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INFLUENCE OF OXYGEN-CONTAINING LEAD MELTS ON THE FATIGUE STRENGTH OF AISI 409L STEEL AT ELEVATED TEMPERATURES

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We study the regularities of the influence of lead and lead–bismuth eutectic melts on the fatigue strength of AISI 409L (Fe–11Cr) steel of the ferritic class within the temperature range 500–600°C. It is shown that they reduce the resistance to long-term static loading of steel as compared with its resistance in a vacuum. As temperature increases, the negative influence of the eutectic becomes more pronounced as a result of the corrosive action of lead melts, namely, as a result of the selective dissolution of chromium along grain boundaries and the formation of iron oxides, which rapidly embrittle under loading and, thus, facilitates the fracture processes in the material.

Keyword: ferritic steel, lead and lead–bismuth eutectic melts, fatigue strength, liquid metal embrittlement.

The development of nuclear power plants (NPP) of a new generation with elevated safety includes, parallel with the other factors, the use of liquid-metal cooling systems. Due to their physicochemical properties, melts of heavy metals (Pb, Bi, Pb–Bi, and their eutectic mixture) serve as candidates for application as cooling media of fast reactors (of the LEADER, ALFREDO, BREST, SFBR, and MBIR types) and subcritical hybrid accelerator-driven systems (ADS) [1–3].

As the main structural materials in NPP, it is proposed to use steels of the ferritic–martensitic class (based on the Fe–Cr system). Due to their high physicomechanical characteristics, compatibility with the main cooling media, and low susceptibility to swelling, these steels prove to be promising materials for the first wall and blanket of fusion reactors, fuel elements, steam generators, and structural elements of the coolant pumps of fast reactors [4, 5].

In service, the melts of hard metals negatively affect the corrosion and mechanical properties of structural materials [6]. The problem of corrosive action of lead media upon steels is solved by using coolants with controlled oxygen content, which promotes the formation of protective oxide films on steel surfaces [7]. In the course of long-term operation, when the creep-induced damage of materials may serve as the cause of fracture of the structural elements of NPP, it is important to study the influence of these media on the mechanical behavior of materials under stresses lower than the yield strength. Under the conditions of interaction of steel with adsorption-active media (lead melts), these media become additional factors of the decrease in fracture stresses and change the picture of development of the corresponding stages of fracture of the material.

The aim of the present work is to establish the regularities of the influence of liquid-metal media (Pb and Pb–Bi) on the strength of the (Fe–11Cr) reactor steel under long-term static loads at elevated temperatures.

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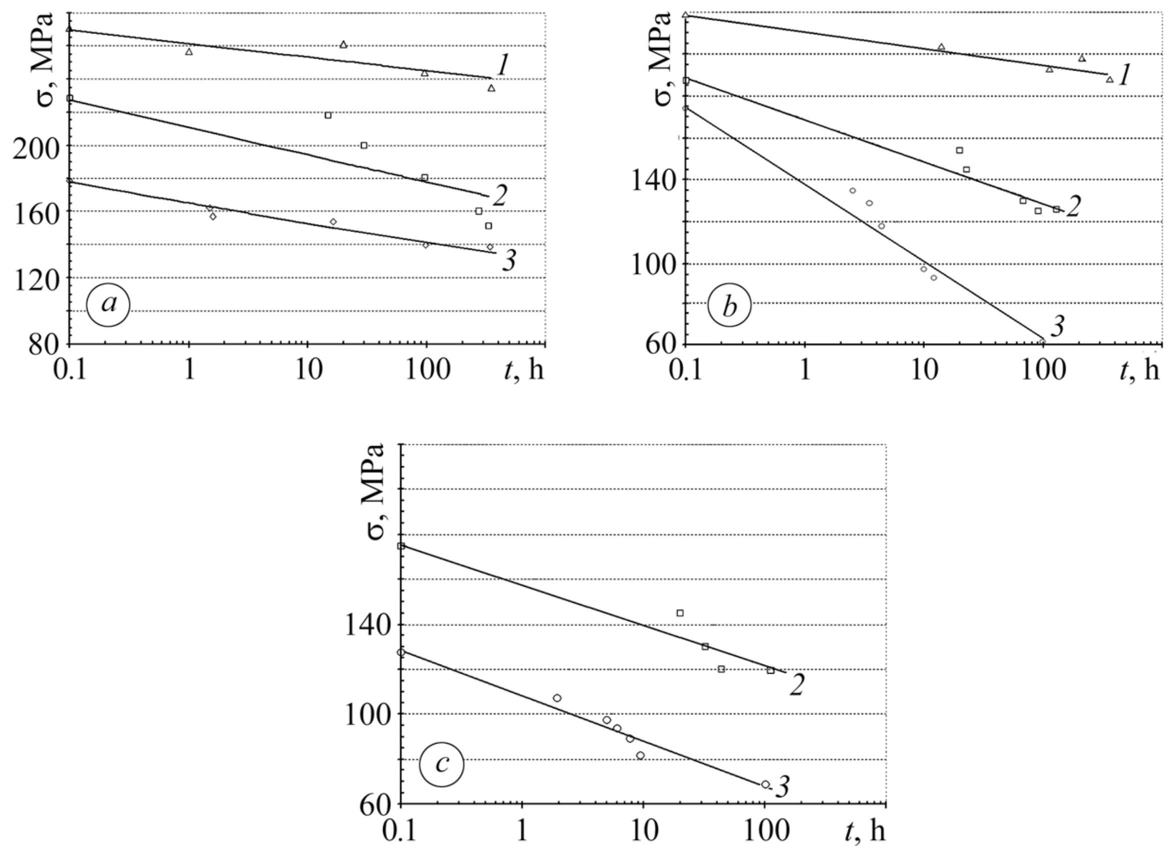


Fig. 1. Dependences of the fatigue strength of AISI 409L steel on the time of testing in a vacuum (a), lead melt (b), and lead–bismuth eutectic melt (c) at 500°C (1), 550°C (2), and 600°C (3).

Materials and Methods

We studied microspecimens of 409L (Fe–11Cr) steel of the ferritic class with a working section of 2 mm cut out from a sheet material with a thickness of 1 mm. Prior to treatment, the specimens were washed in gasoline, acetone, and alcohol and then dried. The technological allowance equal to 1 mm per side after shaping was removed by grinding. The working part of the specimens was brought to the required sizes and its surface was finished in hard-alloy templates by using abrasive paper with zero size of abrasive grains. Prior to testing, the specimens were annealed in a vacuum at a temperature of 1050° C for 30 min.

The fatigue strength was found at temperatures of 500, 550, and 600°C in an R-0.5 multiposition tensile testing machine developed at the Karpenko Physicomechanical Institute of the Ukrainian National Academy of Sciences in a vacuum (10^{-5} Pa) and in media of lead and lead–bismuth eutectic melts, the remaining space over which was filled with commercially pure argon. The fact that the machine is multiposition enables one to get identical testing conditions for a large number of specimens.

To determine the mechanical properties of specimens in metal melts, we used special equipment for working with liquid metals (a high-pressure chamber and the equipment required for melting and pouring liquid metals). The volume of the chamber over the specimens in melts was filled with spectroscopically pure argon in which the concentration of oxygen did not exceed $5 \cdot 10^{-3}$ mm Hg. Prior to testing, the specimens were tinned with lead and eutectics with the use of a flux (for better wetting of the metals).

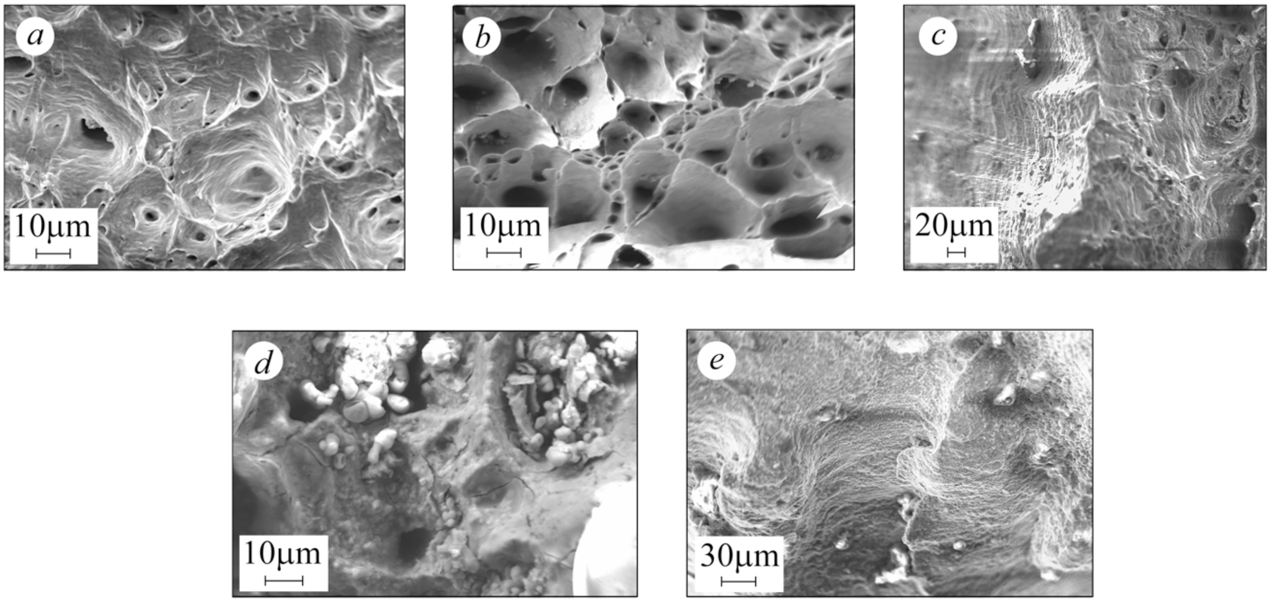


Fig. 2. Microfractograms of the specimens of AISI 409L steel after fracture in a vacuum at 500°C under a stress of 257 MPa (a) and at 550°C under a stress of 218 MPa (b); in lead melts at 500°C under a stress of 198 MPa (c) and at 550°C under a stress of 200 MPa (d); in lead–bismuth melts at 550°C under a stress of 181 MPa (e).

The distributions of chemical elements and the characteristic features of the fracture surfaces of specimens were studied in a scanning electron microscope (Carl Zeiss AG; EVO-40 Series) equipped with a detector for energy-dispersive X-ray diffraction analysis (EDX).

Results of Investigations and Discussion

Fracture in a Vacuum. As the testing time increases, the strength of steel decreases (Fig. 1a) at all testing temperatures. Thus, the ultimate fatigue strength in 10-h tests is equal to 255 MPa at 500°C, to 195 MPa at 550°C, and to 150 MPa at 600°C (decreases by 42%), whereas the ultimate fatigue strength in 100-h tests is equal to 245, 175, and 140 MPa, respectively (decreases by 43%).

The analysis of the surfaces shows that fracture occurs according to the ductile mechanism (Figs. 2a, b). We see numerous deformation crests and valleys and, at the same time, we see that brittle cleavage facets are almost absent. The sizes of the cups characterizing the level of intense plastic strains are fairly large. The cups on the ductile fracture surfaces appear as a result of the formation, growth, and coalescence of numerous micropores (or microcracks) [8]. On the surfaces of destroyed walls and at the bottom of the valleys, we observe slip lines.

Fracture in Lead. As in vacuum, the fatigue strength of steel decreases in lead both with time and as the testing temperature increases (see Fig. 1b). In particular, in the course of 10-h tests, the fatigue strength is equal to 205 MPa at 500°C, to 150 MPa at 550°C, and to 105 MPa at 600°C (decreases by 49%) and, in 100-h tests, it is equal to 190, 130, and 70 MPa, respectively (decreases by 63%).

On the fracture surface, at a temperature of 500°C, we recorded a network of ductile crests and valleys (Fig. 2c). At the bottom of the valleys, we detected slip lines formed as a result of plastic deformation of the specimens prior to fracture. At the same time, the zones with cleavage facets became well visible (Fig. 2d).

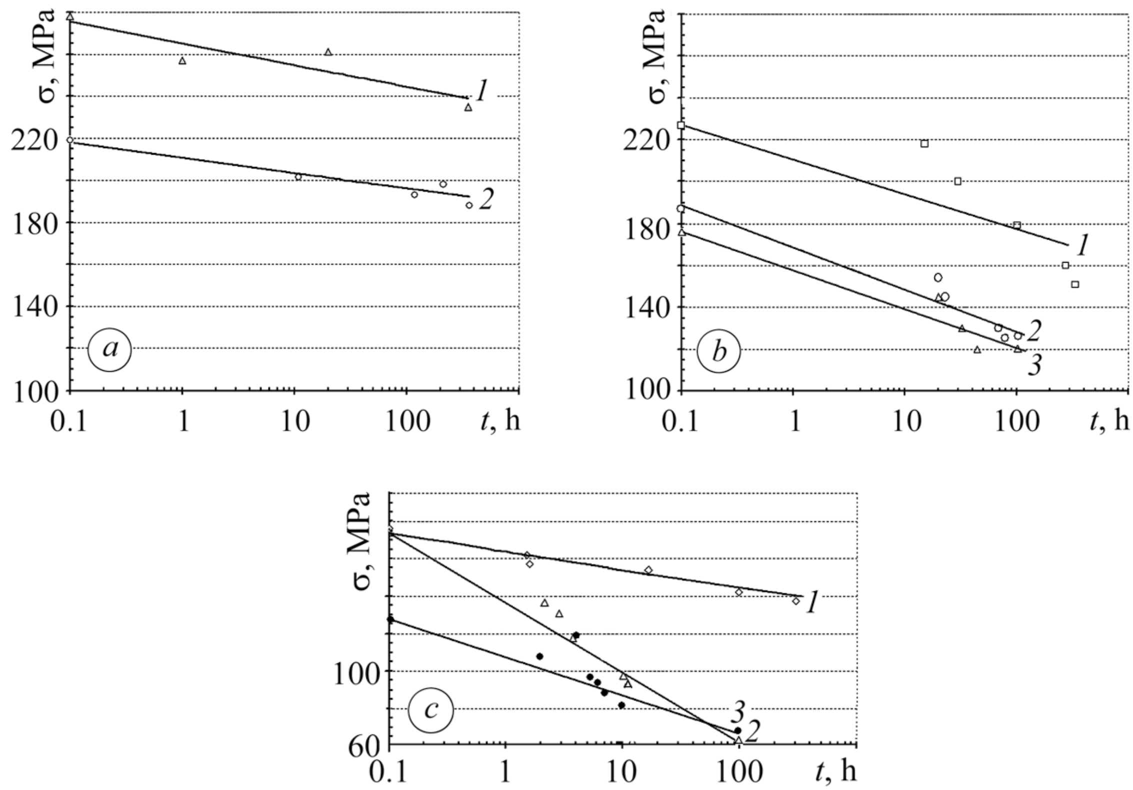


Fig. 3. Comparison of the fatigue strength of AISI 409L steel in a vacuum (1), in lead melts (2) and in Pb–Bi eutectic melts (3) at 500°C (a), 550°C (b), and 600°C (c).

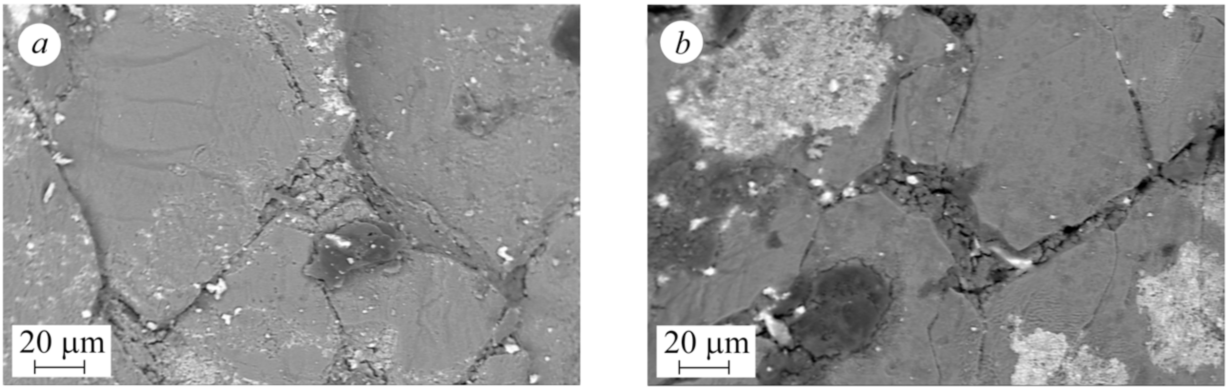
Moreover, we observed secondary cracks on the fracture surfaces (Fig. 2d). This confirms the presence of variable ductile–brittle mechanism of fracture under the analyzed conditions.

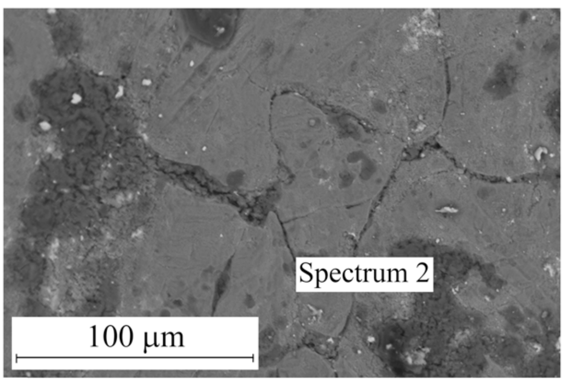
Fracture in Lead–Bismuth Eutectics. As in the previous cases, the fatigue strength of steel decreases with the time of testing in Pb–Bi and as temperature increases from 500 to 600°C (see Fig. 1c). As a result, it becomes almost twice lower in the course of 10-h and 100-h tests (namely, decreases from 120 to 65 MPa).

The results of fractographic analysis show that fracture occurs according to the ductile mechanism and is accompanied by the formation of deformation crests and valleys. In this case, only individual cleavage facets were recorded (Fig. 2e).

The comparison of the fatigue strength of steel in different media (Fig. 3) shows that, as compared with vacuum, lead melts make the resistance of AISI 409L steel to long-term static loading 1.3–2 times lower within the temperature range 500–600°C. As temperature increases (up to 600°C), we observe certain distinctions between the influences of lead and lead–bismuth eutectic depending on the testing time. Indeed, the decrease in the fatigue strength in the eutectic melt is more pronounced than in lead.

The analysis of microstructure of the metal and the local contents of chemical elements in the deformed parts of the specimen held in the eutectic mixture under static loading at 600°C without fracture helps us to explain the decrease in the fatigue strength of the material in lead melts. It was shown that the embrittling action of lead melts promotes the initiation of intergranular cracks in the subsurface layers of the specimen (Figs. 4a, b) and that their corrosion action results in the selective dissolution of chromium, which decreases the energy of bonding on the grain boundaries, where the formation of oxides based on iron is accelerated as a result of the interaction of iron with oxygen present in the melt.





c

Element	wt.%	at.%
O K	41.09	71.60
Cr K	2.88	1.55
Fe K	52.96	26.44
Pb M	3.07	0.41
Total	100.00	100.00

Fig. 4. SEM structure of AISI 409L steel after holding in lead–bismuth eutectic melt at a temperature of 600°C (a, b) and the local contents of chemical elements (c).

The local chemical analysis confirms that dark formations near the grain boundaries are iron oxides, whereas the content of chromium in this region is minimal (Fig. 4c). The process of crack initiation occurs just in this region. This facilitates deformation and, hence, decreases the time to fracture.

CONCLUSIONS

Lead melts and lead–bismuth eutectics make the fatigue strength of AISI 409L (Fe–11Cr) ferritic steel 1.3–2 times lower than in vacuum within the temperature range 500–600°C. The negative influence of the eutectic increases with temperature. As one of the causes of decrease in the fracture resistance of steel, we can mention the corrosion action of lead and eutectics or, more precisely, the processes running along the grain boundaries: selective dissolution of chromium and the formation of oxides based on iron. These oxides embrittle under loading, which facilitates the fracture of the material.

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