NEAR SURFACE MICROSTRUCTURES IN MECHANICALLY SURFACE TREATED MATERIALS AND THEIR CONSEQUENCES ON CYCLIC DEFORMATION BEHAVIOUR

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ABSTRACT

Modern mechanical surface optimization has come into a stage way beyond mere empirical concepts. Especially surface characterization methods have significantly contributed to a more thorough understanding of fatigue mechanisms. Using some important model materials, in this paper a survey of typical surface finishing induced microstructures is given.
A combination of mechanical, electron microscopical and X-ray methods currently has proved to be most effective to provide information about near surface properties, if 'tailored' surfaces are to be aspired at. Special focus is put on the stability of near surface microstructures during cyclic loading and its consequence on cyclic softening/hardening behaviour as well as crack initiation and propagation. Finally, it is demonstrated that with appropriate heat treatments after shot peening further surface optimization can be achieved.

KEY WORDS

Microstructure, cyclic deformation curves, transmission electron microscopy, residual stresses, cracks, artificial strain ageing, SAE 1045, AISI 304, magnesium.

INTRODUCTION

Shot peening is a very effective and cheap mechanical surface finishing method and often used for structural parts, e.g, in the automotive industry. Beneficial effects of mechanical surface treatments are mostly compressive residual stress profiles and strain hardening in near surface regions of components, yielding higher resistance against fatigue loading, corrosive environment or wear. Residual stresses are most important in the case of high strength materials, if they remain stable during fatigue. In the case of softer materials a partial or complete relaxation of residual stresses may occur, rendering strain hardening effects very important, which are generally more stable against cyclic loading than first order residual stresses. Several examples exist demonstrating the effects of mechanical surface treatments on microstructure and cyclic behaviour of various engineering materials [1,2]. However, little work has been done about the stability of near surface micostructures and microstresses in mechanically surface treated materials during cyclic loading, especially when applying cross sectioning transmission electron microscopy of direct surface regions [3-6].

This work is a comparative study about the effects of high cyclic strain and stress on different characteristic near surface microstructures. The stability of these near surface microstructures can be considered as decisive also when assessing the usefulness of mechanical surface treatment in the LCF-regime.

RESULTS

The Low Cycle Fatigue region is usually understood to be the region $10^2 < N_f < 10^5$ [7]. This means that in stress controlled fatigue tests the stress amplitude lies closely to or even above the yield strength of the cyclically loaded material. Such high stress amplitudes lead to considerable microplastic yielding, usually measured by registration of hysteresis loops in form of plastic strain amplitudes. The magnitude of the plastic strain amplitude governs the extent of macro residual stress relaxation in fatigued mechanically surface treated materials (see [8]) For example, in shot peened plain carbon steels a complete macro stress relaxation sets in when cyclic softening occurs and is already finished after 10-20 cycles (Fig. 1). The inhomogeneous microstresses, as represented by the half-width value of Bragg-reflexions in X-ray measurements, also begin to relax when cyclic softening starts and gradually decrease almost down to the initial level before shot peening. It is therefore not very astonishing to note that mechanical surface treatment of such materials very often is rather ineffective if the component or specimen is loaded in the LCF-regime. However, this behaviour is not to be generalized, since obviously some mechanically surface treated materials, like austenitic stainless steels or magnesium base alloys, exhibit pronounced lifetime improvement even in the LCF-regime (Fig. 2). In order to clarify the reasons for this behaviour residual macro and microstress depth profile measurements as well as transmission electron microscopy investigations were carried out. Fig. 3 shows macro and microstress depth profiles of shot peened SAE 1045, shot peened AZ31 and deep rolled AISI 304 after fatigue with high stress amplitudes ($\sigma_a \approx \sigma_{yield}$) after half the number of cycles to failure. One can see that in all cases the compressive macrostresses induced by shot peening or deep rolling were drastically diminished or even eliminated down to the initial level prior to cyclic loading. Nevertheless, the behaviour of half-width values was distinctly different. Whereas the near surface inhomogeneous microstresses were almost completely eliminated by cyclic loading in SAE 1045, total stability of half-width values was observed in AISI 304 and in AZ31. When comparing the stability of residual stress (left column diagramms) with the stabilty of half-width values (right column diagramms) it becomes clear that macrostress relaxation does not depend on the stabilty of microstresses in near surface layers. Being long ranged, they may also relax if only microplastic cyclic yielding of the soft specimen core occurs. Furthermore, it is evident that the stability of macrostresses is no criteria to assess the usefulness of mechanical surface treatment in the low cycle fatigue regime. Instead, the stability of inhomogeneous microstresses determines the extent of lifetime improvement (see Fig. 2).

The reason for the different microstress stability in AZ 31 and AISI 304 compared to SAE 1045 must be found in characteristic differences of the microstructural near surface strengthening mechanisms. Fig. 4 shows typical near surface microstructures in mechanically surface treated SAE 1045, AISI 304 and AZ31. Apart from a general increase of dislocation density towards the surface in all investigated alloys, distinct differences can be stated: Whereas a merely dislocation-induced surface hardening took place in SAE 1045 (with different dislocation arrangements depending on the surface finishing process), very complex microstructures were generated in AISI 304 and AZ31. In AISI 304 the mechanical surface treatment lead to the formation of nanocrystallites and twinned strain induced martensite. A typical feature in AZ31 was deformation-twinning. Additional research by means of cross-sectional transmission electron microscopy revealed that the nanocrystalline surface layer as well as the martensitic regions in AISI 304 remained stable during cyclic loading [9], neither was the twinning structure in AZ31 significantly affected. Thus, near surface microstructures in AZ 31 and AISI 304 are basically irreversible (at least at room temperature), offering a logical explanation why the interference line half-width values were scarcely influenced by cyclic loading.

The disappearance of strain hardening in shot peened SAE 1045 in the wake of cyclic loading is illustrated in Fig. 5, showing TEM-micrographs of direct surface regions of a specimen fatigued with σ_a = 450 MPa after 0, 10, 50 and 1000 cycles. A change of the dislocation arrangement from tangled into cell structures with a low free dislocation density by cross-gliding and successive annihilation leads to the above described collapse of the initial inhomogeneous microstress (half-width value) profile.

The different stability of near surface microstructures in SAE 1045, AISI 304 and AZ31 directly influences the cyclic softening/hardening behaviour in the LCF-regime (Fig. 6). The basic effect of surface strain hardening by mechanical surface treatment is the reduction of plastic strain amplitude in stress controlled tests leading to higher fatigue lifetimes according to Manson-Coffin's law. This reduction of plastic strain amplitude of the shot peened or deep rolled states compared to the untreated state extends until fracture of the specimen if the near surface microstructures remain stable like in the cases of AISI 304 and AZ31. Mechanically surface treated SAE 1045 specimens, however, exhibit almost identical or even higher plastic strain amplitudes after half the number of cycles to failure compared to the untreated material state. This is another clear indication why no significant lifetime improvement can be achieved in SAE 1045 by mechanical surface treatment in the LCF-regime. Note, that deep rolling is always superior to shot peening in terms of cyclic lifetime and reduction of plastic strain amplitude. This can be explained by the fact, that plastic strain amplitudes are rather governed by the thickness of the affected layer than by the intensity of near surface strain hardening [9]. In contrast to stress controlled cyclic loading, in total strain controlled tests a strongly hardened, stable near surface microstructure exibits shorter fatigue lifetimes in the LCF-regime than untreated specimens [10] (Fig. 7). This can be explained by the fact, that severely mechanically surface strengthened materials exhibit higher stress amplitudes in strain controlled fatigue compared to untreated specimens.

Stable near surface microstructures do not only strongly influence the cyclic deformation behaviour during the crackfree fatigue phase, but also directly affect the evolution of surface fatigue damage, e. g. the formation and propagation of microcracks [11]. A common feature of mechanically surface treated materials is the retardation of crack initiation by near surface strain hardening [12] and the absence of slip traces compared to the ductile, slip induced microcrack formation in electrolytically polished specimens [10,13]. Especially nanocrystalline surface layers, as illustrated in Fig. 4, effectively impede dislocation movement and hence slip band formation. Once such a brittle crack has been formed, it exhibits considerably lower propagation velocities than its ductile counterpart in untreated specimens (Fig. 8), owing to a high density of slip obstacles, like martensitic lamellas, for instance.

A recent development in mechanical surface optimization has been the application of combined mechanical and thermal surface treatment, e.g. thermomechanical rolling or peening or heat treatment after mechanical surface treatment [10,14-16]. These techniques are particularly attractive, if the sensitivity for residual stresses in such components is rather low, since thermal treatment is usually accompanied by detrimental relaxation of compressive residual stresses. Additionally, thermal or thermomechanical treatment can lead to a stabilization of near surface residual stresses against cyclic loading. A major mechanism in lifetime improvement by annealing is strain ageing, leading to higher microhardness values and higher yield strength of near surface regions after thermal treatment, if the annealing time and temperature are appropriately chosen. Figs. 9 and 10 show the resulting quasistatic and cyclic mechanical behaviour of shot peened and additionally annealed SAE 1045 ($T_{annealing}$ = 350°C) after different annealing times. It can be seen that optimized thermal treatment after shot peening leads to higher yield strength of hollow specimens and enhanced cyclic lifetimes owing to a reduction of plastic strain amplitude according to Manson-Coffin's law.

CONCLUSION

Criteria of surface layer stability during fatigue at high stress amplitudes in mechanically surface treated materials must follow from a deeper understanding of the nature of cyclic deformation processes. Thus, a classification of stable and unstable microstructures for the assessment of the uselfulness of shot peening or deep rolling in the LCF-regime should be applied (Fig. 11). An improvement of cyclic lifetime by mechanical surface treatment can be expected in the low cycle fatigue regime if the generated near surface microstructures, and hence, microstresses remain stable during cyclic loading and if the surface treatment leads to sufficiently high volume fractions of strain hardened regions.

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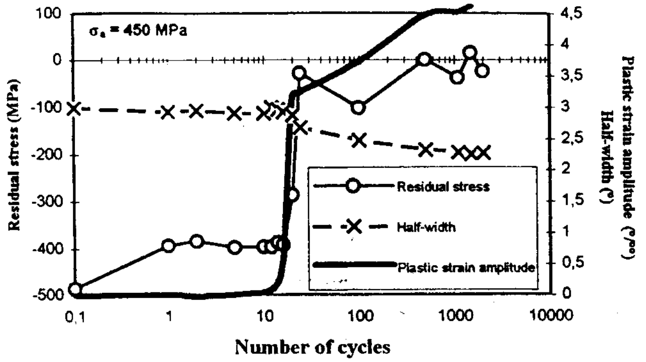


Fig 1 Development of surface residual stress interference line half-width values and plastic strain amplitude in shot peened SAE 1045 as a function of number of cycles (σ_a = 450 MPa)

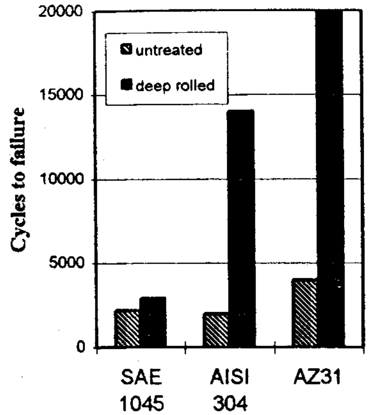
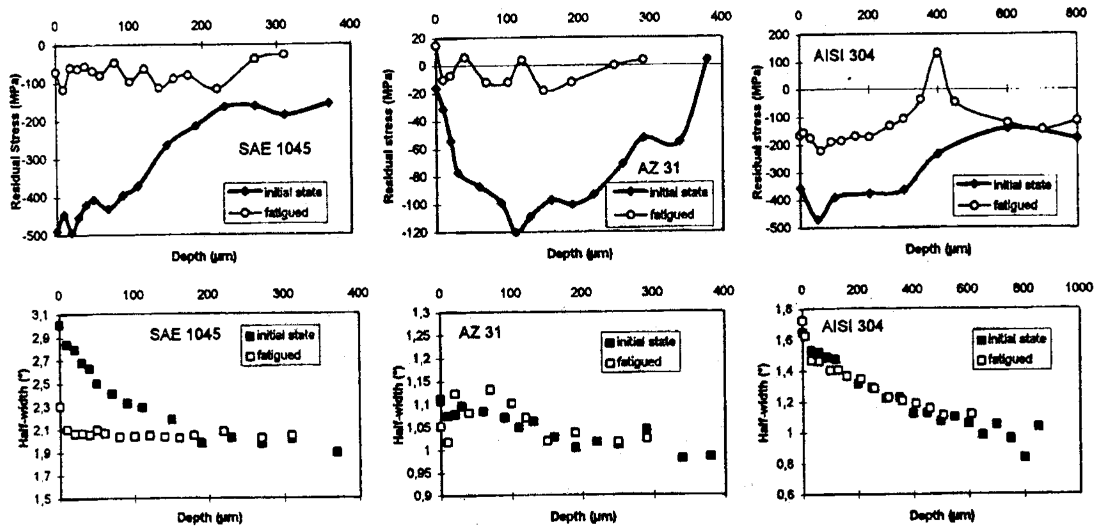


Fig. 2 Lifetime improvement at high stress amplitudes ($\sigma_a \approx \sigma_{yield}$) by mechanical surface treatment



SAE 1045
shot peened
I = 0.175 mmA
σ_a = 450 MPa

AZ31
shot peened
I = 0.2 mmA
σ_a = 125 MPa

AISI 304
deep rolled
p = 150 bar
σ_a = 320 MPa

Fig. 3 Macro and microstress depth profiles of different mechanically surface treated materials fatigued at high stress amplitudes ($\sigma_a \approx \sigma_{yield}$) after $N_f/2$ cycles

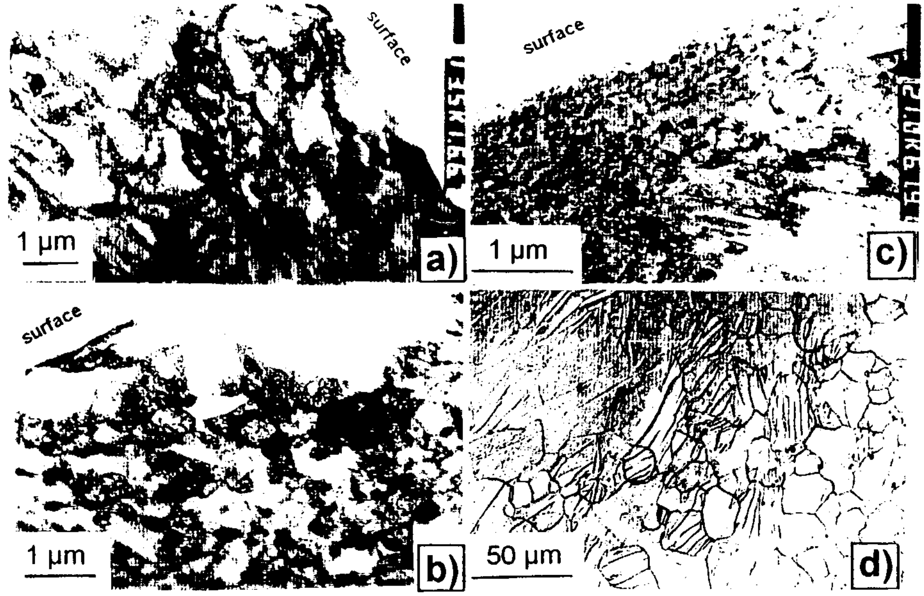


Fig. 4 Typical near surface microstructures of mechanically surface treated materials: (a) Dislocation tangles (Shot peened SAE 1045), (b) Diffuse cells (deep rolled SAE 1045), (c) Nanocrystallites & strain induced martensite (AISI 304), (d) Twinning (Magnesium alloy AZ31)

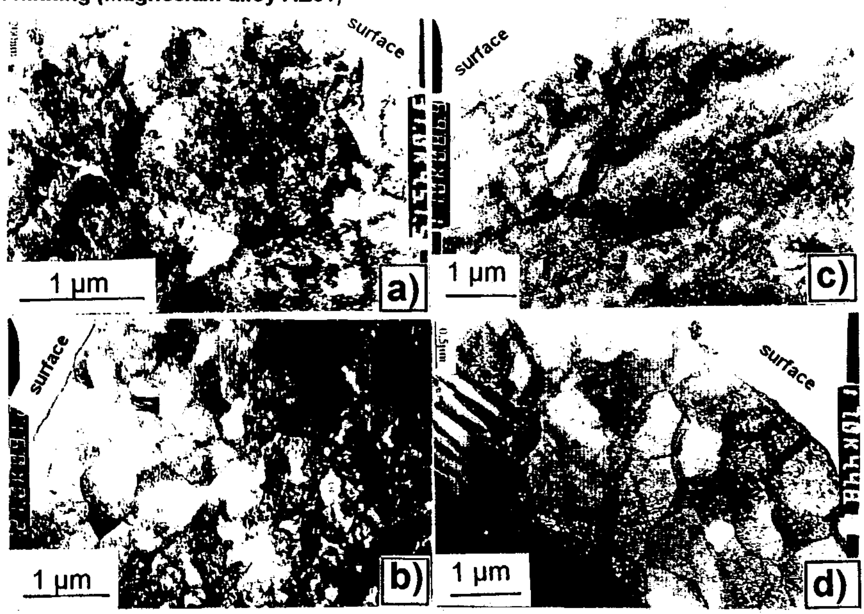


Fig 5 Alteration of near surface dislocation arrangement of shot peened and cyclically loaded SAE 1045 (σ_a = 450 MPa): (a) N = 0 cycles, (b) N = 10 cycles, (c) N = 50 cycles, (d) N = 1000 cycles

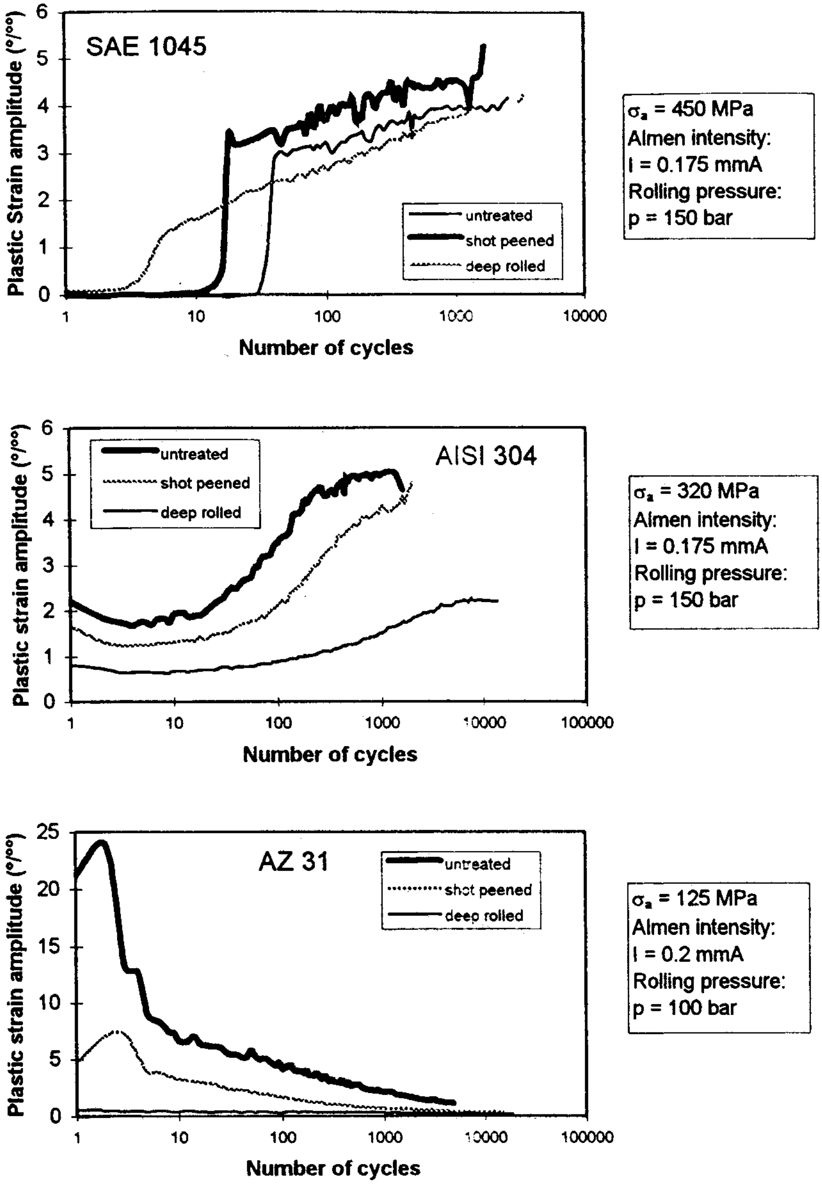


Fig. 6 Cyclic deformation curves of different mechanically surface treated materials for push-pull-loading in the LCF-regime ($\sigma_a \approx \sigma_{yield}$)

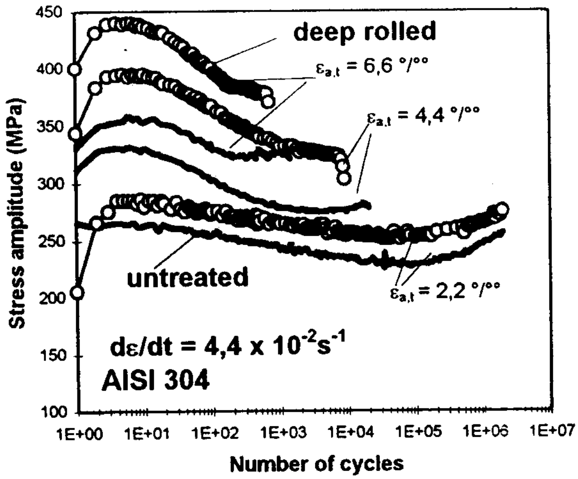


Fig. 7 Cyclic deformation curves of untreated and of deep rolled AISI 304 (rolling pressure 150 bar) for push-pull loading under total strain-control

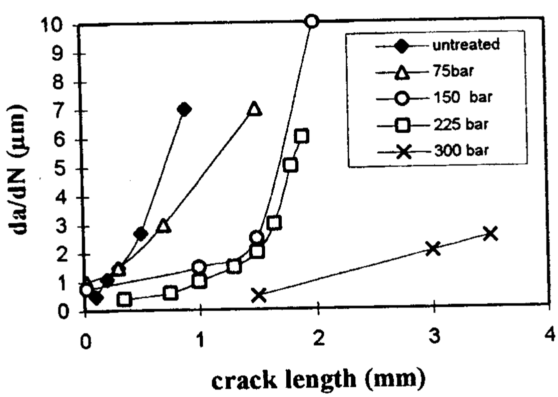


Fig. 8 Fatigue crack propagation velocities in untreated and in with different rolling pressures deep rolled AISI 304 (σ_a = 320 MPa)

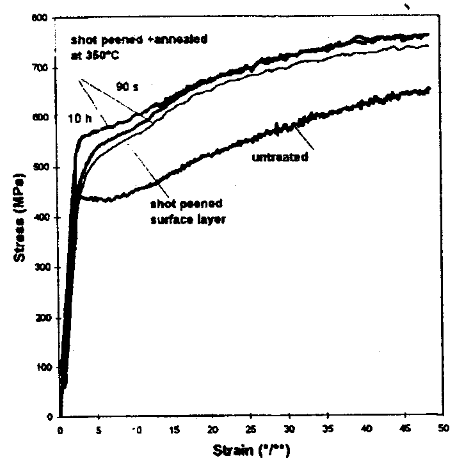


Fig. 9 Quasistatic mechanical behaviour (dε/dt = 10^{-4} s^{-1}) of untreated, of shot peened and of shot peened plus artificially strain aged (T= 350°C) SAE 1045 hollow specimens (remaining wall thickness equals the thickness of strain hardened layer induced by shot peening)

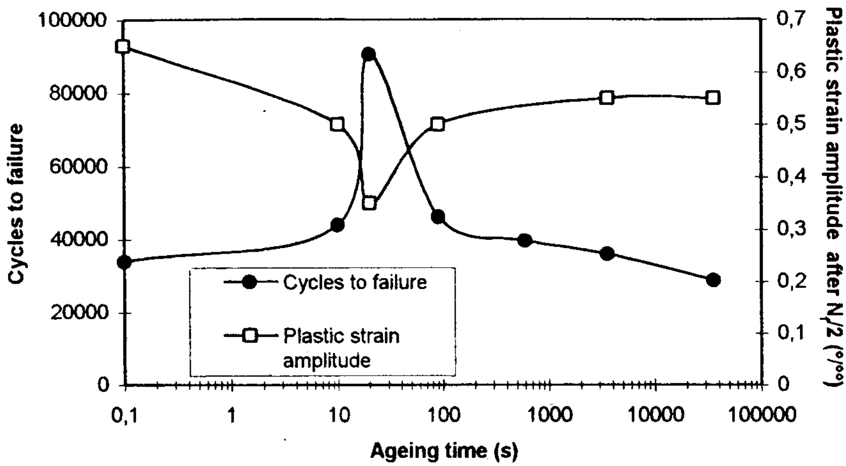


Fig 10 Cyclic lifetime and plastic strain amplitude of shot peened and heat treated SAE 1045 (T = 350°C) in stress controlled push-pull fatigue tests (σ_a = 350 MPa) as a function of annealing time

Near surface hardening mechanism/ microstructure	**Typical material**	**microstress stability**	**macrostress stability**
dislocation hardening	plain carbon steel [3] (High stacking fault energy)	no	no
dislocation hardening	austenitic stainless steel [5], certain aluminium alloys [19], (Low stacking fault energy)	partly	no
twinning	magnesium alloys [17]	yes	no
martensitic transformation	austenitic stainless steel [5]	yes	no
nanocrystallites	nickelbase alloys [18] austenitic stainless steel [5]	yes	no

Fig. 11 Classification of near surface microstructures/microstress profiles in cyclically stable and unstable groups in the low cycle fatigue regime