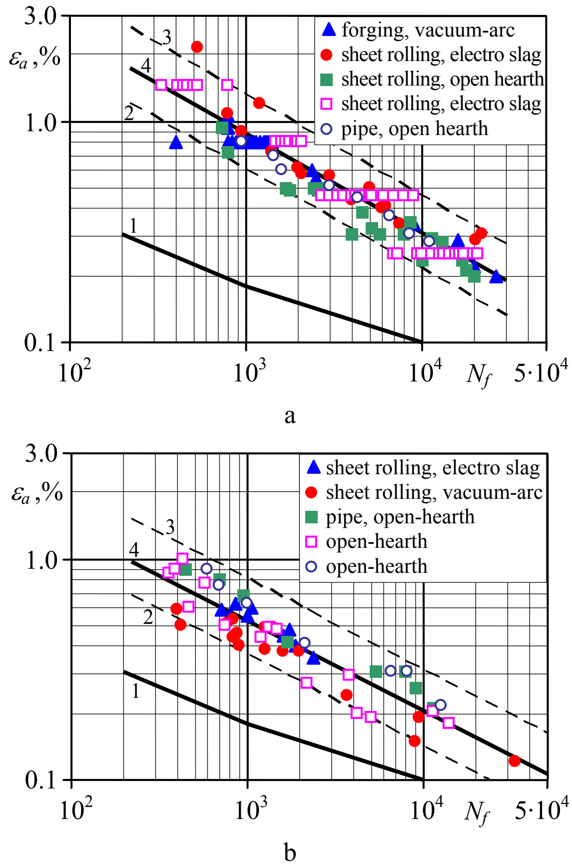



Fig. 6 Low-cycle fatigue curves of 22K steel of different melting: a – at room temperature; b – at 350°C temperature. Dots – experimental data for different heats of steel; *1* – reference curve [5] for low alloyed steel; *2* and *3* – data falling outside the 5 and 95% tolerance bounds for steel at 20°C; *4* – mean square dependence for the scatter band for steel at 20°C

by the formula $log\ \varepsilon_a$ = 1.29154-0.45116 $log\ N$. Comparison of this relation and the lower envelope of the common data array at 20°C with the design curve of fatigue for carbon steels (line 1) [2] shows that the values of safety factors $n_\sigma$ = 2 and $n_N$ = 10 by the lower envelope (line 3) are provided for the base metal [10].

## 5. Conclusions

Experimental results on low cycle fatigue of steel and its welds, widely used in nuclear industry, have been summarized. This information has been received on rather representative number of base metal heats and welded samples for reactor pressure vessels, steam generators and pipe-lines. Experimental data have been compared with Reference curves in Russian Strength Calculation Norms PNAE G-7-002-86. It has been shown that the values of margin factors $n_\sigma$ =2 and $n_N$ = 10 in fatigue strength assessment of equipment from ferrite and austenite steels are provided.

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ATOMINĖJE PRAMONĖJE NAUDOJAMŲ MEDŽIAGŲ MAŽACIKLIS NUOVARGIS

R e z i u m ė

Darbe aptariami plieno ir kitų lydinių mažaciklio nuovargio bandymų rezultatai, plačiai naudojami atominėje pramonėje. Informacija pagrįsta reprezentatyviu skaičiumi pagrindinio metalo ir suvirinimo bandinių, naudojamų reaktorių, garo generatorių slėginiuose induose ir vamzdynuose. Eksperimento duomenys buvo lyginami su etaloninėmis kreivėmis, pateiktomis rusiškose stiprumo skaičiavimo normose PNAE G-7-002-86. Pateiktos ribinių faktorių vertės $n_\sigma$ = 2 ir $n_N$ = 10 atsižvelgiant į įrenginių, pagamintų iš feritinių ir austenitinių plienų, nuovargio stiprumą.

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LOW CYCLE FATIGUE OF MATERIALS IN NUCLEAR INDUSTRY

S u m m a r y

Investigation data on low cycle fatigue of steel and its welds, widely used in nuclear industry, have been summarized. This information has been received on rather representative number of base metal heats and welded samples for reactor pressure vessels, steam generators and pipe-lines. Experimental data have been compared with Reference curves in Russian Strength Calculation Norms PNAE G-7-002-86. It has been shown that the values of margin factors $n_\sigma$ =2 and $n_N$ = 10 in fatigue strength assessment of equipment from ferrite and austenite steels are provided.

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МАЛОЦИКЛОВАЯ УСТАЛОСТЬ МАТЕРИАЛОВ, ИСПОЛЬЗУЕМЫХ В АТОМНОЙ ПРОМЫШЛЕННОСТИ

Р е з ю м е

В работе анализируются результаты малоцикловой усталости стали и других сплавов, используемых в атомной промышленности. Представленный материал иллюстрирован репрезентативным числом плавок основного металла и сварки, применяемых в сосудах давления реакторов, парогенераторов и в трубопроводах. Данные эксперимента сравнены с эталонными кривыми, представленными в российских расчетных нормах на прочность ПНАЕ Г-7-002-86. Представлены предельные значения коэффициентов запаса $n_\sigma$ = 2 и $n_N$ = 10 оценивая, усталостную прочность оборудования, изготовленного из ферритных и аустенитных сталей.

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