Study characteristics of failure multilayered steel materials in conditions at alternating symmetrical bending

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Abstract. The article presents a study of behaviour of multilayered steel materials in conditions of alternating symmetrical bending when heavy stress is applied at low-cycle fatigue conditions with the use of bending unbending test. The study showed different behaviour pattern when applying stress to two compositions of multilayered steel materials – W108+AISI 304 and W108+AISI 430. The fractographic analysis of fatigue rupture surfaces was used to explain the results obtained in studying the number of cycles prior to fracture, which showed that the mode of failure of the two compositions of multilayered steel materials was different.

1. Introduction

The modern level of mechanical engineering development calls for studies in the field of analysis and application of the new classes of structural materials. And among them it is possible to distinguish a class of multilayered steel materials with a multilayer (or lamellar) structure [1]. Lamellar structure is a multilayer composition including hundreds (or thousands) of layers with micron (submicron) thickness (Figure 1). Owing to laminarity of structure, a high complex of fatigue properties is formed in multilayered steel materials [2]. On the other hand, a laminar structure allows to obtain the anisotropy of fatigue properties. Therefore, the multilayered steel materials can develop their fatigue properties to the maximum extent when used in the parts of machines or constructions which operate at conditions of alternating symmetrical bending with normal stress [3]. With that, a short-term heavy stressing at low-cycle fatigue can be a limiting factor when using such materials at conditions of alternating symmetrical bending. Therefore, a study of behaviour and failure characteristics of multilayered steel materials in conditions at alternating symmetrical bending with heavy stressing at low-cycle fatigue is of high relevance.
2. Materials, methods and experiment

An experimental method of procedure was developed for the synthesis of multilayered steel materials, which consists of several process cycles each including the productive method of hot pack rolling [4]. Each process cycle is a series of same-type process operations following one after another:

1) measured cutting of parent steel sheets or finished steel sandwich;
2) preparation of billets (machining of their surfaces);
3) formation of multiple sandwich from billets;
4) hot rolling of multiple sandwich and generation of multilayered steel material sheet.

Rolled steel sheets of two steel grades with thickness of 0.5 mm were the source materials for the synthesis of multilayered steel materials. The following compositions based on carbon steel grade W108, austenitic stainless steel grade AISI 304 and ferritic stainless steel grade AISI 430 were taken for the purposes of this study: W108+AISI 304 and W108+AISI 430.

Only one process cycle of the experimental procedure method was used for the purposes of this study. At the start of the first process cycle the billets – measuring cards cut from the steel sheets of above-mentioned grades – were subjected to surface treatment. Next, a multiple sandwich was formed from the cards, consisting of 100 alternating steel grades, 50 pieces of each grade. The formed multiple sandwich was vacuumed and hot rolled at 1000 °C. As a result, after the first process cycle a multilayered steel material of two compositions was synthesized with the thickness of 2 mm, comprising 100 layers with the thickness of 20 µm each.

Specimens of type No. IV (GOST 25.502-79) were manufactured from the sheets of multilayered steel materials of compositions W108+AISI 304 and W108+AISI 430 for conduction of studies on the analysis of behaviour and failure characteristics of multilayered steel materials at alternating symmetrical bending when applying heavy stress at low-cycle fatigue conditions. For achievement of such type of bend under the given conditions, a device (Figure 2) was used, applicable in the bending unbending test (GOST 1579-93).

According to the method of experiment on this unit, first a test specimen 1 is placed between two drivers 2, which are fixed on the bending lever 3. From one side, a specimen is installed so that the fountain axis of bending lever is aligned with the central axis of the test specimen. From the other end, the specimen is placed between two mandrels 5. From the other side, a specimen is installed so that the mandrels are in one plane and parallel to each other and to the fountain axis of bending lever. Next, the test specimen is fixed by means of jaw details 7 and by means of grip 6. Loading of the test specimen is
performed by turning the bending lever clockwise and back at 90° angle from initial position of the lever. Loading is performed until failure of the test specimen. Changing mandrels with different diameters, simultaneously count the number of cycles to failure.

Figure 2. Layout of the device used in the bending unbending test (GOST 1579-93): 1 – test specimen; 2 – driver; 3 –bending lever; 4 – fountain axis of bending lever; 5 – mandrel; 6 –grip; 7 – jaw details.

The fractographic analysis of failure surfaces of the specimens of multilayered steel materials was carried out with the use of Vega Tescan 5130 scanning microscope at acceleration voltage of 20 kV.

3. Results and discussion
Results of the experiment (Figure 3) showed that by increasing the degree of loading by way of reducing the diameters of mandrels (from 30 mm, to 15 mm, and finally to 3.5 mm) caused the number of cycles to failure in W108+AISI 304 composition to decrease in 6 times (from 12 cycles to 2 cycles to failure). At the same time, on loading the composition W108+AISI 430 identically, it was discovered that when loaded, with the use of any diameter of mandrel, a specimen failed even before completion of one bend. I.e. the number of cycles to failure was zero for the composition W108+AISI 430.
Figure 3. Results of the experiment on studying the behaviour of multilayered steel materials at alternating symmetrical bending with heavy stressing at low-cycle fatigue conditions.

The fractographic analysis showed that, at the fracture (Figure 4) of multilayered steel material of composition W108+AISI 304 in the layer of former W108 steel, it is possible to see the cleavage facets and a large number of dimples, initiating ductile failure around them. In the layer of former AISI 304 steel one can see the fatigue striations, as well as vertical exfoliation joints. The appearance of fatigue striations is explained by the fact that flat glide is typical for stainless steels under cyclic stressing [5]. A large amount of dimples is explained as follows. At the synthesis of multilayered steel material of this composition during the hot rolling both steels are in the same crystalline state (fcc lattice). Therefore, taking into account the processes of diffusion and considerable chemical affinity of carbon to chromium, carbon diffuses without difficulty through interlayer border to the layer of AISI 304 steel. As a result, a large amount of carbides is formed in the layer of AISI 304 steel, causing the appearance of a large number of micropores during stressing, which merge to form a large number of dimples.
Figure 4. Fractography of fractured surface in a multilayered steel material of composition W108+AISI 304.

At the fracture (Figure 5) of multilayered steel material of composition W108+AISI 430 in the layer of former W108 steel, one can see cleavage cracks, exfoliation joints, lines of streamlet pattern. All this is indicative of the brittle mode of fracture in the layer of former W108 steel. In the layer of former AISI 430 steel one can see a small number of dispersed dimples and some cleavage cracks.

Figure 5. Fractography of fractured surface in a multilayered steel material of composition W108+AISI 430

Brittle mode of failure is explained as follows. At the synthesis of multilayered steel material with composition of W108+AISI 430, the steels are in different crystalline state (W108 steel has fcc lattice, and AISI 430 steel has a stable bcc lattice). As the solubility of carbon is different in bcc and fcc lattices, the diffusion of carbon from fcc lattice to bcc lattice is inhibited. However at the synthesis of multilayered steel material it is gradually thinned. This is due to the fact that a process cycle consists of several passes during rolling. During rolling the actual temperature of the billet (Figure 6), due to gradual thinning, might become less than the temperature of direct diffusionless transformation. This will result
in quenching of W108 steel layer on passing through the mill rollers, thus making the layer of W108 steel brittle when subjected to stress.

Figure 6. Flow chart of rolling

On the other hand, considerable chemical affinity of chromium to carbon should be taken into account, which will cause insignificant carbon diffusion and insignificant redistribution of chromium in AISI 430 steel. As a result the concentration of chromium in AISI 430 steel will be reduced [6], and the phase state of AISI 430 steel will change from $\alpha$ to $\alpha+\gamma$ according to the isothermal section of the ternary diagram of Fe-Cr phase equilibrium at 1000 °C (Figure 7), which will lead to the appearance of a small amount of carbides. Appearance of carbides will provoke the appearance of a small number of micropores, the coalescence of which will result in the appearance of a small quantity of dimples. Therefore the contribution of ductile failure to the general fracture mode will be much less than the contribution of brittle failure in the layer of W108 steel.

Figure 7. Isothermal section at 1000 °C of the Fe-Cr phase equilibrium diagram [6]

4. Conclusions
Consequently, the analysis of behaviour of multilayered steel materials with compositions W108+AISI 304 and W108+AISI 430 under conditions of alternating symmetrical bending with heavy stressing at low-cycle fatigue conditions has shown that the composition W108+AISI 304 withstands a large number of bends with unbends, while for the composition W108+AISI 430 this number was equal to zero. This different behaviour is described by different failure mode of the given compositions: in composition W108+AISI 304 the mode of failure is ductile whereas in composition W108+AISI 430 it is brittle. Different mode of failure is explained by different changes occurring in the structure of multilayered steel materials during their synthesis.

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