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Boundaries for increasing the fatigue limit of the bearing steel SAE 52100 by thermomechanical treatments

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Abstract

High end applications often require high strength materials especially regarding the fatigue limit. It is still an open question what the highest fatigue limits are and how to increase them further in high strength steels. A thermomechanical treatment (TMT) in the temperature range of maximal dynamic strain ageing is an auspicious way to increase the fatigue limit of bearing steel SAE52100. Successful attempts have been published for various materials states.

The present investigation deals with the influence of non-metallic inclusions on the fatigue limit and the possibility to increase the fatigue limit by TMT. The fatigue limit of high strength steels increases by reducing the size of the non-metallic inclusions during steelmaking. We found that TMT increases the fatigue limit of a high strength materials state only in cases in which the non-metallic inclusions are the starting points of the fatigue cracks. In the case of high cleanliness of the steel the origin of the fatigue cracks may be at any position in the matrix. If there are no critical non-metallic inclusions a TMT did not increase the fatigue limit further. The reasons for this behaviour will be explained and the border of the fatigue limit of high strength steels will be discussed.

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Keywords: high strength steel; fatigue limit; non-metallic inclusions; thermomechanical treatment, dynamic strain ageing.

1. Introduction

For applications requiring high strength materials high strength steels are the most chosen option. The fatigue limit σ_w of metals corresponds in a wide range linearly with the ultimate strength or hardness [1].

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One approach to reach high strength is the activation of different strengthening mechanisms [2]. But for high strength steels the fatigue limit can be dominated by inhomogeneities in the microstructure, in particular by non-metallic inclusions. They act as crack initiation sites during fatigue. To improve the fatigue limit of high-strength steels the harmfulness of non-metallic inclusions has to be reduced. Technological approaches often modify the surface of high strength steels for instance by residual compressive stresses [3]. In this context it is also an important point to increase the intrinsic fatigue limit which is dominated by the microstructure without special surface effects. One possibility is a cryogenic treatment but until now it is not understood why this process works [4]. Another approach is to reduce the inclusion size, but this procedure is expensive and the existence of inclusions at the critical sites of the structures can never be completely ruled out (avoided). Hence, there is a demand for alternative methods for reducing inclusion harmfulness. A promising way is a thermomechanical treatment in the temperature range of dynamic strain ageing. In low and medium strength steels mechanical loading above the yield strength leads to an increased dislocation density - especially the density of mobile dislocations. Due to the interaction between mobile dislocations and diffusing carbon atoms mobile dislocations can be anchored by gathering carbon atoms in the dilatation region of the dislocations. Thereby, a microstructure is generated which resists higher fatigue loadings in a later room temperature application [5]. In martensitic and bainitic high strength steels there is no remarkable increase in the dislocation density by TMT but there is still an increase in the fatigue limit. In this case the effect of a TMT is the modification of the inclusion's surrounding which results in a higher resistance against crack initiation from inclusions [6, 7]. While in low and medium strength steels the dislocation density is increased by one step cyclic loading during TMT, in the high strength state the dislocation structure is stabilized by a stepwise increased cyclic loading during the TMT which results in a higher threshold for crack initiation and/or crack propagation [6, 7].

In the present work the focus is on the influence of the existence of critical non-metallic inclusions in high strength materials states. It is well known that the fatigue limit of high strength steels increases by reducing the size and amount of the non-metallic inclusions during steelmaking. The question is now whether TMT can further increase the fatigue limit of such charges with high values of cleanliness, too.

2. Experimental setup

The specimen's geometry, the heat treatment, the principle of thermomechanical treatments, the testing conditions and the evaluation of fracture surfaces are described in [5, 7].

2.1. High cleanliness material

The investigated material is bearing steel SAE52100 (German trade name 100 Cr 6). The investigation is based on a commercially available material state with already very good cleanliness, which was used in [5-7]. The variant with higher cleanliness is produced by a repeated remelting process, which reduced the content of large inclusions. The chemical composition of the two variants is given in Table 1. The heat treatment corresponds to the variant B220 (austenitisation at 855° C for 20 min, bainitic transformation at 220° C for 6 h) [7].

2.2. Thermomechanical treatment

The thermomechanical treatment (TMT) is realized with a modified servohydraulic testing machine [5]. The states are named with a prefix B [7] for normal and H for high cleanliness of the material. The schematic courses of temperature and stress are given in [5]. The temperature of maximal dynamic strain ageing for the thermomechanical treatment was identified to be the same as in martensitic states [6] which was 275° C. A TMT was done by bringing one specimen in the frame of the testing machine, heating it up to the treatment temperature forceless and applying a sinusoidal mechanical stress. Different treatments were realized by different stress amplitudes. The main difference between HTMT1 and HTMT2 is that the stress amplitude is constant during HTMT1 (1700 MPa, 20 cycles) while in HTMT2 it is stepwise increased after each 5 cycles by $\Delta\sigma = 170$ MPa starting from 170 MPa ending at the same maximum stress amplitude of 1700 MPa. After the mechanical treatment the specimens are cooled down forceless to room temperature by convection and thermal flux in the water cooled grips. Fatigue bending specimens were cut out of the gauge length of the TMT specimens.

Table 1. Chemical composition of normal (B) and high cleanliness (H) variants

Chemical element	B (*weight-%*)	H (*weight-%*)
C	0.969	1.085
Cr	1.432	1.488
Mn	0.255	0.367
Si	0.283	0.270
P	0.009	0.006
S	0.003	0.003
Al	0.038	0.004
Cu	0.140	0.017
Ni	0.100	0.023
Mo	0.025	0.004
V	0.012	0.001

3. Results

3.1. Microstructure and hardness

The microstructures of the B220 and H220 states do not differ. Both show a fine microstructure consisting of lower bainite with the same hardness of 770 HV 10. Neither microscopy nor roentgenography could reveal any retained austenite. The hardness is reduced by TMT to 725 HV 10 for both states.

3.2. Fatigue Experiments

The results of the alternating bending fatigue test are presented in Fig 1. The fatigue limit, which is the value of the 50% survival probability calculated by the staircase method [8], of the state with higher cleanliness H220 is significantly higher than the fatigue limit of B220 (Fig. 1(a)). It is increased by more than 20%. The two data points of specimens which failed at number of cycles larger than 10^7 were derived as run outs in the staircase analysis. The scatter in lifetime or rather in stress amplitude within the H220 is more pronounced than within B220. Most failed specimens of H220 have a lifetime shorter than 250.000 cycles while most specimens of B220 failed after more than 500.000 cycles.

All except one thermomechanically treated specimen had a lifetime larger than 10^6 cycles (Fig. 1(b)) which is a considerable increase in contrast to the untreated variant H220. However, HTMT1 and

HTMT2 slightly decrease the fatigue limit of H220 by 5% and 3% respectively. The difference of the fatigue limit between HTMT1 and HTMT2 is negligible.

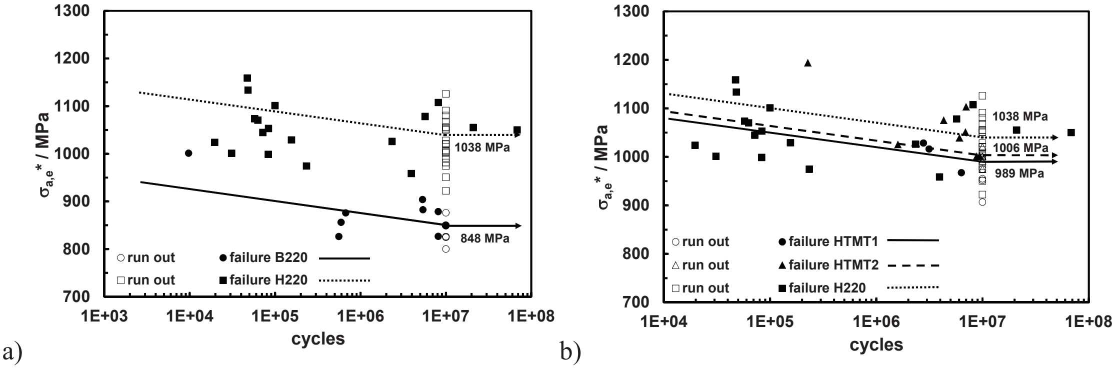

Fig. 1. (a): Wöhler-curve of the two bainitic states: B220 with standard cleanliness [7] and H220 with higher cleanliness, (b): Wöhler-curve for H220, HTMT1, and HTMT2 ($\sigma_{a,e}$* is the fictive edge stress amplitude)

3.3. Fracture surfaces

The fracture surfaces were analyzed for each broken specimen. Most specimens showed crack initiation at or nearby the surface, which was the site of highest stresses caused by the bending load. Fig. 2(a) presents a typical detail of the fracture surface. In this case the crack started at about 50 µm beneath the surface in the upper right corner of this specimen. A typical fish-eye was formed by the fatigue crack before the crack became instable. The crack initiation sites of state B220 are mostly found at non-metallic inclusions. In contrast, the broken specimens of H220 mostly show crack initiation from the surface. The specimens which broke after 10^6 cycles failed featureless from the subsurface (Fig. 2(b)) or from very small inhomogeneities (Fig. 2(c)). A calculation according to [6] results in $K_{max} = K_{mod}$ for the specimens with the inhomogeneities. All but one specimen of HTMT1 and HTMT2 showed featureless crack initiation sites beneath the surface with the same phenomena like they are shown in Fig 2(a) and (b).

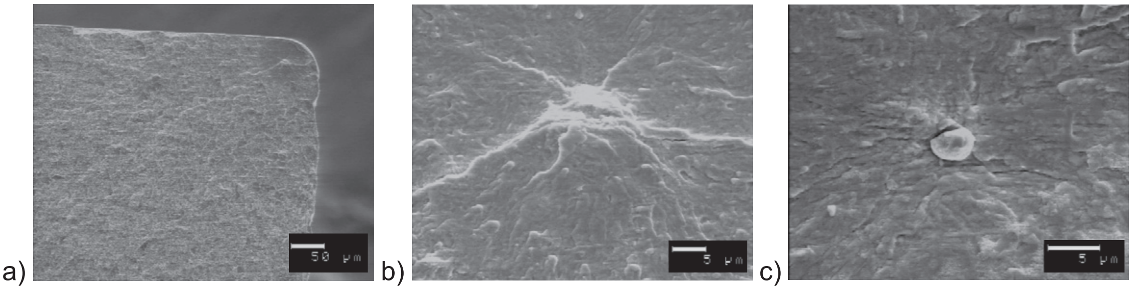

Fig. 2. (a): fracture surface of one specimen of H220, (b): detail of the featureless crack initiation site of (a), (c) crack initiation at a small inhomogeneity after 6.8 10^7 cycles

4. Discussion

The fatigue limit of the investigated high strength steel increased with the reduction of the size of non-metallic inclusions. This is due to a lower stress concentration at smaller inclusions in H220 compared to B220. In consequence the sites for the initiation of cracks which are able to grow are no longer the non-metallic inclusions. [9] presents a clear description of this behavior.

To further increase the fatigue limit of high strength steels a thermomechanical treatment in the temperature range of dynamic strain ageing was successful when the crack is initiated at non-metallic inclusions. The present investigation shows that the steel with high cleanliness which has crack initiation mostly featureless in the matrix is not approachable for increase of fatigue limit by the mentioned TMT. The opposite is the case: the fatigue limit is decreased nearly as much as the hardness. But there is still an effect of the TMT: the lifetime of the treated specimens is higher than without TMT. This is supposed to be generated by carbon anchored dislocations which have in consequence a higher threshold against motion during following cyclic loading. This increases the time before a dislocation gets mobile. The accumulation of dislocation glide takes more time until cracks can be initiated and grow.

The fatigue limit of low and medium strength steels corresponds with the hardness as postulated by [8] and showed in [5] for instance. This behavior is displayed by the open triangles in Fig. 3. However, this statement is only valid for low and medium strength steels for hardness values lower than about 300 HV 10, while at high strength steels the fatigue limit does not increase linearly with the hardness. The additional datapoints from the present investigation and from literature in Fig. 3 display a reduction of the fatigue limit compared to the expectation by linearity which is plotted by the solid line in Fig. 3. The dashed line visualizes the calculation of the fatigue limit for steels containing a non-metallic inclusion with projected area of 100 µm² according to [8]. This dashed line is an upper limit for all states which were fabricated from steel with normal cleanliness and conventional heat treatments, which are martensitic (open and grey circles) as well as bainitic states (open square). The TMT of the bainitic state B220 brings the fatigue limit of BTMT2 (black square) nearer to the dashed line. The martensitic state has a fatigue limit just below the dashed line (open circle) but after TMT2 [6] the fatigue limit is significantly increased above the dashed line caused by the modification of the surroundings of the non-metallic inclusions and the resulting increased resistance against crack initiation at the non-metallic inclusions. This state reaches nearly the solid line. Comparable effects can only be seen by other steel modifications (solid triangle) [4] or by a reduction of cleanliness (H220: open tilt square). But in case of high cleanliness the TMT is not a possibility to further increase the fatigue limit as can be seen by HTMT1 and HTMT2 (grey and solid tilt squares).

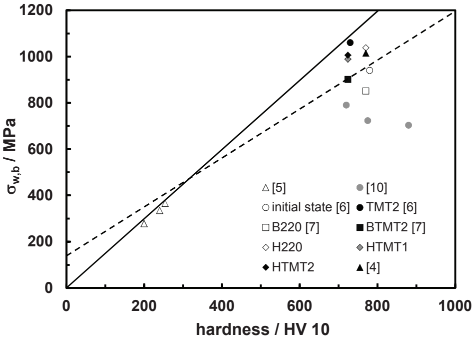

Fig. 3. Correlation between bending fatigue limit and hardness.

The TMT increases the fatigue limit of a high strength materials state only in cases in which the non-metallic inclusions are the starting points of the fatigue cracks. The TMT in [6, 7] produced a higher threshold for crack initiation and/or crack propagation. Thereby, also after TMT the inclusions act as crack starting points but the relation of the stress intensity factor at this initiation site and the stress intensity factor calculated according to [6] is increased compared to the state without TMT [7]. As it was seen in [6, 7] the TMT with stepwise increased load amplitudes leads to the higher fatigue limit than the TMT with constant load amplitude but in contrast to the states with standard cleanliness the differences between TMT1 and TMT2 are very small for steel with higher cleanliness. The crucial difference to the TMT of B220 [7] as well as the TMT of martensitic states [6] is that the fatigue limit of the high cleanliness state is reduced by the TMT while in the other cases it was increased. In the case of high cleanliness the sites of the initiation of the fatigue cracks are featureless if there are no critical non-metallic inclusions present. Thus, the TMT did not increase the fatigue limit further because the positive effect found for martensite [6] and bainite [7] are ascribed to the modification of the matrix just around the critical non-metallic inclusions by the local strengthening and immobilization of dislocations by dynamic strain ageing during the TMT. The fatigue limit of state H220 is not increased by the TMT because the critical non-metallic inclusions which act as stress raisers during the TMT are missing. So the TMT results only in a decrease of hardness due to annealing effects during TMT without the positive effect of higher threshold for crack initiation and/or crack propagation in the surrounding of crack initiation sites. Nevertheless, the increase of the dislocation density and/or the dislocation immobilization by the TMT causes a weak effect resulting in a little higher lifetime as it was found in [5].

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