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Behavior of Fe-Mn-Al-C Steels during Cyclic Tests

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Alloys of the FeMnAlC system have been used for cryogenic purposes and for applications up to 673 K. At low temperatures, they have in general a better performance than austenitic Cr-Ni steels as far as fatigue is concerned, but are inferior to martensitic Cr steels. However, since the fatigue strength of FeMnAlC alloys in the temperature range of 523 to 823 K is higher than at room temperature, the present work has been conducted to describe the behavior of such alloys under the action of cyclic loading, including elasto-plastic deformation and cyclic temperatures. It has been concluded that components can be successfully subjected to cyclic loads in the elasto-plastic regime and to periodic changes in temperature under normal service conditions.

Keywords fatigue, thermal fatigue, Fe-Mn-Al-C steels

1. Introduction

More than 90% of premature failure of parts and structural components is due to the action of cyclic loading. Nevertheless, as far as steels of the FeMnAlC system are concerned, very little can be found in the literature.[1,2,3]

Austenitic steels of the class Fe-Mn[~29wt.%]-Al[~9wt.%]-C[~0.9wt.%] in the as-quenched condition have higher fatigue strength than austenitic Cr-Ni steels, but are inferior to martensitic chromium steels, provided that cyclic stresses do not promote plastic deformation.[4]

The fatigue strength of such steels in the temperature range of 523 to 823 K is higher than that at room temperature. The greatest magnitude of fatigue strength σ_{-1} is obtained at 723 K[4] based on 2×10^7 cycles.

The purpose of the present research was to elucidate the behavior of these steels under the action of cyclic loading, including elasto-plastic deformation and cyclic temperatures.

2. Experimental Procedures

A 415 mm square cross section ingot (2200 kg) was produced by electroslag refining (ESR) in an industrial plant with the following composition: Fe-28Mn-9Al-0.86C-0.7W-0.43Mo-0.49Nb (wt.%).

Specimens of ϕ 20 mm and ϕ 60 mm were used, water quenched from 1323 K. For fatigue testing (rotating bending Schenk machine (Carl Schenk GmbH, Darnstadt, Germany)), the samples were similar to the ones described in Ref 4. For comparative purposes, a base of 2×10^7 cycles was chosen. For thermocyclic tests, samples with a ϕ 5 mm working part were used in a chamber (Fig. 1a) with a degree of 80% thermal expansion restriction. Heating of samples by electric resistance up to 873 K was made by a contact method in limited condition, thus ensuring cyclic thermoplastic deformation. The cyclic alternation of temperature from 873 to 313 K was promoted by cooling to 313 K by a jet of compressed air, monitored by a contact thermocouple.

Bending tests were conducted in a ZDM-200PU machine (LIIJT, Leningrad), according to Fig. 1(b), using specimens with ϕ 50 mm working part. The derivation of the free end of each sample was constant and equal to 150 mm. Specimens for tensile test had 5 mm diameter and 25 mm gage length.

Metallographic examination was conducted with a Neophot-21 (Carl Zeiss Jena, GDR) light microscope, the sections preliminary etched with a 4 to 7% solution of nitric acid in ethanol. The structural observation was conducted by transmission eletron microscope (TEM) EMV-100L (Jeol Ltd., Japan) at an accelerating voltage of 100 kV. Thin foils were prepared by electropolishing in a solution of chromic (60 g CrO_3) and phosphoric (400 mL H_3PO_4) acid solution at 20 to 50 °C. The electropolishing was conducted at 15 to 20 V and 5 to 8 A/cm^2.

3. Results and Discussion

3.1 Fatigue Tests

According to Kalashnikov *et al.*,[4] the best results in terms of fatigue strength are obtained when testing at 723 K. Therefore, the investigation of thermocycling influence on the fatigue process was conducted at the temperature of 673 K. It was assumed that thermocycling could increase or reduce the effect of strengthening. At the temperature of 673 K, an increase in fatigue strength was detected, in agreement with Ref 4, but maximum strengthening at this temperature was not attained.

Thermocycling was imposed by constant alternation of heating samples up to 673 K and pulse cooling in distilled water to 293 K. From the data in Fig. 2, it follows that the curve of fatigue strength obtained in conditions of thermocycling occupies an intermediate position between curves of tests at 293 and 673 K. Therefore, the degree of steel strengthening (*i.e.,* the development of deformation aging[5] in zones of microplastic deformation) is clearly time dependent at higher temperatures.

3.2 Thermal Fatigue Tests

The cyclic tests of samples in limited conditions have shown that steels of the Fe-Mn-Al-C system can stand up to 16,000

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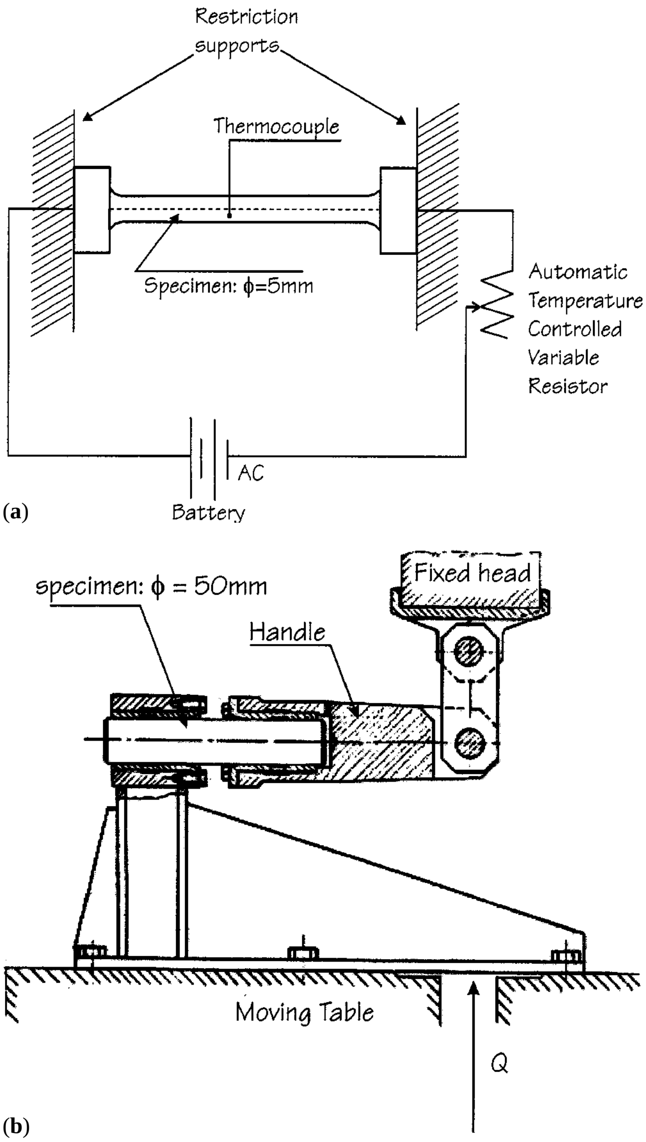


Fig. 1 **(a)** Termocycling test apparatus. **(b)** Elasto-plastic bending test machine ZDM - 200PU

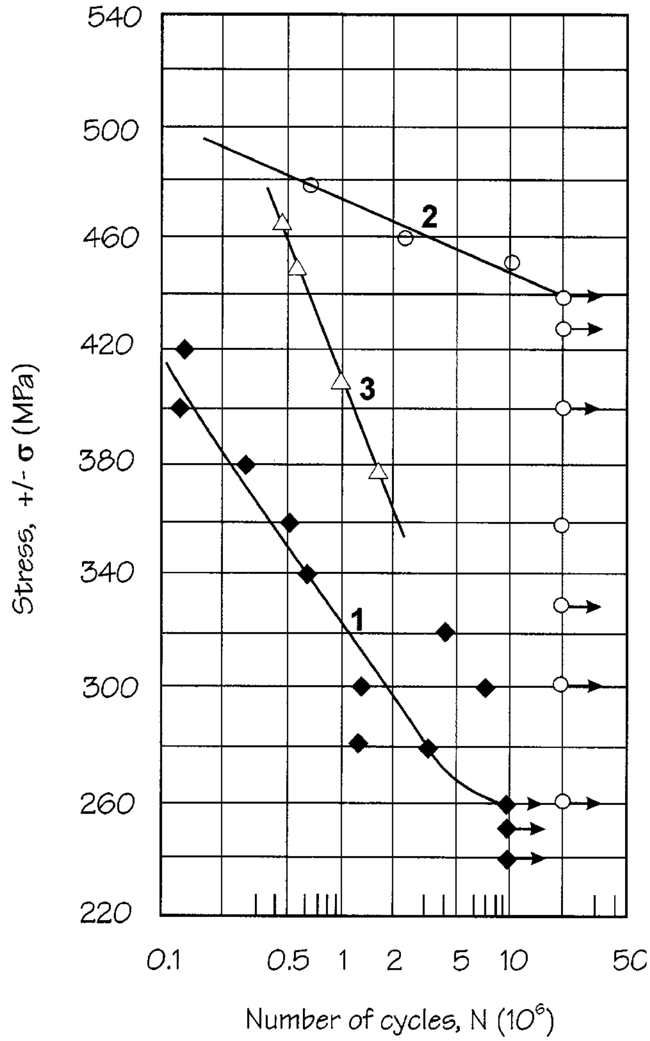


Fig. 2 The $\sigma_{-1} - N$ curves in fatigue test: (1) 293 K, (2) 673 K, and (3) [293 K $\leftrightarrow$ 673 K]

cycles before failure. The martensitic chromium steel Fe-12Cr-1.5Ni-0.2V-1.8W-0.5Mo-0.15C, tested in similar conditions, failed after 9000 cycles; *i.e*, it is nearly two times less resistant.

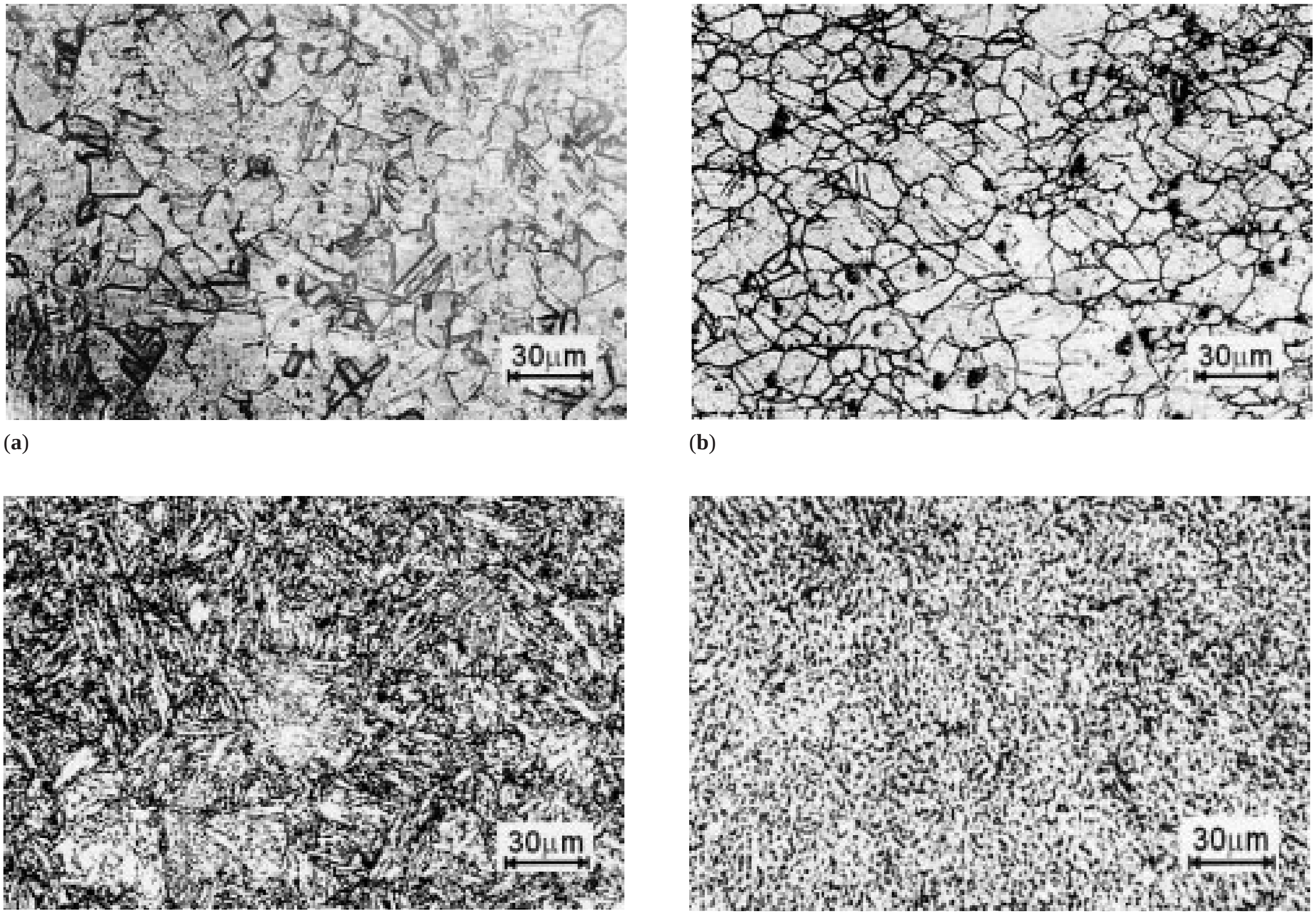
Microstructural examination has shown that, in the case of the Fe-Mn-Al-C steel, the process of high-temperature aging, characterized by the thickening of grain boundary κ phase precipitates, takes place during thermal cycling (Fig. 3a and b).

In the case of the martensitic steel, a solid solution decomposes into a ferrite-carbide mixture characterized by an equilibrium condition. The orientation of the martensitic structure disappears (Fig. 3c and d) and mechanical strength decreases.

3.3 Cyclic Tests in Conditions of Elasto-Plastic Deformation

During alternate bending tests, the work spent on elasto-plastic deformation from cycle to cycle practically did not vary; the loop of a hysteresis is repeated (Fig. 4). The samples that did not fail were able to sustain four times more cycles than similar samples of a martensitic chromium steel of composition Fe-13Cr-0.2C.

The great capacity of strengthening revealed by the Fe-Mn-Al-C alloy is related to features of its austenitic structure during plastic deformation (Fig. 5), whose basic mechanism is mechanical twinning.[6,7,8] Deformation twins act as obstacles to further plastic deformation by sliding and twinning.[9,10] With increasing deformation, the amount of dislocations sharply increased (Fig. 6), and localized tangles of dislocations formed where slipping systems crossed. At each cycle of loading, such highly strengthened local volumes are created, and new sites like these are continuously formed during cyclic loading, what explains the high endurance in conditions of elasto-plastic deformation and the invariance of absorbed energy in each cycle. Failure will occur when every region of the entire volume of the working part has undergone such a process.



(**a**) (**b**) (**c**) (**d**)

Fig. 3 *Austenitic Fe-Mn-Al-C steel:* **(a)** before tests and **(b)** after tests. *Martensitic Cr-Ni steel:* **(c)** before tests and **(d)** after tests. Optical microscopy

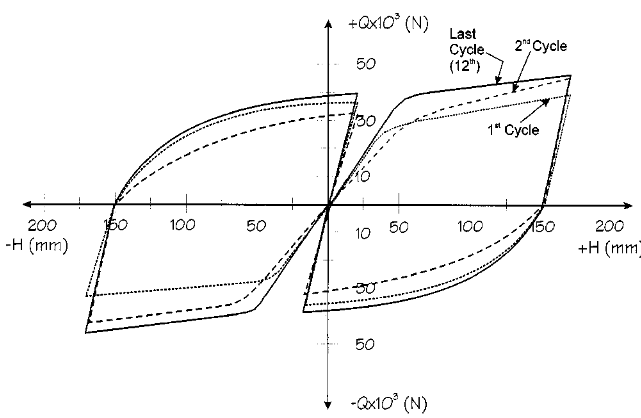


Fig. 4. Force-deflection diagram. Variations with increasing number of cycles. Specimen ϕ 50 mm. (Q) applied load and (H) deflection

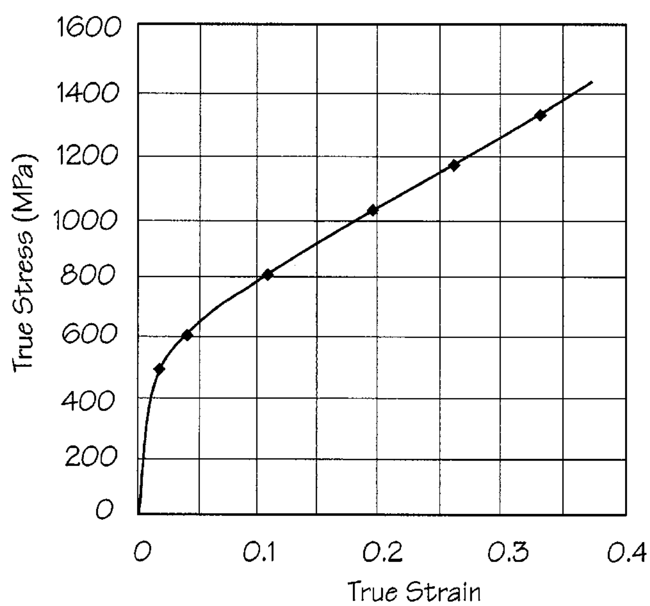
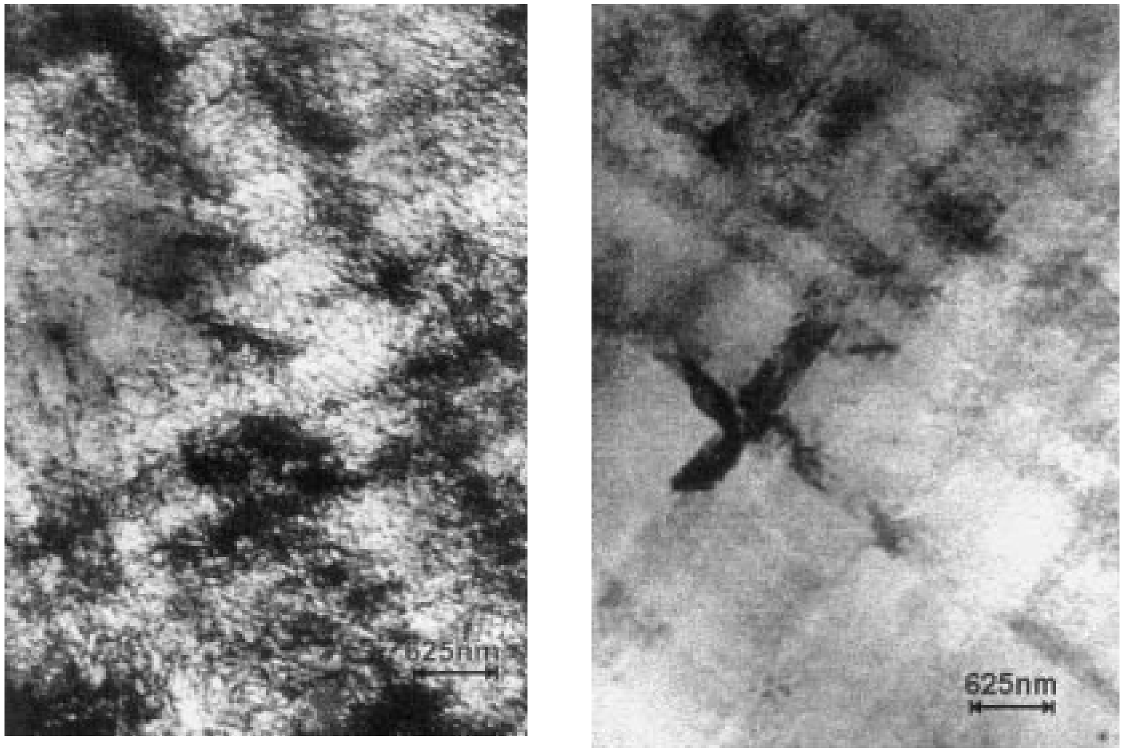


Fig. 5. Strain hardening of Fe-Mn-Al-C austenite. Strain rate 1 mm/min



(a) (b)

Fig. 6 Dislocation structure after cold working Fe-Mn-Al-C austenite: **(a)** 10% and **(b)** 20%

4. Conclusions

The influence of cyclic loading and temperature changes on an austenitic Fe-29Mn-9Al-0.9C alloy were analyzed by different fatigue tests. The main conclusions are as follows.

- Components made of this kind of steel can be successfully used in structures subjected to cyclic loads in the elasto-plastic regime.
- Periodic changes in temperature during normal service conditions do not have any negative influence on the performance of parts manufactured with this kind of steel. The increase in fatigue strength depends upon temperature and exposition time.

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