Influences of the manufacturing process chain design on the near surface condition and the resulting fatigue behaviour of quenched and tempered SAE 4140

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Abstract. To analyse interactions between single steps of process chains, variations in material properties, especially the microstructure and the resulting mechanical properties, specimens with tension screw geometry were manufactured with five process chains. The different process chains as well as their parameters influence the near surface condition and consequently the fatigue behaviour in a characteristic manner. The cyclic deformation behaviour of these specimens can be benchmarked equivalently with conventional strain measurements as well as with high-precision temperature and electrical resistance measurements. The development of temperature-values provides substantial information on cyclic load dependent changes in the microstructure.

1. Introduction
The fatigue properties of metallic construction units are affected strongly by their near surface condition which is influenced by manufacturing processes and their individual parameters. Because of their complexity, the influence-cause-effect-relations of process chains are not understood satisfactorily until now [1-4].

The aim of the current investigations is the evaluation of the influence of the process chain design on the fatigue properties of metallic components and specimens. In particular, the microscopic change of the near surface area was regarded over the entire process chain from semi-finished parts to finished specimen.

2. Material and process chains
To estimate the influencing factors of process chain design and process parameters on the fatigue behaviour, specimens with tension screw geometry were manufactured (Fig.1a).

Five typical manufacturing process chains (PC), consisting of the processes heat treatment, turning and grinding, were applied. The studies are focused on the fatigue relevant “extension areas”. The investigated SAE 4140 was supplied in a quenched and tempered condition as round bars with a diameter of 25 mm. The microstructure is characterised by a tempered martensite microstructure with ferrite and fine dispersed Fe₃C carbides.
The overview matrix of the investigated process chains is given in Fig. 1b. Areas machined in the particular processes are marked in grey. After normalisation ($T_a=860°C$, $t=120$ min) the workpieces of PC 1 and 2 were soft-turned and in step three quenched and tempered ($T_a=850°C$, $t=120$ min; $T=550°C$, $t=90$ min), PC 1 ended with this heat-treatment-process. The workpieces of PC 2 were turned with a tolerance of 300 $\mu m$. PC 3-5 were started with quenching and tempering. The extension areas of PC 1, 3, 4 and 5 are machined with only one chipping process: soft turning / hard turning / grinding and consequently large chipping volume. In PC 2 the chipping volume was realised in two steps: soft turning and grinding.

3. Experimental setup
Light and scanning electron microscopy, surface roughness, micro hardness und residual stress measurements as well as fatigue tests were carried out. The experimental setup for the fatigue tests is shown detailed in [5]. In addition to stress-strain hysteresis measurements $\varepsilon_{ap}$, deformation-induced changes in temperature $\Delta T$ [6-8] and changes in electrical resistance $\Delta R$ [9-12] were measured with high precision.

The mechanical stress-strain hysteresis measurements were carried out with an extensometer in the extension area two (EA 2). $\Delta T$ was detected with four thermocouples ($T_1$, $T_4$) fixed along the specimen. $T_1$ and $T_2$ were fixed in the middle of the extension areas EA 1 and 2 and $T_3$ and $T_4$ at the elastically loaded shafts. The local change in temperature for the extension areas 1 and 2 can be evaluated with the subtraction of the mean of $T_3$ and $T_4$ from $T_1$ and $T_2$ respectively. $\Delta R$ was measured integrally across both extension areas. The experiments yield cyclic deformation $\varepsilon_{ap}$, cyclic temperature $\Delta T$-N and cyclic electrical resistance $\Delta R$-N curves representing the actual fatigue state.

The stress-controlled constant amplitude tests (CAT) were performed at the load ratio $R=0$ on a servohydraulic testing system at ambient temperature with a frequency of 5 Hz and triangular load-time functions.

4. Results
The surface roughness of PC 2-5 was determined in average of 4.5 $\mu m$. The values of PC 3-4 were slightly better than the values of PC 2 and PC 5. The as heat-treated surface of PC 1 with oxide layers was detrimental with respect to fatigue properties.
As a consequence of the grinding process, the near surface area of the specimens manufactured according to PC 2 is characterised by significant plastic deformations reaching to a depth of 3 $\mu m$. 

![Figure 1. Specimen with tension screw geometry (a); Process chains PC 1-5 (b)](image)
Compressive residual stresses $\sigma_n = -330$ MPa were measured (Fig. 3a). The grinding process in PC 5, inducing compressive residual stresses of -350 MPa, leads to changes in the microstructure to a depth of about 7 μm (Fig. 3b). The pronounced plastic deformations are caused by the larger chipping volume in PC 5. The microstructural changes due to the hard-turning process in PC 3 (Fig. 3c) can be divided into a primary (P) zone near the surface to a depth of 2 μm where the distance between the carbide lines is nearly zero and in the secondary (S) zone for further 3 μm where the carbide lines are strongly deformed. The feed rate ($a_p$) of 50 μm and the depth of cut ($V$) of 0.6 mm/rev. lead to a nearly residual stress free state. The double feed rate and half depth of cut applied in PC 4 result in the microstructure shown in Fig. 3d with tensile residual stresses of about +430 MPa. In comparison to PC 3, the primary zone is smaller and the secondary zone is significantly enlarged. The process type and the process parameters, respectively, are responsible for the different developments of the microstructural changes and the resulting amount and sign of the near surface residual stresses.

**Figure 3.** Changes of the near surface area in the extension areas due to the process chains PC 2 (a) and PC 5 (b) after grinding as well as PC 3 (c) and PC 4 (d) after hard-turning.

Fig. 4a shows the development of $e_{ap}$ measured in the EA 2, $\Delta T$ measured individually in EA 1 and EA 2 and $\Delta R$ measured integrally across both extension areas of a specimen machined according to PC 4, for a CAT with $\sigma_n=440$ MPa. Fig. 4b gives an overview of $\Delta T$-courses for specimens machined according to PC 3, PC 4 and PC 5 for $\sigma_n=440$ MPa measured in EA 2.
Figure 4. Development of plastic strain amplitude, change in temperature and change in electrical resistance in a constant amplitude test for a tension screw specimen of PC 4 (a); cyclic temperature curves and residual stresses for tension screw specimens of PC 3, PC 4 and PC 5 (b).

A significant increase of $\Delta T_2$ and $\Delta R$ is measured at $4.6 \times 10^4$ cycles due to a proceeding fatigue damage in EA 2. The course of EA 1 ($\Delta T_1$) increases at distinct higher number of cycles, right before failure because of thermal conduction. Obviously, $\Delta T$- and $\Delta R$-measurements indicate fatigue failure earlier than $\varepsilon_{ap}$-measurements. This is caused by very small and localised plastic deformation volumes in high-strength steels leading to very small plastic strain amplitudes. The local application of $\Delta T$ and $\Delta R$ allows to identify precisely component areas which are critical for fatigue damage.

Specimens with higher (lower) $\Delta T$-values reach lower (higher) number of cycles to failure. With increasing residual stresses from compression to tension, $\Delta T$ increases and the lifetime consequently decreases.

5. Conclusion

It was shown that machining processes and their parameters influence the near surface condition and consequently the fatigue behaviour in a characteristic manner. Significant changes in distance and arrangement of the carbide lines were observed as a result of turning as well as grinding processes. The process type and its parameters, respectively, lead to different developments of microstructure and the resulting amount and sign of residual stresses. The plastic strain amplitude, temperature and electrical resistance measurements can be equivalently used for fatigue assessment of specimens with tension screw geometry. The temperature and electrical resistance measurements seem to be more beneficial for the evaluation of fatigue life.

6. References

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