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Lifetime Behavior at Superimposed Thermal-Mechanical and Mechanical Loading

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ABSTRACT

More and more thermally and mechanically highly stressed components fail under superimposed low and higher frequency loadings. A typical example is the cylinder head of combustion engines. Permanently rising temperatures and faster heating-up and cooling-down processes increase the thermal induced low frequency loadings which are combined with start-stop cycles or load changes. Increasing injection pressures and severing combustion processes force up the higher frequency mechanical induced loading component which corresponds to the speed of the engine. The superposition of such a higher frequency loading may reduce the number of low frequency basic cycles to failure drastically. It has to be assumed that the superimposed loading changes both the conditions for the initiation and the growth behavior of fatigue cracks. To clarify the lifetime behavior under such complex loading conditions thermal-mechanical fatigue tests without and with a superimposed higher frequency loading were carried out on cast iron materials. The experimental technique for these tests, characteristic results and an approach for the assessment of the lifetime behavior of the investigated materials are introduced.

INTRODUCTION

For many technical applications the cyclic loading of critical components may be differentiated in a low-frequency basic loading cycle and a superimposed higher-frequency loading cycle. The basic loading can be induced either mechanically, as for example in the case of a submarine hull, or thermally as in the case of the disk or a blade of an aircraft turbine engine. The basic loading cycles frequently lie in the low cycle fatigue (LCF) range whereas the superimposed loading typically lie in the high cycle fatigue (HCF) range.

A typical component which mainly fails due to superimposed LCF/HCF loadings is the cylinder head of a combustion engine. Here, the basic loading arises from temporally and locally transient temperature fields which are generated, for example, by start-stop-cycles. Due to the hindrance of the thermal expansion within the cylinder head these temperature fields induce stresses therewith a so called thermal-mechanical fatigue (TMF) loading. The superimposed higher-frequency loading emerges, for example, from the variation of gas pressure in the combustion engine and/or because of resonant vibrations. Therefore, these loading components are generally mechanically induced.

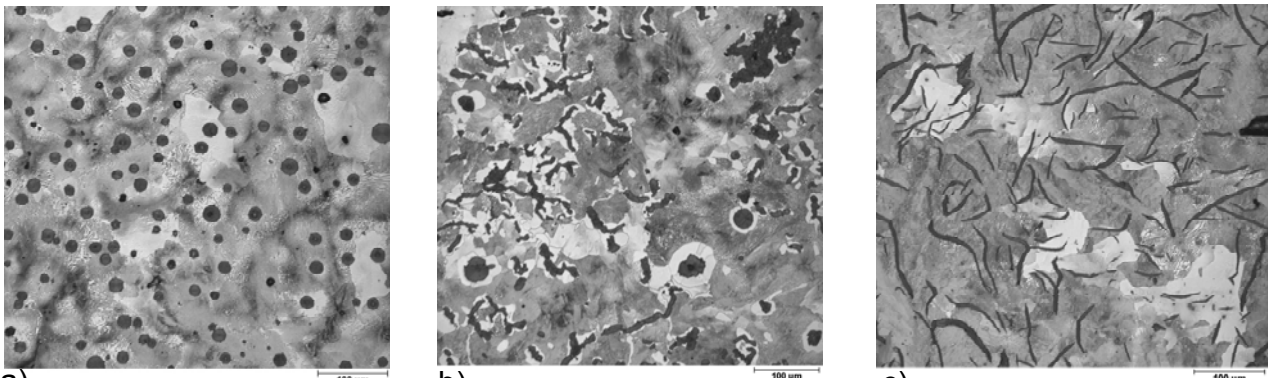
Despite the fact that this type of combined loading occurs in many technical applications, only relatively few systematic investigations in this field are to be found in the literature.

With respect to the complex loading of submarines, experiments have shown that a superimposed higher- frequency mechanical loading reduced the lifetime considerably [1-3]. Similar results have been obtained in experiments with cast Aluminum alloys for internal combustion engines [4,5], and a Ni-base superalloy for gas turbines [6,7]. In addition, experiments which simulated the loading of titanium alloy components of combustion engines or compressor disks showed that the growth of fatigue cracks was considerably accelerated by a higher-frequency superimposed loading [8,9]. Nonetheless, although there are only a few references, it is clear that the problems associated with superimposed low frequency and higher-frequency loading of components are very important in many technical applications, especially for components of high power combustion engines.

Therefore, in the present study the lifetime behavior of three typical cast iron materials which are used for cylinder heads of diesel engines was investigated. These materials cover different types of engines ranging from small engines for automobiles to large-bore diesel engines for marine and power plant applications.

MATERIAL

The experiments were carried out with three typical cast iron materials. Solid round specimens were used. The gauge length had a diameter of 7 mm and was 17 mm long. The clamping ends of the specimens were cylindrical with a diameter of 12 mm. The slugs from which the specimens were manufactured were taken from the compression bottom of standard cylinder heads. The first material was a gray cast iron with a perlitic matrix and globular graphite according to the European standard EN GJS 700 (Fig. 1, on the left). This material was provided by MTU, Friedrichshafen, Germany. The second material was a gray cast iron with a ferritic perlitic matrix and vermicular graphite according to the European standard EN GJV 450 (Fig. 1, middle) supplied by MAN, Nuremberg, Germany. Supplementary examinations were carried out using specimens made from a gray cast iron with a perlitic matrix and lamellar graphite according to the European standard EN GJL 250 (Fig. 1, on the right) which was provided by Ford, Cologne, Germany. Fig. 1 shows etched micrographs of the test materials.



a) b) c)

Fig. 1: Etched micrographs of the materials investigated. a) EN GJS 700, b) EN GJV 450, and c) EN GJL 250.

EXPERIMENTAL DETAILS

The experiments were carried out on servohydraulic fatigue testing machines which had a maximum loading capacity of 63 and 100 kN. For the strain measurements, a high-temperature capacitive extensometer was used. The temperature of a specimen was determined by means of a Ni-CrNi band thermocouple which entangles the specimen within the gauge length. During the thermal-mechanical fatigue (TMF) tests the specimens were heated up in an inductive furnace which was equipped with a closed loop control. The specimens were cooled by thermal conduction to the water cooled grips and additionally, if necessary, by blowing with a proportionally controlled air jet on the surface of the specimen.

All experiments were performed under total strain control as so called “out-of-phase” TMF tests. The minimum temperature of all experiments T_{min} was 50 °C. The maximum temperature T_{max} was set at a value between 350 and 450 °C. The heating and cooling rate was 10 K/s, resulting in cyclic periods between 60 and 80 s. At the beginning of a TMF test, each specimen was first heated up $T_{min,}$ and then subjected to seven triangle-shaped temperature cycles between T_{max} and 50 °C while under stress control with the stress maintained at zero. The purpose of this initial testing was to establish the magnitude of the thermal strains. It is noted that because of differences in the thermal gradients on heating and cooling, the thermal expansion of the specimens during heating up and cooling down were not exactly equal. After determining the magnitude of the thermal strains, the testing machine was switched to total strain control and the TMF loading was started. Out-of-phase (OP) thermal-mechanical fatigue tests were performed with and without a superimposed higher frequency mechanical (HF) loading. Pure OP experiments without a superimposed HCF loading were carried out at different mechanical strain amplitudes. For selected OP loadings a sinusoidal HCF loading was superimposed. The frequency of the superimposed loading was 5 Hz and the strain amplitude varied between 0.01 and 0.06 %. In this case the total mechanical strain amplitude is $\varepsilon_{a,t}^{me} = \varepsilon_{a,t}^{TMF} + \varepsilon_{a,t}^{HCF}$ which is the sum of the mechanical strain amplitude of the TMF-loading $\varepsilon_{a,t}^{TMF}$ and the amplitude of the superimposed mechanical loading $\varepsilon_{a,t}^{HCF}$.Therefore, the superposition of the HCF loading led to an increase in the total strain amplitude.

RESULTS

TMF Experiments without superimposed HCF loading

Fig. 2 shows the mechanical total strain amplitude as a function of the number of cycles to failure of OP-TMF tests at different maximum temperatures. For the experiments specimens made of GJV 450 were used. Three series of experiments were carried out. In the first series the maximum temperature was varied between 400 und 450 °C. These experiments were carried out under total constraint of the thermal expansion of the specimens. Therefore, the mechanical strain amplitude arises from the total suppression of the thermal expansion and, therefore, increases with increasing maximum temperature. In two additional series – one at a maximum temperature of 400 °C and the other at a maximum temperature of 450 °C – the thermal strain was overcompensated by a factor of

1.2 and 1.4, respectively. As expected, there is a clear dependence of the lifetime of the applied mechanical strain amplitude. With increasing mechanical strain amplitudes the lifetime decreases. The Lifetime behavior could be described by a straight line for each of the respective series. Due to the double logarithmic scaling the lifetime behavior could be characterized by a power function,

$$\varepsilon_{a,t}^{me} = A \cdot N_f^{-b} \tag{1}$$

where A and b are constants which depend on the loading conditions. The different slopes of the straight lines show clearly that a simultaneous increase of the maximum temperature and the mechanical total strain amplitude reduces the lifetime considerably more as an increase of the mechanical total strain amplitude at constant maximum temperature.

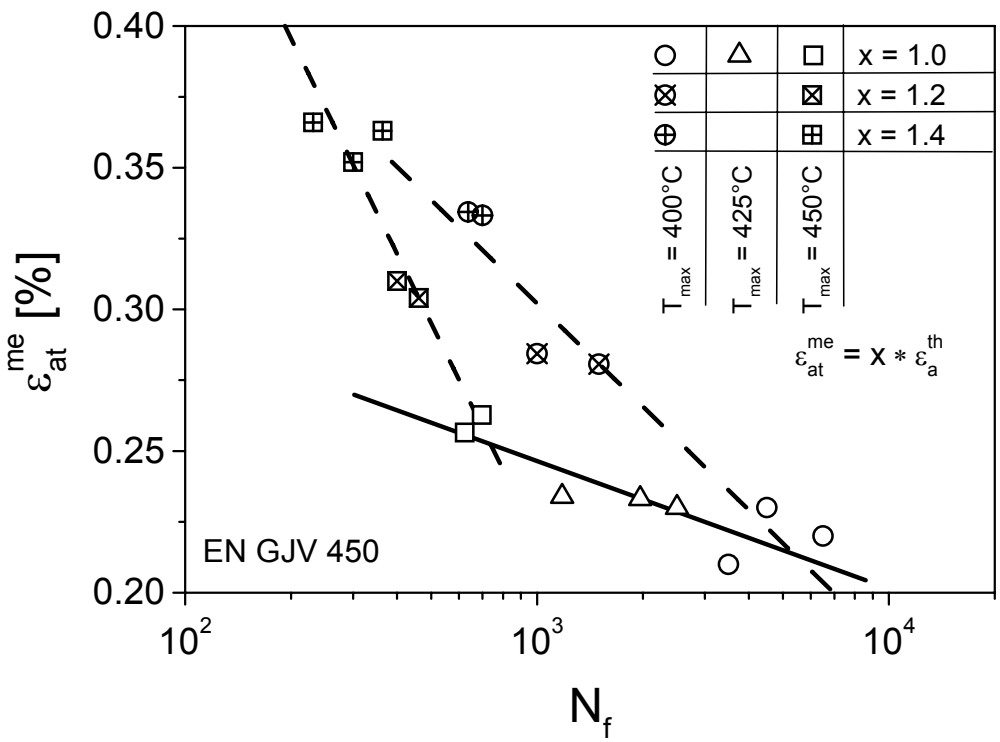


Fig 2: Lifetime behavior of GJV 450 at pure thermal-mechanical fatigue loading.

TMF Experiments with superimposed HCF loading

In Fig. 3 the results of two additional test series are added to the diagram represented in Fig. 2. In one series the HCF loading was superimposed to an out-of-Phase TMF loading with T_{max} = 400 °C and in the other series to an OP TMF loading with T_{max} = 450 °C. In both series the mechanical strain amplitude of the TMF loading results from total constraint conditions ($\varepsilon_{a,t}^{me} = \varepsilon_a^{th}$). The results of both series again could be described by a straight line for each series. But for both maximum temperatures the straight line for the superimposed TMF/HCF loading did not match the straight line for pure TMF at the same mechanical strain amplitude. The TMF/HCF curve is shifted to higher strain amplitudes in both cases. This means that for lower amplitudes of the HCF loading the increase of the

total strain amplitude due to the superimposition reduces the lifetime significantly less than the same increase of the mechanical strain amplitude of the pure TMF loading. At T_{max} = 400 °C the shift of the straight line describing the lifetime behavior at TMF/HCF loading against the one which represents the pure TMF loading amount to approximately 0.03 %. For T_{max} = 450 °C a shift of about 0.025 % appears. These shifts mean that amplitudes of a HCF loading superimposed to a TMF basic loading which did not exceed these values did not reduce the lifetime significantly compared to the lifetime under the pure TMF loading. Therefore, these amplitudes may be interpreted as a threshold. A superimposed loading must exceed this threshold to reduce the lifetime at all. But then, even a slight increase of the HCF amplitude results in a significant lifetime reduction. The absolutely appearing amount of lifetime reduction depends on the loading conditions on hand. This could be seen from the different slopes of the straight lines for the two TMF/HCF test series. For T_{max} = 450 °C the straight line rises stronger than for T_{max} = 400 °C which means, that GJV 450 responds more sensitive to a superimposed TMF/HCF loading at T_{max} = 450 °C than at T_{max} = 400 °C.

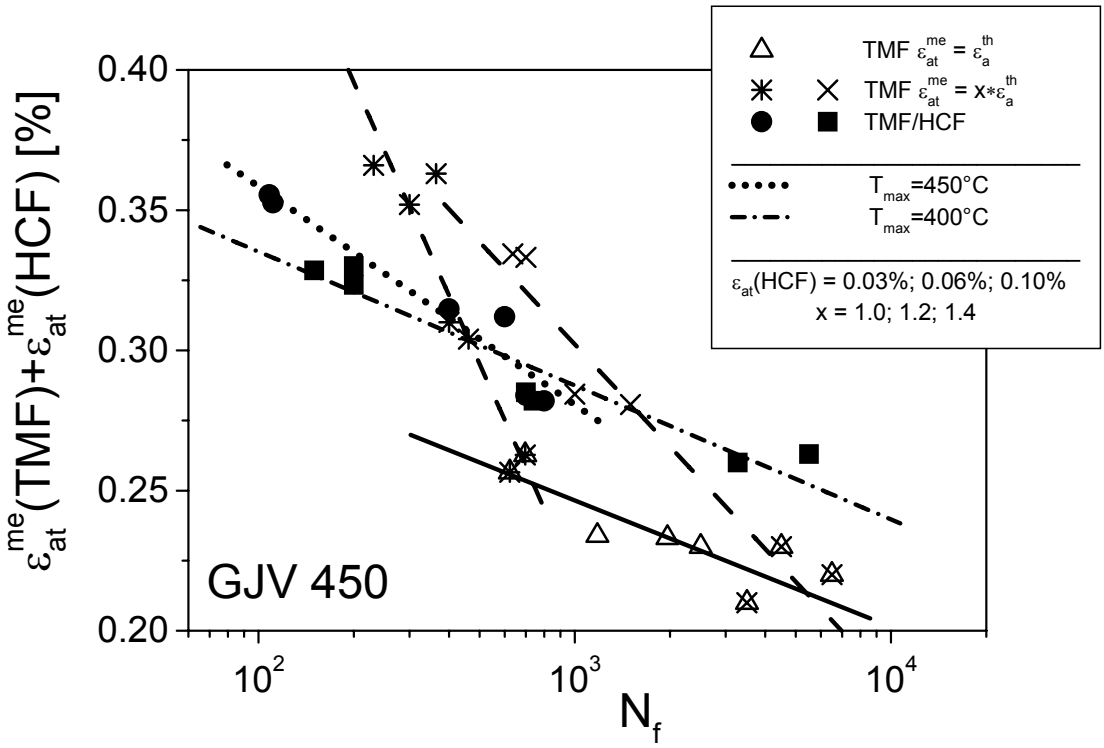


Fig. 3: Lifetime behavior of GJV 450 at pure TMF and superimposed TMF/HCF loading.

Fig. 4 shows a comparison of pure TMF as well as of superimposed TMF/HCF tests of the three gray cast iron materials investigated. The maximum temperature of the tests shown was always 400 °C. The open symbols represent pure TMF tests and the full symbols superimposed TMF/HCF tests. As can be recognized, every material has a specific life time behavior. At TMF tests without superimposed HCF loading which are comparable with regard to mechanical total strain amplitude GJL 250 shows the lowest and GJS 700 the highest numbers of cycles to failure. The lifetime of specimens made of GJV 450 lies in-between. At the lamellar gray cast iron GJL 250 a superimposed HCF loading already

causes a very strong reduction of the lifetime already at very low HCF amplitudes below 0.03%. Amplitudes of the superimposed HCF loading up to this value practically do not influence the life time behavior of the other two gray cast irons investigated. Higher amplitudes of the superimposed HCF loading cause a stronger lifetime reduction at the cast iron with vermicular graphite GJV 450 than at the cast iron with globular graphite GJS 700. This can be recognized by the different slopes of the respective Wöhler curve.

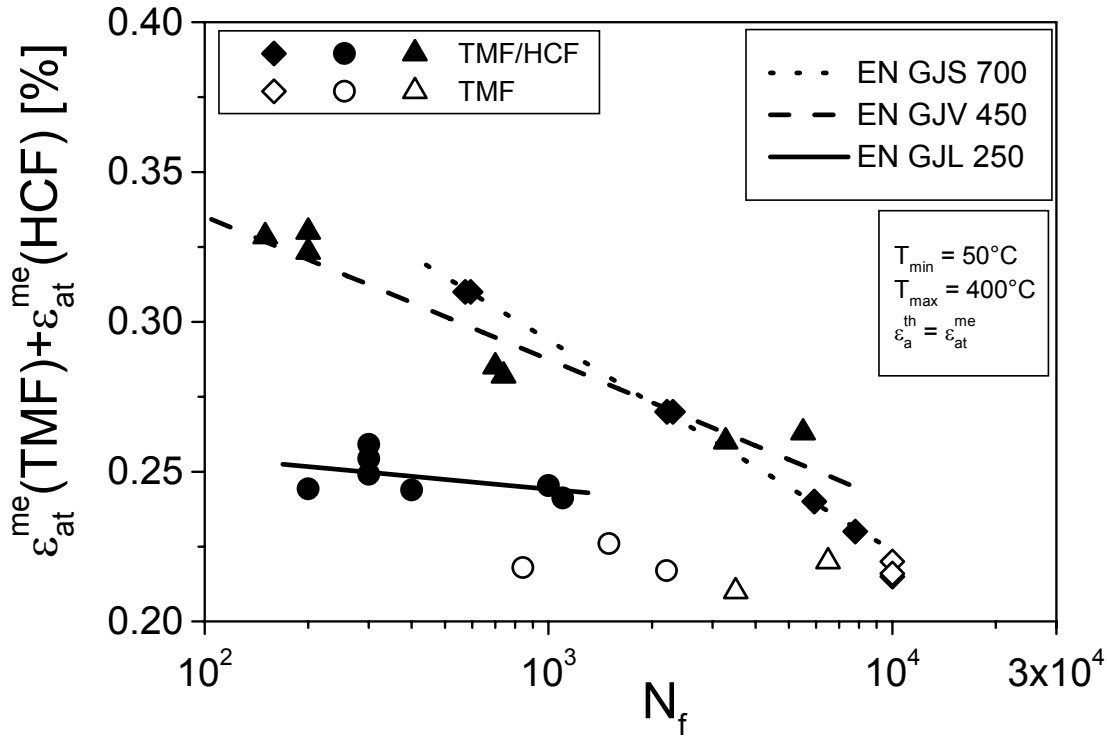


Fig. 4: Comparison of the lifetime behavior of GJS 700, GJV 450 and GJL 250 at pure TMF and superimposed TMF/HCF loading.

DISCUSSION

The lifetime under TMF loading superimposed by a higher frequency HCF loading results from a complex interaction between the two loading components. As in the typical technical application the amplitude of the HFC loading is significantly below the endurance limit even assuming worst case condition of the TMF base loading. Therefore, it is clear that first fatigue damage must originate due to the TMF component of the loading which lies in the LCF range. As could be shown for GJS 700 the initiation of first fatigue cracks is nearly not influenced by the superimposed loading [10]. Only the increase of the peak loads due to the superposition of the HCF loadings have a small influence. It is also clear that cracks which initiate and propagate due to the TMF base loading will be accelerated by the HCF loading when they are long enough. This could also be proved for GJS 700 [10]. As shown for a Ni-base superalloy the complex damaging effects of a superimposed HCF loading can not be accounted for on the basis of a straightforward linear damage summation [7]. It would be a challenging task, but if the damaging effect of the HCF cycles

could be properly accounted for, especially in terms of their influence on the growth of existing fatigue cracks, a non linear damage summation will result in a correct (or better) description of the lifetime behavior. At the moment, the lifetime behavior could only be described by the phenomenological based power laws with the total mechanical strain amplitude as loading parameter. Therefore, to estimate the lifetime under superimposed TMF/HCF loading, first the lifetime under pure TMF load must be estimated. From a given point of this Wöhler curve the reduction of the lifetime caused by the superimposed HCF loading could be estimated using the power law introduced above. Depending on the material and the given loading condition on hand threshold values for the HCF loading must be regarded additionally [4,5,7].

SUMMARY

From the results and the discussion presented the following conclusions may by summarized:

- The cast iron investigated is very sensitive to a HCF loading superimposed to a TMF base loading.
- Both the lifetime behavior under pure TMF loading and the lifetime reduction due to a superimposed HFC loading could be described by a power law using the total mechanical strain amplitude as loading parameter.

ACKNOWLEDGEMENT

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