Cyclic softening of P91 steel during thermomechanical low-cycle fatigue tests

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1. General

Thermomechanical low cycle fatigue is one of the dominant failure modes in high temperature structural components, such as electric power boilers, boiler pipes, engine elements etc. Many studies show the complexity of the cyclic elasto-visco-plastic-damage behaviour, such as effect of non-proportional loading, cyclic softening/hardening behaviour dependent on the strain amplitude and on the loading path, plastic strain range memorization effect or damage [1,2].

2. Experimental background and results

Experimental tests were performed on P91 steel specimens. The chemical composition of steel was 0.197 C, 0.442 Si, 0.489 Mn, 0.017P, 0.005 S, 8,82 Cr, 0.971 Mo, 0.307 Ni, 0.012 Al, 0.017 Co, 0.036 Cu, 0.074 Nb, 0.004 Ti, 0.201 V and 0.02 W. Low-cycle fatigue tests were strain controlled, with constant total strain amplitude (where frequency of loading 0,2 Hz) and constant temperature in each test. Five levels of total strain amplitude (0.25%, 0.30%, 0.35%, 0.50%, 0.60%) and three levels of temperature (20^0C, 400^0C and 600^0C) were applied. Experiments were performed on testing machine Instron 8502, equipped with heating chamber.

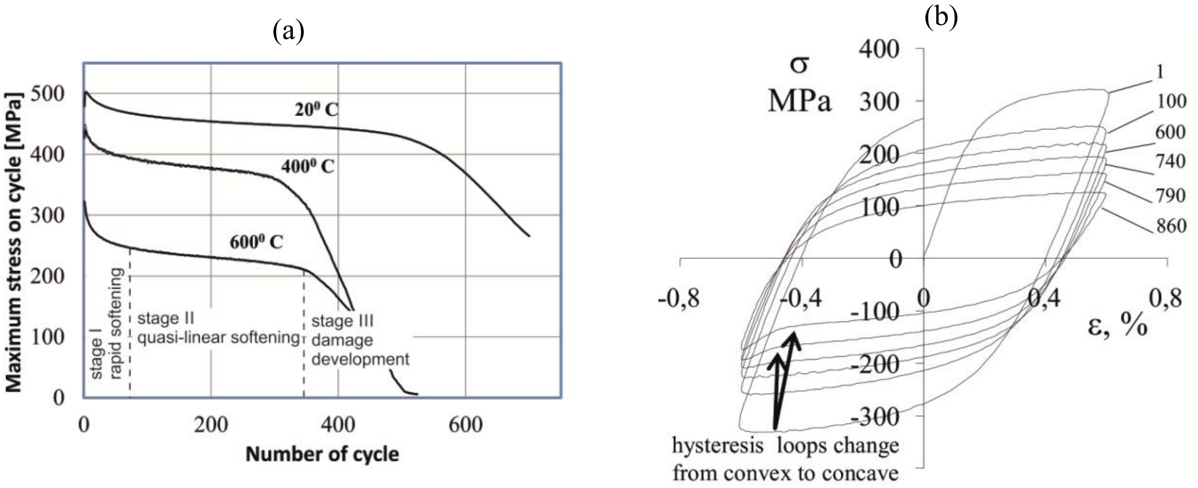

Fig. 1. (a) Maximum stress on cycle versus number of cycle for chosen test temperatures; (b) chosen hysteresis loops for fatigue test performed at 600^0C.

Tested steel exhibits cyclic softening, regardless of the testing temperature (half-stress amplitude decreases with increasing cumulated plastic strain. This softening could be divided into three phases, which are: the rapid softening phase during the initial up to a hundred cycles, followed by a slow quasi-linear softening phase, and finally again fast softening till rupture (see Fig. 1). The first phase is generally explained by the rapid change of dislocation density inherited from the quench treatment, the second is related to the formation of dislocation sub-structure and carbide coarsening under the action of time, temperature and cyclic load, while the third phase is a consequence of micro-damage development in the material that ultimately causes failure of the tested sample.

3. Modelling

The dimension of the elasticity domain can be controlled with a law of the type:

(1) $$R = Q(\theta)(1 - e^{-b(\theta)r})$$

where $b(\theta)$ and $Q(\theta)$ are two coefficients that are material and temperature dependent. However, such description leads to a typical saturation , therefore it is not suitable for steels that soften continuously without a saturation period. To take into account the non-saturating cyclic softening observed experimentally in the case of P91 steel, the drag stress R can be divided into two parts, R_1 and R_2 ([3]):

(2) $$R_1 = Q(\theta)(1 - e^{-b(\theta)r}),\ R_2 = H^R\left(\theta\right)r$$

The first part, R_1 corresponds to the initial strong softening, while the second one, R_2 allows to reflect the continuous softening. Due to quasi-linear character of the second stage of softening drag stress R_2 was here adopted in a linear form, where $H^R\left(\theta\right)$ (see Fig. 2b) reflects the slope of the second stage of cyclic softening (see Fig. 2a).

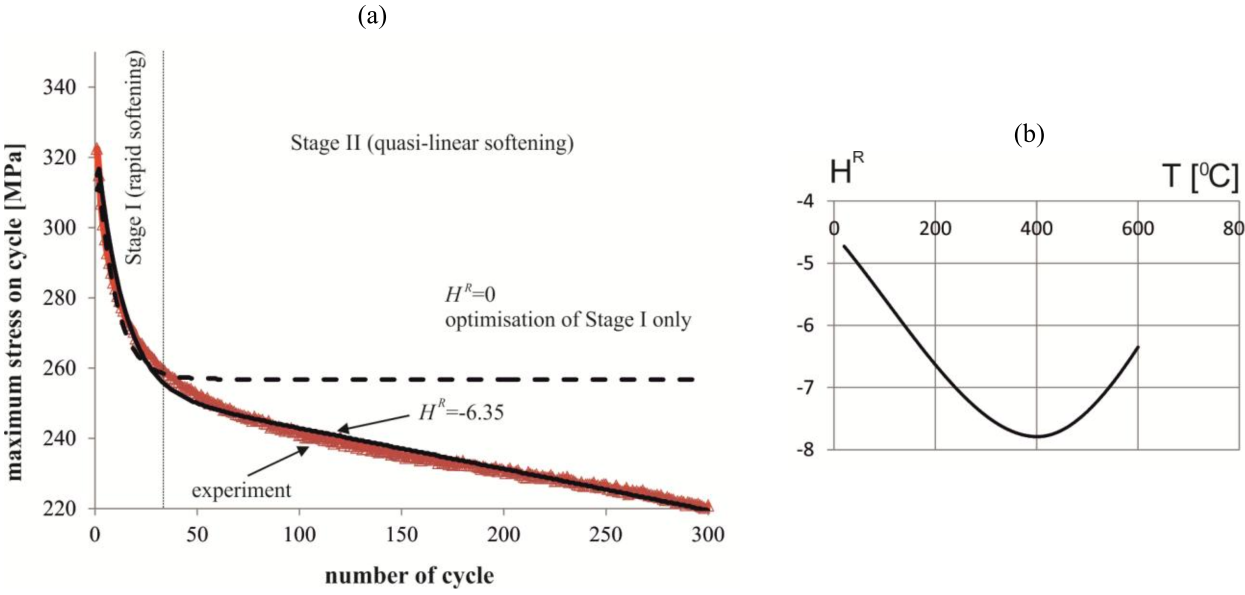

Fig.2 (a) Influence of linear part of isotropic softening (isothermal fatigue test at a temperature of 600^{0}C); (b) H^R versus temperature (T denotes temperature in Celsius scale)

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References

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