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# The effect of mean stress on the high-temperature fatigue behaviour of SAE 1045 steel

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**Abstract**

Specimens of the mild steel SAE 1045 in normalized condition were subjected to stress-controlled push–pull fatigue tests at temperatures ranging from 20°C to 375°C. Up to about 250°C, the steel shows a decrease in cyclic strength and in the number of cycles to failure $N_f$ with increasing temperature. A further increase in temperature leads to an increase in strength due to dynamic strain ageing (DSA) which reaches its maximum effect at a temperature $T_{DSA,max}$ of about 325°C. As a consequence of the strongly reduced plastic strain amplitude, a maximum of the cyclic lifetime could be observed at a temperature close to $T_{DSA,max}$. Tests with superimposed mean stresses varying from $\sigma_m = -80$ MPa to $\sigma_m = +60$ MPa showed that a positive (tensile) mean stress generally increases the plastic strain amplitude and reduces the fatigue life and vice versa. The study of the microstructure revealed dislocation arrangements in the form of debris/bundle structures at $T_{DSA,max}$ and cell structures below and above the temperature range of DSA. At a given temperature in this range, positive mean stresses promote the formation of a cell structure because of the superimposed cyclic creep deformation taking place. © 1997 Elsevier Science S.A.

*Keywords:* SAE 1045 plain-carbon steel; Fatigue; Mean stress; Dynamic strain ageing

## 1. Introduction

The cyclic deformation behaviour of plain-carbon steels with carbon contents between 0.01 and 0.80% in different heat-treated conditions has been studied in numerous works and can be considered to be well understood [1–7]. It is reported that the cyclic stress–strain response of this class of materials is strongly affected by the interaction of the interstitially dissolved carbon atoms and the dislocations which at sufficiently low temperatures and stress amplitudes gives rise to a strong cyclic softening connected with a Lueders-band-type inhomogeneous plastic deformation in the beginning of the cyclic deformation curve, after an incubation phase of almost purely elastic deformation. At higher temperatures, the effect of dynamic Lueders-band propagation ceases. However, the impeding effect of the interstitials to dislocation glide still exists and is expressed in the phenomenon of dynamic strain ageing (DSA). The maximum strengthening due to DSA occurs when the diffusion rate of carbon equals the dislocation velocity. According to Pan [2] and Becker et al. [5], the temperature of maximum DSA, $T_{DSA,max}$, lies in the range between 300°C and 350°C for SAE 1045, depending on the test conditions applied.

The effect of a superimposed mean stress $\sigma_m$ has mostly been studied at room temperature [1,3]. Tensile mean stresses are known to be dangerous, because they can lead to cyclic creep causing monotonic strains which exceed tolerable limits. Moreover, the number of cycles to fracture, $N_f$, is reduced. Compressive mean stresses shorten the above-mentioned incubation period prior to cyclic softening. However, cyclic life increases [6,8].

The results presented in this paper are part of a comparative study on ferritic and austenitic steels [9] and deal with the effect of mean stresses on the cyclic stress–strain response, the microstructural development and the cyclic life of SAE 1045 in the normalized

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condition. Special emphasis is put on the temperature range around the temperature of maximum DSE.

## 2. Experimental procedure

Specimens with cylindrical gauge length were machined from rods of a plain-carbon steel of type SAE 1045 (containing 0.46 wt.% C, 0.26 wt.% Si, 0.65 wt.% Mn, 0.018 wt.% P, and 0.027 wt.% S) after normalizing at 870°C for 30 min. The surface within the gauge length was mechanically ground in order to minimize the influence of surface roughness on $N_f$. Prior to testing the specimens were annealed at 600°C for 90 min to eliminate internal stresses from machining. After this two-step heat treatment, the volume fraction of pearlite was found to be about 55% and the mean grain size of ferrite was determined to be 10 μm.

Fatigue tests were performed in an electro-mechanical test system equipped with a three-zone resistance furnace. During testing at elevated temperatures, this furnace was continuously flushed with argon containing 1% hydrogen in order to reduce oxidation effects. The tests were carried out under stress control with a stress amplitude $\Delta\sigma/2$ of 400 MPa and a frequency of 0.25 Hz at constant temperatures ranging from room temperature up to 375°C with emphasis on the temperatures around $T_{DSA,max}$. Additional tests under true plastic-strain control were conducted which will not be considered further in this paper (see [10] for details). In order to study the effects arising from mean stresses $\sigma_m$, values of $\sigma_m$ between $-80$ and $+60$ MPa were superimposed in the stress-controlled tests.

Transmission electron microscopy (TEM) was applied to characterize the dislocation arrangements and to reveal differences in the microstructure resulting from the influence of temperature and mean stress.

## 3. Results and discussion

As already stated above, the cyclic deformation behaviour of normalized plain-carbon steels at sufficiently low stress amplitudes is characterized by an incubation phase with almost purely elastic deformation at the beginning. This is due to the pinning of the dislocations by Cottrell clouds, a subsequent cyclic softening as a result of dynamic Lueders-band propagation and a continuous cyclic hardening, when a fully plastic condition within the gauge length is reached [3,7]. Basically, this behaviour could be confirmed in this study at temperatures up to 200°C and at mean stresses of 0, 20 and $-20$ MPa. With increasing temperature and increasing absolute value of $\sigma_m$, a transition to a cyclic deformation curve occurs that exhibits a continuous cyclic hardening throughout the total cyclic life. This change in the cyclic stress–strain response is reasonable from a physical point of view, since both mean stress and elevated temperature promote a homogeneous plastic deformation from the first loading cycle [1,2,5,6,8]. The cyclic hardening is a consequence of a steady increase of the dislocation density due to dislocation multiplication.

In Fig. 1 the influence of temperature on the plastic strain amplitude $\Delta\varepsilon_{pl}/2$ which was taken at $N_f/2$ (Fig. 1a) and on $N_f$ (Fig. 1b) is represented. The curves connecting the data points obtained at room temperature and at 200°C are plotted as dashed lines because no additional tests have been performed in this temperature range. Rather, the fatigue tests have been focused on the interval around $T_{DSA,max}$. The strengthening effect of DSA can be seen in Fig. 1a by a distinct decrease of $\Delta\varepsilon_{pl}/2$. The minimum of $\Delta\varepsilon_{pl}/2$ was obtained at 325°C and can be attributed to a maximum effect of DSA processes. Value and sign of $\sigma_m$ are obviously of minor influence on $T_{DSA,max}$. However, a slight tendency exists to raise $T_{DSA,max}$ with increasing mean stress. This trend is in accord with the idea that the reduction of $\Delta\varepsilon_{pl}/2$ which takes place if $\sigma_m$ is decreased

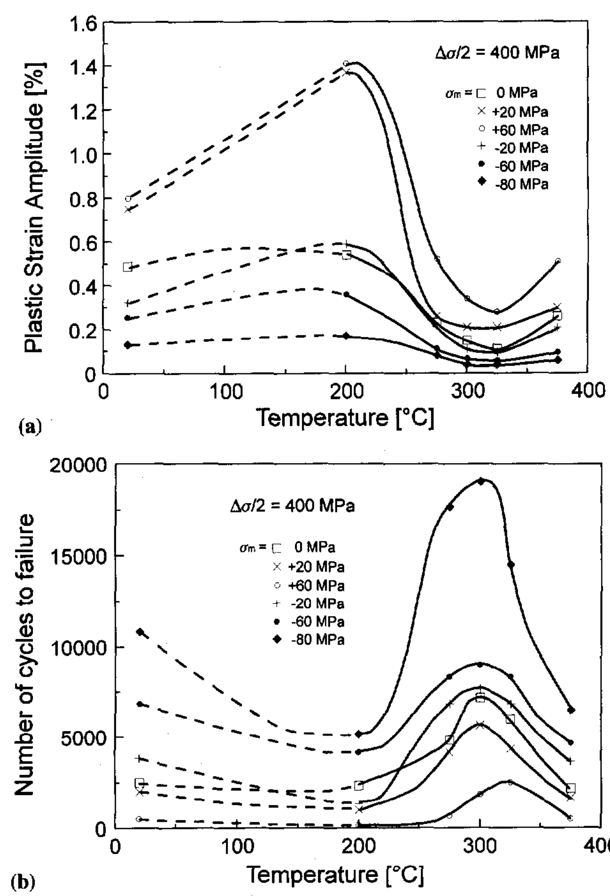


Fig. 1. Influence of temperature on the plastic strain amplitude (a) and on the number of cycles to failure (b) at six different values of mean stress.

stepwise from positive to negative values, corresponds to a reduced mean dislocation velocity. Therefore, the carbon diffusivity is already sufficiently fast to cause maximum DSA at lower temperatures.

The course of the cyclic life with temperature shown in Fig. 1b corresponds to the change of $\Delta\varepsilon_{pl}/2$ in the sense that a maximum of $N_f$ exists at about the temperature of minimum of $\Delta\varepsilon_{pl}/2$ ($T_{DSA,max}$). A closer comparison of Fig. 1a and Fig. 1b reveals that the temperature of maximum life is slightly shifted from $T_{DSA,max}$ to a lower temperature and that this shift is more appreciable at high values of $N_f$. This minor effect can be attributed to additionally acting time-dependent damage, for instance resulting from oxidation. From Fig. 1 it can be stated that lowering $\sigma_m$ from positive (tensile) to negative (compressive) values generally causes a decrease of $\Delta\varepsilon_{pl}/2$ and leads to an increase of $N_f$. The intersection of curves in Fig. 1 is probably due to experimental scatter. It is worth mentioning that a decisive influence of the testing mode applied exists. In tests with a constant value of $\Delta\varepsilon_{pl}/2$, DSA leads to an increase of the stress amplitude and therefore gives rise to a reduction in $N_f$ [10].

An additional effect that has not been discussed so far, but which must be expected to strongly affect $N_f$, is cyclic creep as a result of superimposed mean stresses [1,6,8]. In Fig. 2, the cyclic creep behaviour as a function of the magnitude of $\sigma_m$ applied is shown in the form of a plot of the mean plastic strain $\varepsilon_{pl,m}$ in each cycle versus the cycle number for room temperature (Fig. 2a) and for 325°C ($T_{DSA,max}$, Fig. 2b). At temperatures up to about 200°C only the cyclic creep rate in compression approaches a value of zero with increasing number of cycles, while positive mean stresses lead to a continuous and remarkably large elongation due to high cyclic creep rates. The strengthening effect of DSA reduces cyclic creep as shown in Fig. 2b. With the exception of a high tensile mean stress, a constant value of $\varepsilon_{pl,m}$ is quickly established during the first stage of cyclic deformation.

It should be noted that the two basic effects of mean stress, the change of both the amplitude and the mean value of plastic strain, determine the cyclic life in a combined way. Under tensile mean stresses both effects are detrimental, whereas under compressive mean stresses mainly the reduced plastic strain amplitude is responsible for the beneficial influence.

In Fig. 3 the dislocation arrangements formed in tests with zero mean stress at three different temperatures are shown. It is evident that at temperatures below (e.g. room temperature) and above (e.g. 375°C) the temperature range of DSA, dislocation cells are formed (Fig. 3a and c). At $T_{DSA,max}$ (Fig. 3b), a less orderly arrangement consisting of broad dislocation walls and bundles is established. This difference in the microstructure can be considered as a result of the

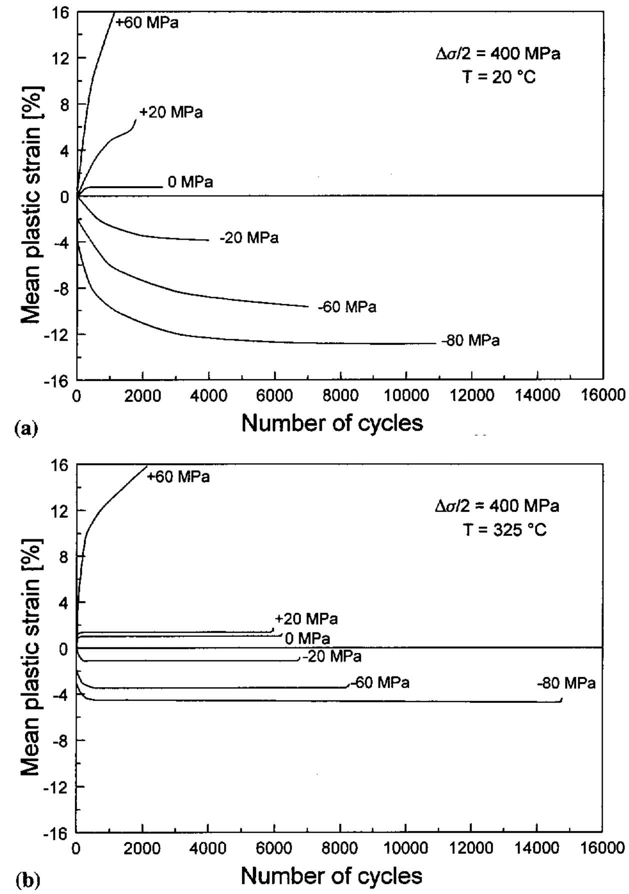


Fig. 2. Cyclic creep curves of SAE 1045 steel cyclically deformed at various mean stresses at room temperature (a) and at the temperature of maximum DSA (b).

impeded mobility of dislocations due to DSA in combination with a small plastic strain amplitude (Fig. 1a). A compressive mean stress was found to have no appreciable influence on the dislocation arrangement. However, if a tensile mean stress is applied, even at 325°C a cell structure is established. It seems that the temperature range in which a less orderly dislocation arrangement prevails is slightly shifted to higher temperatures. This observation is in accord with the increased plastic deformation taking place under tensile mean stress conditions. The higher mean dislocation velocity requires an increased temperature in order to provide the necessary carbon diffusion rate for a maximum impeding effect.

## 4. Conclusions

The main results of this study on SAE 1045 steel on the influence of a superimposed mean stress on the cyclic stress–strain response, the microstructure and

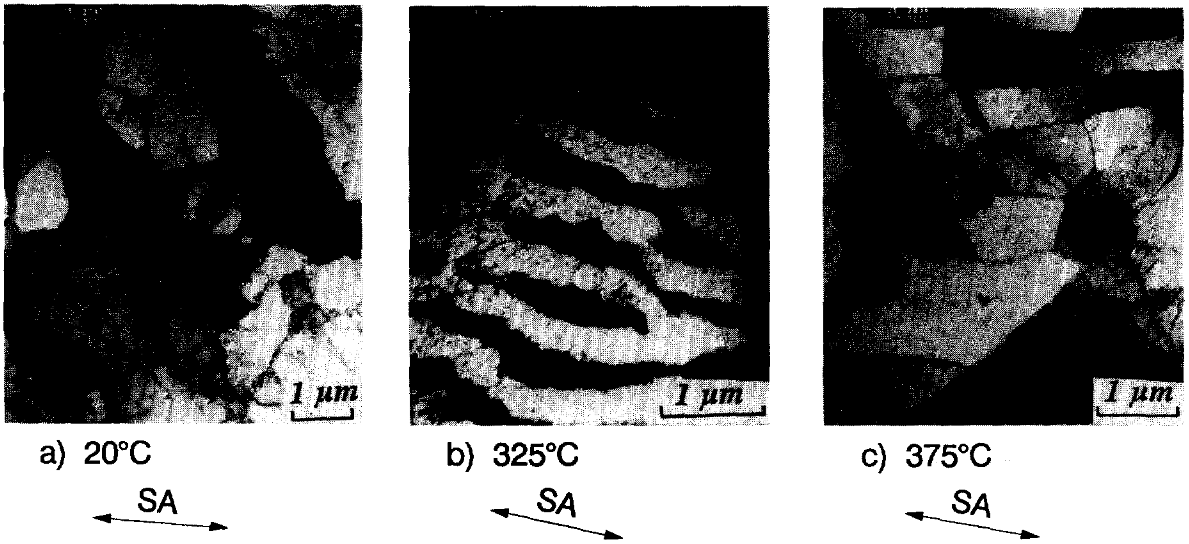


Fig. 3. TEM micrographs comparing the dislocation arrangements established in tests with zero mean stress at different temperatures. SA denotes the stress axis.

the cyclic life in the temperature range of DSA can be summarized as follows:

1. Elevated temperature and/or high absolute values of the mean stress lead to a fully plastic condition from the very beginning of stress-controlled cyclic deformation.

2. DSA processes which were found to be most effective at about 325°C under the test conditions applied reduce the plastic strain amplitude drastically.

3. As a consequence of the strengthening effect of DSA, cyclic creep is diminished or even vanishes.

4. As expected, a positive (tensile) mean stress generally reduces cyclic life, whereas a negative (compressive) mean stress leads to life extension. The number of cycles to failure reaches its maximum at a temperature close to that of maximum DSA effects.

5. Under the experimental conditions used, the dislocation arrangement is characterized by cells below and above the temperature range of DSA, whereas in this temperature range, which is shifted to higher temperatures at positive mean stresses, dislocation bundles and broad walls prevail.

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