ABSTRACT

After a survey about characteristic results, residual stress effects on cyclic deformation of materials, on crack initiation as well as on crack propagation are outlined. In all cases, macro-and micro-residual stress effects have clearly to be separated. In the case of cyclic deformation, stability or relaxation of residual stresses is correlated with microstructural observations. For the case of corrosion fatigue, the complex interactions between residual and loading stresses in the neighborhood of corrosion pittings or small cracks are demonstrated. Finally, the influence of residual stress fields on propagation of long cracks is discussed.

INTRODUCTION

Today is well-known that almost no technical materials, components or structures are available completely free of residual stresses. Consequently, if residual stress distributions are not quantitatively known, considerable uncertainty exists in designing components correctly. There is no doubt that consequences of residual stresses are especially pronounced in the case of fatigue loaded components. Perhaps it is interesting to note that A. Wöhler, after whom the relationship between loading amplitude and number of cycles to failure, the „Wöhler curve“, (S,N-curve) is named, probably gave the first correct description of a residual stress state in a technical component when he described the residual stress state of a bent bar [1].

Because of the outstanding importance of near surface materials’ states for the fatigue behavior, especially consequences of surface treatments and manufacturing processes were studied to investigate the influence of residual stress states on fatigue life. Significant contributions were made by Jacob [2], who suggested the autofrettage process, Thum and Foepl [3,4] who, in a controversial way, discussed the mutual influence of strain hardening or residual stresses due to mechanical surface treatments and Horger [5] who worked in the field of surface rolling. In 1936 for the first time Ruttmann [6] clearly demonstrated the consequences of machining induced residual stress states on the fatigue behavior of components. Residual stress states due to shot peening - a very important industrial technology today -, however, were measured by Milburn only in 1945 for the first time [7].

In the following the well-established definitions of the terms macro- and micro-residual stresses will be used [8]. A considerable advantage of X-ray stress analysis is that macro-as well as micro-residual stresses and also mean values of phase specific stresses in multi-phase materials can be measured. Residual stresses resulting from technological processes are always superpositions of macro-and micro-residual stresses and it is mandatory for the assessment of residual stress states to clearly differentiate between them. Only macro-residual stresses can be
looked upon as stresses to some degree equivalent to loading stresses from external forces or moments.

Fig. 1: Depth distributions of grinding residual stresses and resulting Wöhler-curves in bending fatigue tests [9].

Fig. 2: Influence of manufacturing induced residual stresses on Wöhler-curves in corrosion fatigue tests [10].

CHARACTERISTIC EXAMPLES AND DISCUSSION

Meanwhile, the number of papers and presentations dealing with residual stress effects in fatigue is enormous. Characteristic examples are given in Figs. 1 and 2. On the left-hand side of Fig. 1, depth distributions of residual stresses are shown, introduced in quenched and tempered SAE 1045 steel by different grinding processes [9]. CBN-grinding under prestress leads to compressive surface residual stresses of about -1200 MPa. Grinding with corundum yields considerable tensile residual stresses. Residual stress distributions of other grinding processes are to be found between these curves. Wöhler-curves on the right-hand side show a clear tendency.
Specimens with tensile surface residual stresses have a small fatigue strength, which can be considerably increased by compressive residual stresses. Also in the case of corrosion fatigue a small, but distinct difference between Wöhler-curves of specimens with different manufacturing induced residual stresses can be observed (see Fig. 2 [10]). Ground specimens made of SAE 1045 with almost no residual stresses show smaller lifetimes than shot peened ones with a 0.2 mm thick surface layer with compressive residual stresses. But there are also cases demonstrating that almost no residual stress effect can be observed, e.g. in the case of normalized or recrystallized steels. Altogether, the following conclusions about the consequences of residual stresses on fatigue behavior of components can be drawn: Perhaps the most important fact is that there is no unique and simple relation between residual stress state and fatigue strength or lifetime. The reason is that in most cases the process which introduced residual stresses also leads to other characteristic alterations of the materials’ state, e.g. alterations of surface topography, strain hardening or softening, phase transformations and of other properties, which also have a great impact on fatigue strength and lifetime [11].Because quite a number of these properties can be analyzed by X-ray techniques, it becomes obvious that X-ray diffraction is very useful for the assessment of fatigue processes. Another important point is that residual stresses are not in all cases stable during the fatigue process, but they may relax as a consequence of cyclic plastic deformations. A good example is presented in Fig. 3, which shows that during cyclic deformation the plastic strain amplitude, measured by registration of individual hysteresis loops, controls stress relaxation. In this case, a normalized and shot peened steel SAE 1045 was investigated [12]. During the first cycles, residual stresses reduce only slightly, but as soon as cyclic plastic deformation sets in, indicated by drastically increasing plastic strain amplitudes, macro-residual stresses relax almost completely. Inhomogeneous micro-residual stresses represented by half-width values of Bragg-reflexions, also relax almost down to the initial value before shot peening. It is obvious that processes or process parameters improving the stability of macro-and/or of micro-residual stresses also may have a significant impact on fatigue strength and lifetime. When regarding residual stress effects in fatigue, it has proved to be useful to discuss separately the crack-free deformation phase, crack initiation and finally micro-crack as well as macro-crack propagation. For crack initiation, micro-residual stresses and the underlaying defect structure of the material is of importance. Processes introducing residual stresses lead to characteristic microstructures, e.g. to characteristic dislocation distributions. One has to keep in mind that residual stress distributions are always consequences of inhomogeneous plastic deformations. Typical examples of near surface dislocation distributions after mechanical surface treatments are summarized in [12-14]. Macro-residual stresses, if at all, have only a secondary influence on crack initiation. Their importance is more dominant in the case of crack propagation. If cracks start at the surface - which not always is the case - in addition to surface roughness also local fluctuations of macro-residual stresses existing in technical surfaces may be of importance for the crack initiation sites and propagation of small cracks. Fig. 4 shows an example of inhomogeneous macro residual stress distributions in a shot peened surface of steel SAE 1045 [15]. As a consequence of the individual impacts of the shots, considerable fluctuations of stress amounts are observed, which easily can be detected by X-ray stress analysis using small areas irradiated by the X-ray beam. Inhomogeneity of residual stresses is considerably more pronounced immediately at the surface compared with subsurface layers. Such measurements are rather time consuming, and there is not very much known about the consequences of local inhomogeneities of residual stress distributions on fatigue strength and lifetime.
Fig. 3: Relaxation of macro-residual stresses and FWH together with development of plastic strain amplitude as a function of number of cycles in push-pull-tests [12].

Fig. 4: Local residual stress distributions in the surface of a shot peened steel SAE 1045 (peening medium: S330)[15].

Because of the importance of micro-residual stresses and defect microstructures for fatigue lifetime, attempts are made for a better understanding of the microstructural processes of stress relaxation and to improve residual stress stability. One idea is to stabilize microstructures created during the process used to introduce residual stresses. For this purpose, in [16] shot peening processes at higher temperatures were carried out. In this case dynamic strain ageing processes stabilized dislocation arrangements created and, hence, improved the stability of residual stress states during cyclic deformation. For macroscopic residual stresses, this is shown in the upper part of Fig. 5, where surface residual stresses during bending fatigue are plotted as a function of number of cycles. Residual stresses in specimens peened at 290°C are more stable than those in specimens peened at room temperature. Inhomogeneous microstresses, analyzed by measurements of interference line half-width values are also much more stable for specimens peened at 290°C compared with specimens treated at room temperature (see lower part of Fig. 5). As a consequence, fatigue strength at room temperature of specimens can be increased by more than 20% using the high temperature peening process.
In this case, X-ray stress analyses were very helpful to identify the decisive mechanisms of fatigue life improvements, e.g. the better stability of micro- and macro-residual stresses. In [17] it is shown that also annealing processes after mechanical surface treatment - shot peening or deep rolling - can lead to significant lifetime improvements compared to only mechanically surface treated specimens. In this case, indeed the annealing process leads to a decrease of macro-residual stresses as well as of inhomogeneous micro-residual stresses. Microhardness measurements in the affected surface layers, however, showed a small increase as a consequence of the annealing operation. As a decisive process static strain ageing could be identified, pinning dislocations by diffusing carbon atoms. Consequences for cyclic plastic deformations during fatigue are enormous. Fig. 6 shows, as a function of number of cycles in push-pull-tests, the plastic strain amplitudes of three different materials’ states, cyclically loaded with a stress amplitude of 350 MPa: normalized, normalized and surface rolled and, finally, normalized, surface rolled and additionally annealed at 350°C for 90 s.
In the normalized state, after an incubation period of about 100 loading cycles, cyclic softening sets in with a pronounced increase of the plastic strain amplitude. This is the well-known, typical behavior of a normalized ferritic-pearlitic steel. In the normalized and additionally deep rolled state plastic deformation starts earlier. This can be attributed to the already existing high dislocation density. However, because of the restricted free path of the dislocations, for higher numbers of cycles, plastic strain amplitude is considerably smaller than in the normalized state. Smallest plastic strain amplitudes are observed for the deep rolled and additionally annealed state. Note that as a consequence of dislocation pinning, a purely elastic behaviour is observed up to 1000 loading cycles. Then, plastic strain amplitudes remain considerably smaller than in the other cases.

In the case of corrosion fatigue, residual stress analyses lead to an improved understanding of the damage process. Fig. 7 shows an example [18]. It deals with fatigue tests in seawater of steel SAE 1045. Compressive residual stresses of about 200 MPa were introduced by CBN-grinding. Then, after bending fatigue with a stress amplitude of 300 MPa and \(5 \times 10^5\) loading cycles, local residual stress distributions (diameter of the irradiated area: 0.5mm) were measured in the vicinity of corrosion fatigue cracks and pittings. In addition, stresses were measured in the loaded state to analyse the superposition of loading and residual stresses. As one can see, along the crack, smaller residual stresses were measured compared with undamaged surface areas. It is interesting to note that in the loaded state, in the cracked area almost no stress alterations compared with the unloaded state were detected. Corrosion cracks lead to highly inhomogeneous loading stress distributions with maximum stresses at the crack tips. Similar observations were made for corrosion pits (see Fig. 8). In this case, however, if loading stresses are applied, corrosion pits act as stress raisers and maximum total stresses are observed in the area of corrosion pits.

Also in the case of macroscopic cracks, X-ray stress analysis has considerably contributed to a better understanding of crack propagation. It is well-known since long that a propagating fatigue crack, as a consequence of inhomogeneous plastic deformations around the crack tip, is characterized by a typical crack tip residual stress field, which propagates with the crack similar to a bow-wave of a ship [19,20].

Fig. 6: Plastic strain amplitudes as a function of number of cycles of differently treated SAE 1045 \((\sigma_u = 350\,\text{MPa})\) [12].
Fig. 7: Distribution of residual and total stresses in the vicinity of a crack during a corrosion fatigue test [18].

Fig. 8: Distribution of residual and total stresses in the vicinity of a corrosion pit during a corrosion fatigue test [18].

A typical example is shown in Fig. 9, where the residual stress component $\sigma_y^{RS}$ acting perpendicular to the crack, is plotted along the crack propagation direction. The crack was produced by constant amplitude loading up to a stress intensity of 47.3 MPa$\cdot$m$^{1/2}$. At the tip of the fatigue crack, a small area of considerable compressive residual stresses exists followed by smaller tensile residual stresses. It is interesting to note that at the crack flanks also compressive residual stresses exist, indicating that the crack is closed and the crack flanks are pressed together in the unloaded state. When overloads are applied during the fatigue loading sequence, crack tip residual stress distribution is characteristically changed. In the case shown in Fig. 10, overload ratios $\lambda$ of 2 and 3 were used, where $\lambda$ denotes the relation between the load amplitudes of overload and base load conditions resp.
Fig. 9: Residual stress distribution along a fatigue crack propagating under mode-I loading condition ($\sigma_y^{RS}$ is the residual stress component perpendicular to the crack) [21].

After applying 20 overload cycles and continuing with base load fatigue cycles, compressive residual stress distributions at the crack flanks are completely reduced. In front of the crack tip, larger areas with compressive residual stresses are induced and also higher amounts of compressive or tensile residual stresses can be observed. The influence of these overload cycles on crack propagation rate is plotted on the right-hand side of Fig. 10, which shows crack propagation rates as a function of crack length. For both overload ratios, a delayed retardation of crack propagation is observed, which is much more pronounced for $\lambda = 3$ than for $\lambda = 2$. If overload cycles are applied as mode II-overloads, (shear mode loading of cracked components), quite a different crack propagation behavior is observed. As one can see in the lower right hand
part of the diagram, almost no crack retardation effects are observable and cracks propagate with the same velocity as if no overloads had been applied. The reason for this behavior is explained by the residual stress distributions, resulting from mode II-overloads. After applying mode II-overloads, crack tip residual stresses of the base load condition are almost completely wiped out. No compressive residual stresses can be observed in front of the crack tip and, consequently, there is no reason for any crack retardation.

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REFERENCES