

Evaluation of the Influence of MnS in Forged Steel 38MnVS6 on Fatigue Life

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ABSTRACT

Manganese sulfides (MnS) are nonmetallic, ductile inclusions with high melting temperature (1610 °C) which improve the machinability and retard the grain growth in steels, in addition of contributing to avoid cracking during hot working. In this paper, the effect of manganese sulfides on the fatigue life of the vanadium micro-alloyed forging steel 38MnVS6 is discussed. Force-controlled fatigue tests are performed on small sized specimens until the crack occurs. The fatigue life of the forged material, presented by Wöhler curves, is considerably reduced at high levels of the nominal stress amplitude compared to the wrought material. Moreover, it is evident that the presence of longer and thinner particles of MnS reduces the scatter band of Wöhler curves and decreases the fatigue strength of the material. This paper presents a first attempt to find a relation between the shape and content of manganese sulfides due to the forging process and the fatigue life of the material.

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INTRODUCTION

Micro-alloyed forging steels are widely used as structural materials for automotive components in order to satisfy needs such as lightweight design and high performance allowing low costs. By means of an appropriate control of the cooling temperature after hot deformation, the mechanical properties obtained are comparable to those achieved through a heat treatment on traditional quenched and tempered steels. The process results simplified with consequent decreasing of costs. As a consequence of the thermo-mechanical process, the material shows a ferritic and pearlitic microstructure [1]. The machinability of these steels is also improved by alloying additions of sulphur which produce manganese sulfides (MnS), responsible of short-braking chips and tool lubrication. This property is needed, since the component is first forged and then machined to match the final shape and tolerances. This last operation takes the 50% of the whole part's cost [2]. The result is a material with good mechanical properties, but at fabrication costs that are consistently reduced due to the substitution of multiple expensive heat treatments on high alloyed steels by a single thermo-mechanical process and a cheap machining on micro-alloyed steels. It is known from experimental investigations by Murakami [3] that nonmetallic inclusions under cyclic loading have a negative influence on the mechanical properties of the steel. The presence of manganese sulfides in the material causes anisotropy in its structure, provoking an effect similar to a stress concentration factor [4]. It can

significantly influence the fatigue life of components as already observed by Temmel et al. in 2006 [5]. The aim of this paper is to investigate on the relation between shape and content of MnSs and the fatigue strength of a vanadium micro-alloyed forging steel before and after the upsetting process. As the initial state, a wrought product of rolled steel with a high sulfur content of 0.073% is used. Orthogonal to the direction of rolling, a cylinder is extracted and forged in the axial direction, decreasing the height by a factor corresponding to an upset (logarithmic) strain of -1.35 at a temperature of 1200°C. Due to this upset forging process, the MnS are compressed to thin and long particles. In addition to the upset forged block material, samples from the lateral position and from the center position of the wrought material are investigated. Small-scale specimens extracted from the two previously defined positions within the wrought material and from the center of the forged material, are subjected to force-controlled fatigue tests with a stress ratio of $R=-1$ at a frequency of 150 Hz using a piezo actuator. The fracture regions are evaluated with respect to shape and content of MnS.

EXPERIMENTAL CAMPAIGN

Case of Study

The material used is the commercial grade medium carbon micro-alloyed (MC-MA) steel 38MnVS6, supplied as rolling product with a square section of 120 mm × 120 mm orthogonal to the rolling direction (Figure 1 a)).

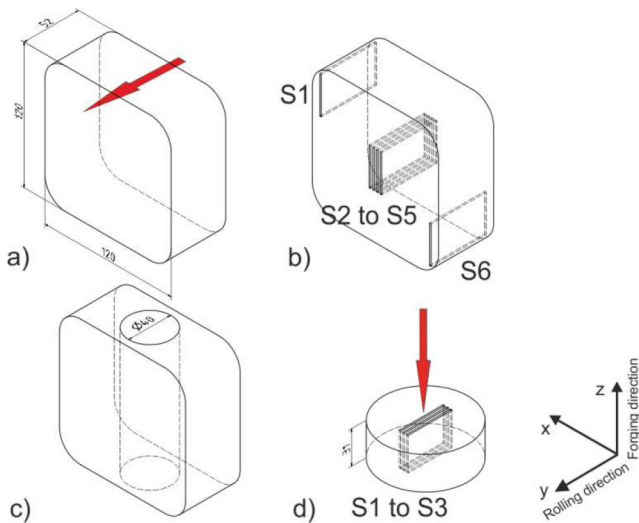


Figure 1. Rolling and forging directions for: a) delivered wrought material, b) slices extracted from it, c) cylinder to be forged and d) upset forged block.

Since the section of the base material has previously been reduced by rolling process, the manganese sulfides within it may differ significantly in content and shape. For this reason, as first step, slices of the material with 1.5 mm thickness and 35 mm width have been manufactured along the rolling direction from both the side (S1 and S6) and the center (S2 to S5) of the wrought material (Figure 1b)). From a similar block, a cylinder of 40 mm diameter has been extracted with the axis orthogonal to the rolling direction, i.e. z-direction (Figure 1c)). The cylinder is then subjected to a reduction of its height by an upset forging, executed at a temperature of $T=1200\text{ }^{\circ}\text{C}$ by a factor corresponding to an upset logarithmic strain of $\varphi = -1.35$.

The upset forging process consists in reducing the length of a cylinder of material, with consequently increasing of the diameter. The unsupported hot billet is placed between the dies and pressed along the axial direction. This process is widely used due to its tendency to be executed automatically and repetitively. The process has been simulated using an implicit FE-Solver and the results are shown in Figure 2. The upset logarithmic strain, which is defined as the logarithm of the ratio between the final and the initial height, is not constant, but variably distributed inside the material, so that for one nominal logarithmic strain, differences in the local values (φ_L) are present. The core of the material is subjected to a higher strain and the manganese sulfides are stretched along the plane orthogonal to the forging direction squashed along the moving direction of the die. Three slices are extracted from the forged material, as represented in Figure 1d). Six specimens are manufactured from each slice of the wrought material and called P1 to P6 depending on their position between the slices, while from the slices of the forged material five specimens are produced (P1 to P5). Each specimen is polished, tested and analyzed under the microscope in order to evaluate how the fatigue life of the material is linked to the forging process and to the shape and content of manganese sulfides.

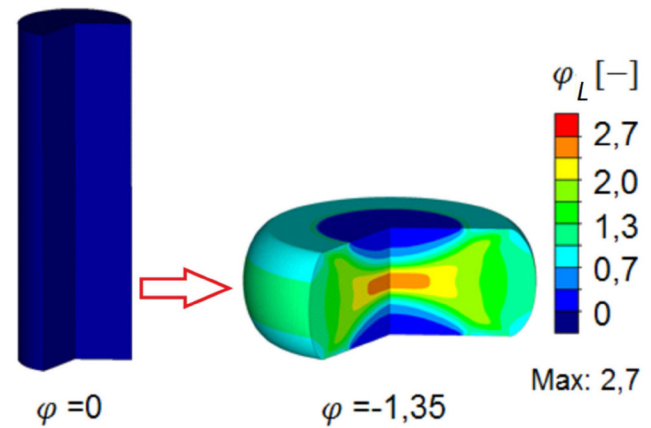


Figure 2. Simulation of the upset forging process, and local upset strain.

Specimen's Manufacture

The slices and the specimens are manufactured by wire electro discharge machining (WEDM). The geometry of the specimens is shown in Figure 3. The specimen geometry is not linked to any testing standard. Very small specimens for fatigue testing are necessary to investigate the logarithmic strain we are interested in for technical relevant material states. Therefore a specimen's geometry for fatigue testing purposes with a 2 mm long constant cross section has been chosen based on experience.

The products of this process are specimens which need a subsequent process of polishing before fatigue testing. This fact is due to the dependency of fatigue life on the surface roughness but also to the metallographic analysis of the fracture surface that follows each test, and that requires a surface free from scratches.

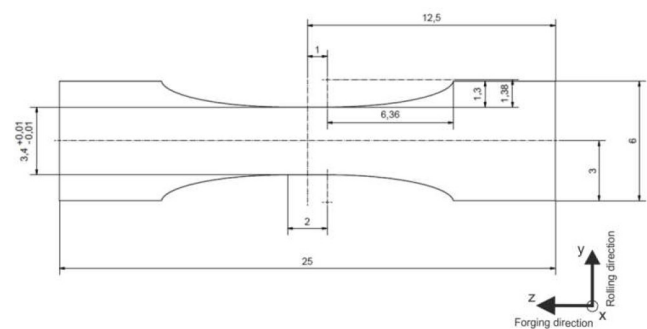


Figure 3. Geometry of the specimens in mm.

For this reason, the sides and the edges of the specimens are previously hand polished, using three different types of sandpaper, according to the grit size: P800, P1200, P4000. The surfaces have been prepared in two steps using a metallographic sample polishing machine, and a specific adapter, which supports the specimen and transmits the force required for the process, has been made with an epoxy resin. The process parameters for surface polishing are summed in Table 1. After being polished the specimens present a surface roughness R_z which goes from $0.6\text{ }\mu\text{m}$ for the surfaces polished using the machine and $1.7\text{ }\mu\text{m}$ for the hand-polished sides.

Table 1. Parameter setting for surface polishing

Type/ Grit size	Time	Force	Speed
Allegro / 9 μm	5 min	30 N	150 round/min
Mol / 3 μm	5 min	35 N	150 round/min

Fatigue Test Setup and Process Parameters

Due to the small size of the specimens and accuracy of the testing procedure, fatigue tests are performed using a testing machine, where an actuator of piezoelectric material [6] transmits a load to the sample, using a clamping system. Forces are controlled by a load cell. The mounting of the specimen on the clamping system is presented in Figure 4. Using a piezoelectric actuator, it is possible to perform tests at a high frequency, because of the reduced inertia of the masses which are involved in the system. The tests performed are load controlled, and the specimen is subjected to a fully reversed cyclic loading ($R = -1$) at a frequency of 150 Hz until the crack occur and the displacement limits, which are set to 10 μm , are exceeded or 10^7 cycles are achieved. The specimens are tested at different levels of the stress amplitude, and non-failed specimens removed from the test rig after 10^7 cycles (run-out) are tested again at higher levels of stress, until the crack occurs. Even though, these tests are not part of the Wöhler line evaluation, information about the shape and content of MnS in the critical (fracture) region is obtained.

All the specimens are tested using this procedure and the results are presented in a diagram with the nominal stress amplitude $\sigma_{a,n}$ on the ordinate and the number of cycles to failure N_f on the abscissa in logarithmic scale.

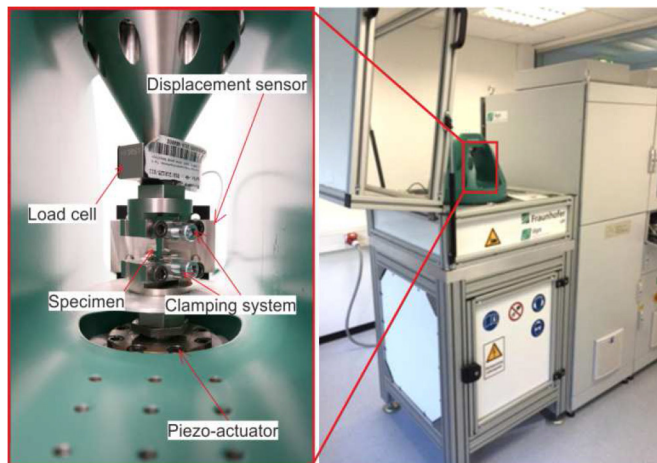


Figure 4. Equipment and clamping system

Fatigue Test Results

Wöhler Curves

The failure criterion is crack initiation and the Wöhler curves are evaluated using the Maximum Likelihood estimation (MLE) [7]. The method consists in maximizing the likelihood function, which is given by the product of all single probabilities for each test with a fatigue failure. These probabilities correspond to the probability density function in case of a failure, and to the cumulative distribution function in case of a run-out of a predetermined

probability distribution. Only the first test performed on a specimen is considered, that means that the results of the tests performed on specimens re-tested at higher stress level are not included in the analysis. In this case the lognormal distribution is used to represent the results, and since a bi-logarithmic scale is used, the survival probability of $P_s = 50\%$ of the Wöhler curves before the knee point follow a linear relation, and can be fully described by two parameters, while the scatter band is considered constant and consequently characterized by one single parameter. The slope after the knee point is fixed to 45.0 based on the recommendations of Sonsino [8]. Therefore, the parameters that have to be maximized are the three previously mentioned and the knee point, which is considered variable. The four parameters that maximize the likelihood function lead to the approximation for plotting the Wöhler curves. Since the knee point has to be the same for each test series in order to compare the results, it is fixed to $N = 3 \cdot 10^5$, that is close to all the values obtained processing the results for each test series.

In Table 2 are summarized the results of the MLE, represented by the coordinates of the knee point N_k and $\sigma_{a,k}$, the slope before and after the knee point (k and k^*) and the scatter T_σ defined as $\sigma_{10\%}/\sigma_{90\%}$.

Table 2. Results of the Maximum Likelihood Evaluation.

	N_k	$\sigma_{a,k}$ [MPa]	k	k^*	T_σ
Center	$3 \cdot 10^5$	159	4.4	45.0	1.54
Side	$3 \cdot 10^5$	226	12.7	45.0	1.15
Forged	$3 \cdot 10^5$	167	11.1	45.0	1.12

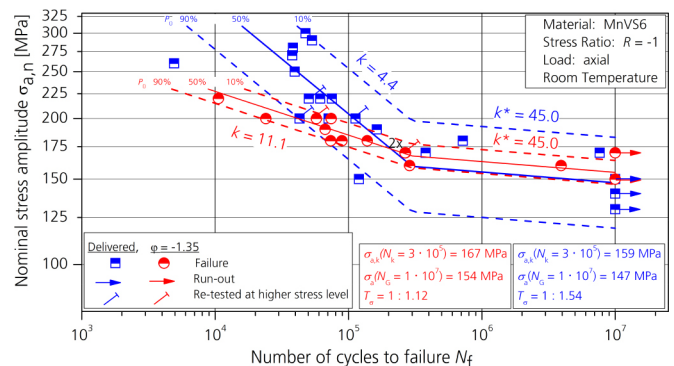


Figure 5. Wöhler curves for the central material before and after forging.

In Figure 5, the Wöhler curves obtained for the central material as delivered and after forging are shown. The difference in fatigue strength between the two curves at high stress levels and the difference in scatter bands are due to the forging process resulting in a variation in shape and content of manganese sulfides. Figure 6 shows the Wöhler curves for the material as delivered extracted from the center and the side of the rolled block. The increase in fatigue strength for the Wöhler results of the side material in the high cycle fatigue (HCF) and long life fatigue (LLF) is due to the structure and content of MnS in the material, caused by the previous process of rolling.