Fatigue Properties of Steels SAE 1045 and SAE 4140 upon Integrated Inductive Heat Treatment and Deep Rolling at Elevated Temperature

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Introduction

Mechanical surface treatments like deep rolling are well-established and commonly used in everyday practice, allowing for high strength and light weight vehicle components. The comparatively simple application on standard machines associated with a positive influence on fatigue life of cyclically loaded components are two of the numerous advantages [1]. It has been found in previous research that deep rolling at elevated temperature leads to a stabilisation of beneficial compressive residual stresses (see e.g. Fig. 1) [2, 3]. Responsible for this effect are dislocations pinned through static or dynamic strain ageing and precipitation of small carbides. Due to short austenitization times by fast and homogenous heating, inductive heat treatment leads to a favourable microstructure [4] with the advantage of short process time. For this reason, a systematic investigation of inductive heat treatment combined with deep rolling at elevated temperature is of high interest regarding safe and reliable components.

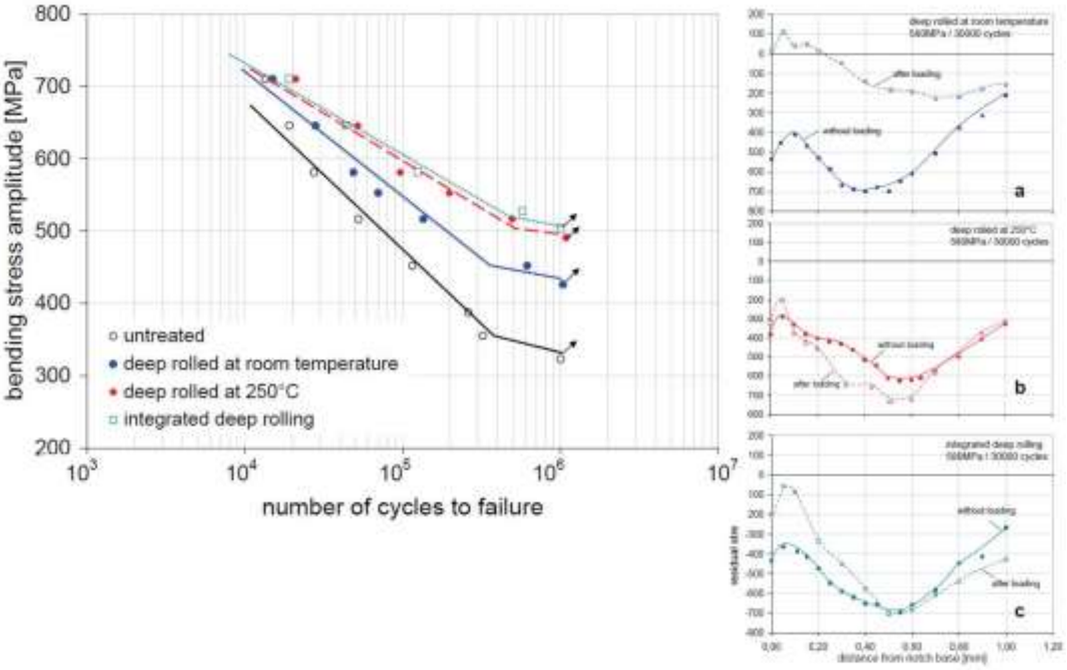

Fig. 1: Fatigue life and residual stress stability after high temperature deep rolling of steel SAE 1045 [5]

Objectives

Heat treatment and mechanical surface treatment like deep rolling are usually applied separately and therefore both processes represent an individual step in the production chain. In order to combine the advantages of these processes it requires an integrated process chain to identify optimum process parameters. A test facility meeting the requirements is detailed in this paper. The determination of physical correlations between near surface material properties and fatigue life allows for establishing superior component states with enhanced safety and reliability. For this purpose resulting microstructures and residual stress profiles in near surface regions of characteristic conditions are shown. Positive effects of the surface treatments are revealed by fatigue tests. Cyclic deformation behaviour is analysed and crack formation as well as crack propagation behaviour is assessed by evaluation of fracture surfaces.

Methodology

The investigated materials were steels SAE 1045 and SAE 4140 with the chemical compositions given in Tab. 1 and the specimen geometry shown in Fig. 2. To take several material conditions into account, different kinds of heat treatment were performed.

	C	Mn	Si	Cr	Mo
SAE 1045	0,49	0,59	0,21	0,03	-
SAE 4140	0,47	0,94	0,20	0,82	0,17

Tab. 1 - Chemical composition of the investigated materials [wt-%]

All conditions were inductively hardened (900°C, 1s), using a water-miscible polymer quenchant, and afterwards tempered either conventionally in a furnace (SAE 1045) and a salt bath (SAE4140) or inductively (SAE 4140). Heat treatment parameters and resulting material properties are given in Tab. 2. To identify the influence of deep rolling parameters regarding highest fatigue life for all conditions, the deep rolling force was varied between 0.5 kN and 2.5 kN and the number of passes between one and three.

The deep rolling processes were carried out at room temperature and at elevated temperature in a temperature range of 250°C to 280°C using inductive heating controlled by thermocouples. The used deep rolling tool with a diameter of 40 mm was custom-built for the requirements imposed by high temperature deep rolling at the University of Kassel. The rotational speed was 80 revolutions per minute with a feed rate of 1 mm per revolution. For the characterization of the near surface regions, residual stress depth profiles and integral width values were measured using X-ray diffraction (XRD) ($\sin^2 \Psi$ – method, CrKα radiation, {211}-planes, $\frac{1}{2}\, s_2 = 6{,}095 \cdot 10^{-6}$ mm^2/N) and successive electrochemical removal of the surface layers without stress correction. In addition, hardness (HV0.3) measurements were carried out to determine hardness profiles on polished cross sections. Fatigue tests were performed on servo-hydraulic devices under stress control and a stress ratio of R=-1, i.e. uniaxial tension-compression loading.

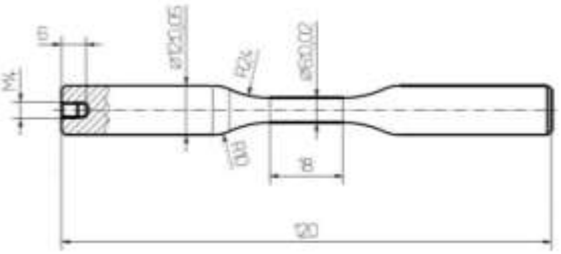

Fig. 2 Specimen geometry (dimensions in mm)

Material and tempering conditions	SAE 1045	SAE 4140	
	400°C/1h	280°C/1h	280°C/197s
ultimate tensile strength	1400 MPa	1800 MPa	1770 MPa
yield strength	1340 MPa	1600 MPa	1550 MPa
elongation to fracture	28 %	12 %	9%
medium hardness	430HV0.3	520HV1	550 HV1

Tab. 2 - Heat treatment parameters and resulting material properties

Results and analysis

To study the interaction between deep rolling and heat treatment processes, a newly designed production chain, shown in Fig. 3 (left) was realised, which is suitable to ensure the required process conditions. The system allows controlled inductive hardening and tempering followed by a deep rolling process at elevated temperature. The tempering process can either be carried out directly after austenitizing and quenching or consecutively as well as simultaneously using the deep rolling device. This leads to numerous possibilities of process variations regarding the process time and temperature, for example carrying out the deep rolling process at lower, equal or higher temperatures compared to the tempering temperature, see Fig. 3 (right). Equal or higher temperatures result for example in an additional tempering effect during the deep rolling process.

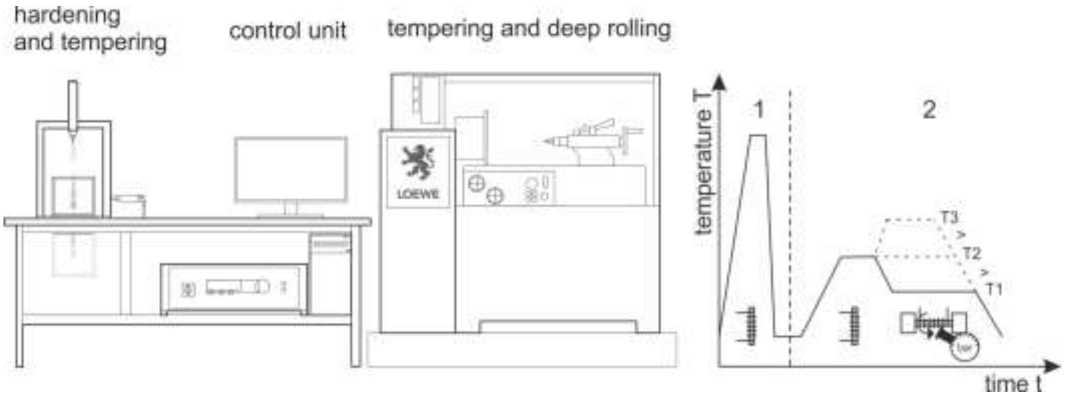

Fig. 3: Schematic sketch of the developed system for heat treatment and deep rolling (left) and possible process variants (right)[8, 9]

In the beginning, basic information about the influence of different process parameters (e.g. deep rolling force, number of passes) on the surface properties based on [5, 6] were gained to identify suitable conditions for further investigation. For this purpose, specimens were inductively through-hardened and conventionally tempered in a salt bath. Representative results of depth distributions of longitudinal residual stresses and integral width values for three deep rolled specimen with a rolling force of 1.5 kN (three passes), deep rolled at 280°C and room temperature, are shown in Fig. 4 (right).

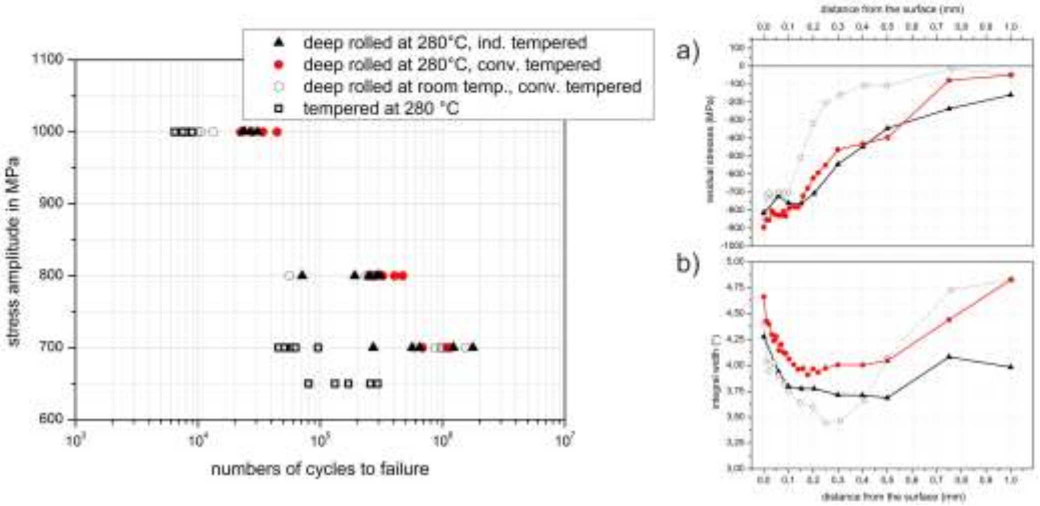

Fig. 4: S,N – curves of differently tempered conditions untreated and deep rolled at 280°C and at room temperature (1.5 kN, 3 passes) (left) and depth distributions of a) longitudinal residual stress states and b) integral width values (right). Experimental data are taken from [8, 9] complemented with new data.

The compressive residual stresses of the high temperature deep rolled specimen are slightly higher than for room temperature. This can possibly be explained by the higher plastic deformation at elevated temperature. All stress profiles show maximum compressive residual stresses at the surface with approximately equal values. The measured integral width values are typical for the investigated material states, beginning with a maximum at the surface and decreasing to a minimum at a distance of approximately 0.3 mm under the surface. Regarding the fatigue life, deep rolling at elevated temperature for this particular material condition leads to a life improvement especially at higher loading amplitudes, Fig. 4 (left). For lower amplitudes, the numbers of cycles to failure of both states are converging and meet at the lowest loading amplitude of 700 MPa. Next, parameters for the inductive tempering process were determined by variation of tempering time in consideration of the available devices (induction coil etc.). Hardness values of the conventionally tempered material state were the basis for the determination in a first step. Afterwards the parameters were adjusted based on the results of tensile tests to get almost identical material states compared to the conventionally tempered specimen. After deep rolling at elevated temperature (280°C) with 1.5 kN and three passes, the inductively tempered specimen show almost identical profiles of compressive residual stresses and integral width values. Comparing the fatigue life, the numbers of cycles to failure of the inductively tempered specimen are in the same range as the reference. Decreasing the load, the results show a slightly larger spread. However, S,N – curves shown are not statistically evaluated. The improvement of the fatigue performance of the high temperature deep rolled specimen can also be seen on the fracture surfaces. Due to stabilised compressive residual stresses, crack initiation does not start at the surface but rather in the interior of the specimen and is therefore delayed, see SEM picture in Fig. 5. The initiation point of the crack corresponds approximately to the zero crossing of the residual stress profiles. This applies on both, conventionally and inductively tempered specimen.

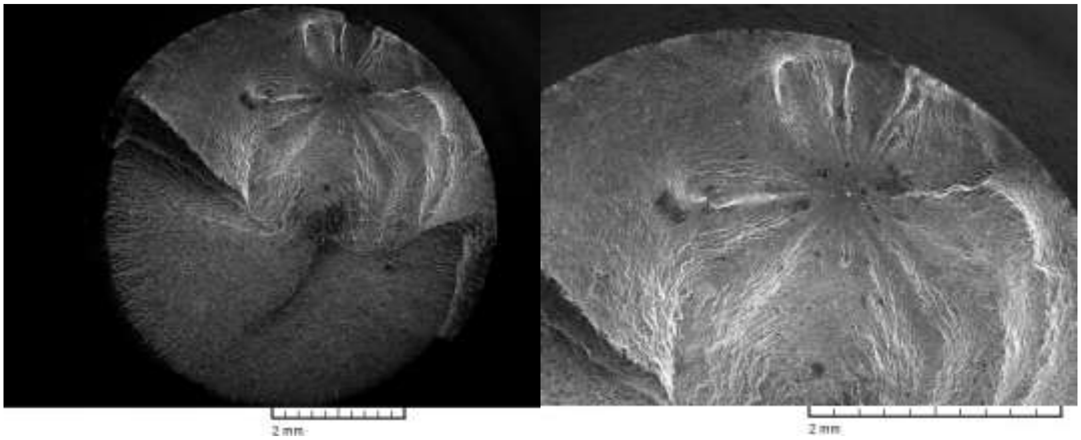

Fig. 5: SEM pictures of a representative fracture surface after fatigue loading of steel SAE 4140 (stress amplitude 700 MPa, R = -1, $N_f = 6.5 \cdot 10^5$)

Upon deep rolling, besides the stabilisation of residual stresses, a decreased fatigue life on higher loads is generally observed, exemplary shown for steel SAE 1045 in Fig. 6 (left). As one can see, the increase of the fatigue lifetime in the high-cycle fatigue regime is remarkable. The fatigue strength increases from 450 MPa to 625 MPa for the room temperature deep rolled and to 675 MPa respectively for the high temperature deep rolled specimen, which corresponds to an improvement of about 40% to 50%. The higher the fatigue loading the smaller is the difference between untreated and deep rolled specimen. At approximately 900 MPa the fatigue life for untreated and deep rolled specimen at room temperature is equal. Deep rolling at elevated temperature leads to slightly higher fatigue life so that the point of intersection of the trend lines can be seen at around 1000

MPa. The reason for the difference between the two deep rolled material states can clearly be found in the stabilisation of the compressive residual stresses. The development of the residual stresses on the surface in longitudinal and tangential direction as a function of the number of cycles is shown in Fig. 6 (right). In the beginning the residual stresses of the high temperature deep rolled specimen in longitudinal direction (loading direction, Fig. 6 a) are approximately 100 MPa higher than for the room temperature case. In both conditions with increasing numbers of loading cycles a continuous decrease of the residual stresses can be observed but residual stress relaxation of the room temperature deep rolled specimen is clearly faster than the other. For example, after 4000 cycles the value of the compressive residual stresses on the surface of the room temperature deep rolled specimen is below -200 MPa, in contrast to nearly -500 MPa of the specimen deep rolled at elevated temperature. The measurements in tangential direction (Fig. 6 b) show similar results. Starting from approximately -500 MPa in both cases, the residual stresses of the high temperature deep rolled specimen stay nearly constant and decrease to approximately -420 MPa after 4000 cycles, whereas the residual stresses of the room temperature deep rolled specimen decrease to almost -200 MPa. Compared to the deep rolled conditions, the residual stresses of the untreated specimen are constantly on a neutral level in both cases.

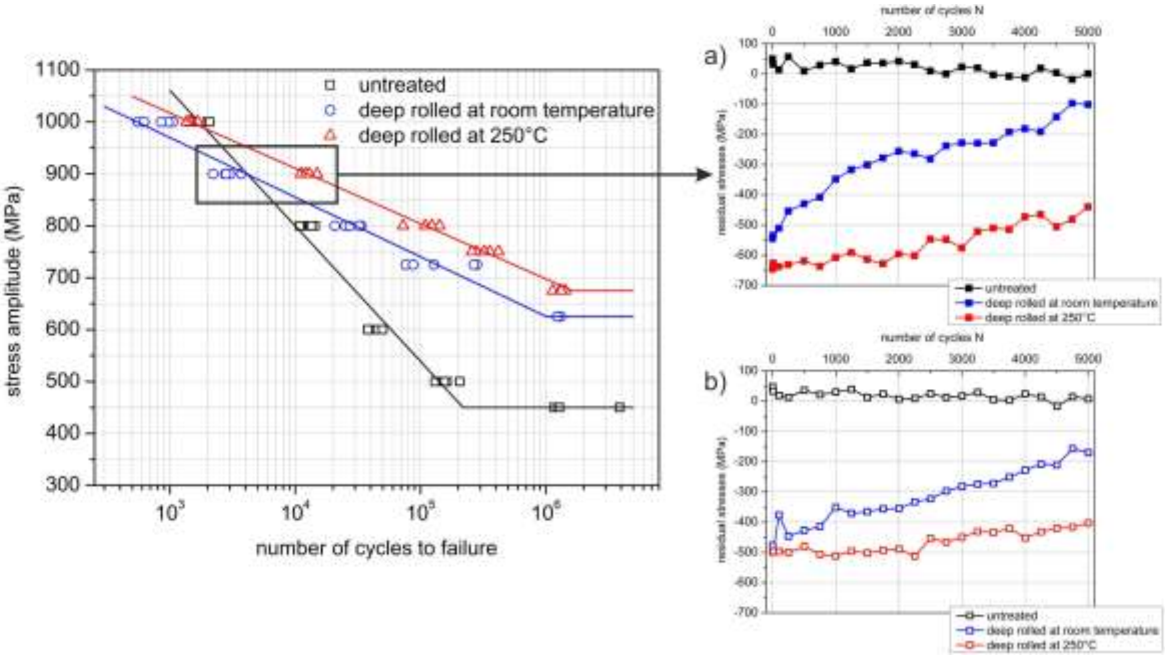

Fig. 6: Fatigue life of untreated and deep rolled SAE1045 (1,5 kN, 1 pass) (left)[9] and the development of the residual stresses on the surface of the deep rolled specimen after increasing number of cycles at constant load of 900 MPa (right) in longitudinal (a) and tangential (b) direction

Conclusion

It has been shown that process integration of inductive heat treatment and deep rolling is a promising way to realise safe and reliable components. Compared to conventional consecutive processes, almost identical results can be achieved, which opens up interesting industrial application possibilities. Most important is the stabilisation of beneficial compressive residual stresses, but also further microstructural aspects have to be taken into account, which result from the interaction of plastic deformation and other thermally activated processes. To achieve optimum process parameters, a sound understanding of the elementary mechanisms and their consequences on the mechanical properties is necessary.

Acknowledgement

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