2002055

Alternative Mechanical Surface Treatments: Microstructures, Residual Stresses & Fatigue Behavior

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1 Abstract

In comparison to the most widely used mechanical surface treatment shot peening, common alternative methods such as deep rolling and less common methods such as laser shock peening, ultrasonic shot peening, water peening or various burnishing methods have been introduced into practical applications only rarely, or for highly specialized components, or are just on the verge from laboratory research into larger scale applications. However, in the future it is expected that these so called "alternative" mechanical surface treatment methods will be more widespread owing to superior benefits for materials' behavior, improving process technology and dramatically decreasing costs.

The basic principles of all mechanical surface treatments are well known: In all cases a localized elastic-plastic deformation in near-surface regions leads to the formation of compressive residual stresses and severe microstructural alterations (usually associated with intense work hardening), enabling the thus strengthened near-surface regions to withstand higher resistance against fatigue crack initiation and propagation. Moreover, in some cases, additional effects may give rise to further fatigue life/strength enhancement such as surface smoothening or deformation-induced phase transformations. At closer look, near surface properties and thus fatigue behavior might be distinctly different for different surface treatment methods. It is the objective of this contribution to shed some light on these basic effects and to propose some basic guidelines for the utilization of 'optimized' treatments from a materials science perspective.

2 Introduction

The prime objective of this paper is to summarize the basic *mechanical and metallurgical* effects associated with specific mechanical surface treatment methods. It is not the aim of this paper to give an overview on the *technological* aspects of different mechanical surface treatment methods. Such studies can be found elsewhere [1,2,3]. Also, even when comparing the metallurgical alterations by different surface treatments, one should always keep in mind that different process parameters for a single surface treatment method can lead to a broad range of possible properties, thus rendering such comparisons very difficult. A systematic comparative study on mechanical surface treatments from a technological point of view has been presented, for instance, in [3]. There, surface treatment methods such as shot peening, deep rolling, water peening, laser shock peening are also discussed in terms of residual stresses, hardness increase, case depth and effect on stress-life behaviour. Other comparative studies on different mechanical surface treatment methods can be found in [1,2,4–9] with varying thematic emphasis. In this chapter, the most important results of former and recent studies on various mechanical surface treatments will be summarized. Most importantly, recent results on the nature of stability of near surface microstructures under severe loading conditions will be discussed.

The following surface treatment methods can be considered as "mechanical": Shot peening, deep rolling and roller burnishing, laser shock peening, ultrasonic shot peening, water peening, hammering, needle peening, tumbling.

The effects of mechanical surface treatments on near-surface properties can be characterized by a multitude of primary and secondary parameters such as case depth, magnitude of residual stresses and hardness, roughness, nature of near-surface microstructures, phase contents, porosity, texture, corrosive properties, quasistatic and cyclic yield strength, stability against mechanical loading under quasistatic and cyclic conditions, stability against thermal loading and stability against thermomechanical loading. The effects on fatigue behaviour are the sum of all these near-surface alterations and therefore even more complex. Firstly, it shall be discussed how different surface treatment methods characteristically affect materials' near–surface properties. Secondly, the consequences of different surface treatments on fatigue behaviour will be discussed.

3 Near-Surface Alterations by Various Mechanical Surface Treatments

3.1 Roughness

It is irrefutable that surface topography severely influences fatigue life and strength of hard and notch-sensitive materials: The higher the surface roughness the higher the stress concentrations by notches and the lower the fatigue strength. Therefore it is mandatory to not only optimize residual stresses and near-surface microstructures, but also to optimize the surface topography by mechanical surface treatments. Specific mechanical surface treatments can have quite different effects on surface roughness and of course they give rise to a broad range of surface topographies by varying process parameters. Nevertheless some basic guidelines can be stated: In general, for typical as-turned or as-milled surfaces, deep rolling and roller burnishing are the only treatments which diminish surface roughness of machined components significantly. Surface roughnesses R_Z of 0.5 to 1 µm are quite common for these treatments. In contrast, shot peening is typically associated with surface roughnesses between 4 and 8 µm, depending on the exact Almen intensity and shot geometry. The surface roughness by laser shock peening and after water peening is hardly altered as compared to the untreated state. Whereas water peening scarcely influences surface roughness, laser shock peening usually increases the surface roughness of the as-machined part slightly [1].

3.2 "Case" Thickness

One of the most important parameters in surface treatment is the "case"-thickness which is defined as the thickness of the near-surface layer exhibiting compressive residual stresses and strain hardening or in other words the affected depth of the surface treatment.

The "case" thickness depends strongly on the surface treatment method as well as on the parameters within one treatment itself such as rolling force, Almen intensity, coverage etc.. The maximum "case" thickness can range between 2–3 mm for laser shock peening and deep rolling [3,8] and 0.1–0.2 mm for water peening. Usually the typical affected depth is around 0.3–0.5 mm for shot peening and around 1 mm for laser shock peening and deep rolling. The thickness of the affected layer through water peening rarely exceeds 0.1 mm [1,10]. The right choice of an "optimized" case thickness should always consider the material state and the loading conditions. For example, a deep "case" is much more essential in push-pull loaded components than in parts subjected to bending with high stress gradients. It should be noted that the deepest "cases" in surface treatment are not caused by mechanical treatments, but by thermochemical (case hardening) or thermal (induction hardening) methods [3].

3.3 Residual Stresses

The formation of compressive residual stresses in near-surface regions by surface treatment is considered as one of the main causes for fatigue life enhancement. In general, the maximum possible amount of compressive residual stresses is much more influenced by the material properties than by the process parameters, e.g. the maximum possible level of residual stress strongly correlates to the yield strength of the surface treated material [2,11]. Therefore, it can be assumed that all mechanical surface treatments generate very similar levels of surface residual stress for the same material if the process parameters are optimized in such a way that maximum compressive residual stresses are formed. On the other hand, it has been shown that different mechanical surface treatments also give rise to different levels of strain hardening [6], thus altering the yield strength differently. Indeed, it appears that treatments with very high deformation grades such as deep rolling lead to slightly higher residual stresses than "low plasticity" surface treatments such as laser shock peening [12], however, much more work in this field is needed to give a systematic assessment. Finally, different mechanical surface treatments are also associated with different stress states (e.g. different degrees of multiaxiality) during the treatment itsself, depending on the contact geometries of the utilized tools, and consequently different residual stress depth distributions: For example 'hook'-like residual stress depth distributions are quite common for shot peening and deep rolling, but are not very typical for laser shock peening.

3.4 Work Hardening

Most metallic materials exhibit work/strain hardening through mechanical surface treatments. An exception are severely cold deformed alloys and hardened steels which show near-surface softening as indicated by lower FWHM-values in near-surface layers as compared to the bulk FWHM-values. For the assessment of work hardening states it is recommended to use x-ray peak broadening values (FWHM- or half-width values) as a means of characterization instead of simple hardness values, since the latter ones are not as sensitive and can be significantly influenced by residual stresses [2,13]. A difficult issue is the extent of work hardening for different surface treatment methods. Here, again the exact process parameters significantly influence the work hardening state and render a systematic comparison difficult. One possible method of characterizing work hardening of mechanically surface-treated near surface layers is the depth-dependent registration of FWHM-values after successive electrolytical removal of material. The obtained FWHM-values can be compared to FWHM-values after uniaxial deformation and thus deformation grades can be estimated at least roughly [14]. Another indirect method for estimating deformation grades in mechanically surface treated materials is to conclude the deformation state by comparing their cyclic deformation behaviour with that of uniaxially predeformed non-surface treated samples [6]. Of course, in that case residual stress effects have to be eliminated (e.g. by hollow-drilling/eroding or annealing) without affecting the work hardening state. An overview on the induced cold work, microhardness increase, dislocation density as well as other factors by different mechanical surface treatments is given in table 1. The results are taken from references [1-12,14-19]. In spite of being somewhat arbitrary, they give a first hint of what magnitudes of work hardening and microhardness increases can be expected for different treatments. The readers are strongly encouraged to complete and expand these results by own investigations and experiences!

Table 1: Consequences of various mechanical surface treatments on near-surface properties of metallic materials

	Amount of residual stress	Dislocation density	Estimated Strain rate	Surface microhardness increase	Maximum "case" depth	Surface Roughness	Cold work
Roller burnishing (low pressure)	$\cong \sigma_{Yield}$	Low - medium	$< 10^2\ s^{-1}$	< 60 %	< 0.1 mm	≅ 1 µm	?
Water peening	$\cong \sigma_{Yield}$	Low - medium	?	?	≅ 0.1 mm	1–2 µm	< 10 %
Shot peening	$\cong \sigma_{Yield}$	Very high $5–8 \times 10^{11}\ cm^{-2}$	$10^3–10^4\ s^{-1}$	150 % AISI 304 60 % SAE 1045	0.3 mm	4–8 µm	5–50 %
Explosive hardening	$\cong \sigma_{Yield}$	Very high	?	80 %	0.3–0.8 mm	< 5 µm	?
Ultrasonic shot peening	$\cong \sigma_{Yield}$	High	?	?	0.8 mm	>> 5 µm	?
Gravity peening	$\cong \sigma_{Yield}$	High	$10^3–10^4\ s^{-1}$	?	0.8 mm	>> 5 µm	10 %
Laser shock peening	$\cong \sigma_{Yield}$	Medium $2,6 \times 10^{11}\ cm^{-2}$ $6,2 \times 10^{10}\ cm^{-2}$	$10^5\ s^{-1}$	40 % 2024 Al 30 % 7075 Al 92 % AISI 316 L 80 % plain carbon steel 130 % maraging steel	2 mm	1 – 5 µm	1–2 % 7 % (Fe-3Si) 10–20 % (Ti-6Al-4V)
Deep rolling	$\cong \sigma_{Yield}$		$< 10^2\ s^{-1}$	60 %	3 mm	≤ 1 µm	> 20 %

Several authors have observed that shot peening leads to most severe work hardening, whereas laser shock peening and water peening lead to significantly lower dislocation densities [9,12,14,20]. Surface states after deep rolling are characterized by intermediate dislocation densities of 10^{11} cm^{-2} or lower [6].

3.5 Microstructure

The possible microstructures created by mechanical surface treatment can be extremely manifold and depend strongly on the chosen process parameters as well as on the material itself. Typical near-surface microstructures may involve high dislocation densities (either homogeneously distributed in tangles [20,21] or in various stages of cell-formation [22]), slip bands [17], nanocrystallites [23,24], twinning [17,25], martensitic transformations [18,23] or stress induced precipitates [26]. In all cases, the observed defect structures are strongly influenced by the strain rate of the surface treatment and by the specific glide behavior of dislocations in the material, especially in bcc-metals. "Wavy slip" materials and low or medium strain rates (as for rolling or burnishing treatments) favor the creation of cell-like dislocation arrangements, whereas "Planar slip" materials and high strain rates (as for laser shock peening, explosive hardening, shot peening or water peening) typically produce more homogeneous, tangled dislocation arrangements. In bcc metals, laser shock peened substructures tend to resemble typical low-temperature substructures generated by conventional low strain rate plasticity [27]. Under deformation at high strain rates or low temperatures, the edge components of dislocations can move at higher rates than the screw components which are unable to cross slip, thus preventing the formation of cell structures [28]. Fig. 1 shows typical near-surface dislocation arrangements as a consequence of a high strain rate (here: conventional shot peening) and a medium strain rate (here: deep rolling) mechanical surface treatment of a ferritic steel SAE 1045. A predominant feature of severely surface deformed metals and alloys can also be the formation of a thin nanocrystalline layer. Interestingly, high coverage and high deformation grades seem to promote near-surface nanocrystallization while high deformation velocities appear to lead to the opposite effect. Fig. 2 shows direct near-surface microstructures of deep rolled, of laser shock peened and of shot peened austenitic stainless steel AISI 304 (as prepared by cross-sectional transmission electron microscopy [21–23]). It can be seen that in deep rolled and in shot peened samples nanocrystalline surface layers were formed. However, after laser shock peening no such structures were found; instead, the near-surface microstructure of laser shock peened AISI 304 is characterized by a dense highly tangled dislocation arrangement similar to near-surface microstructures observed after water peening [20].

3.6 Stability under Mechanical and Thermal Loading

A necessary prerequisite for the effectiveness of mechanical surface treatments to enhance fatigue behaviour is the mechanical and thermal stability of near-surface residual stresses or microstructures. Only stable residual stresses influence fatigue strength/life and are usually regarded as local mean stresses, and only stable near surface microstructures (e.g. increased dislocation density) are able to serve as effective dislocation obstacles impeding localized slip and thus crack formation.

Figure 1: TEM cross-sectional micrograph of near-surface microstructures in shot peened (left) and deep rolled (right) normalized steel SAE 1045 (Almen intensity 0.175 mmA, rolling pressure 75 bar)

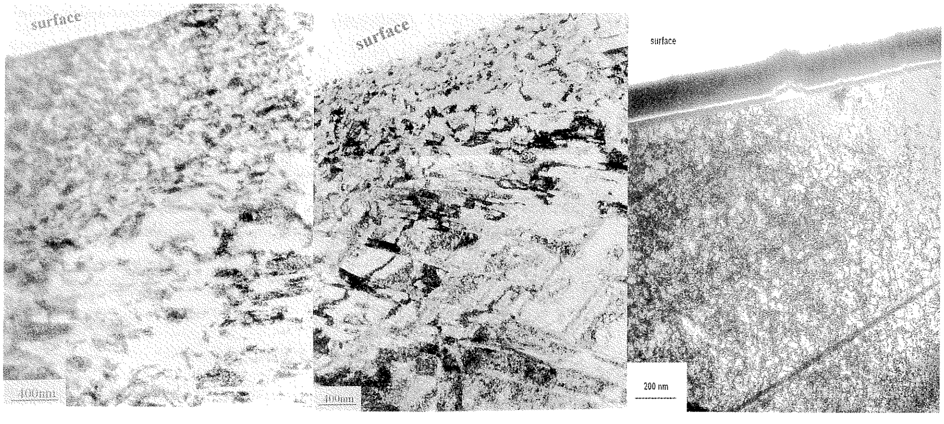

Figure 2: Cross-sectional TEM micrographs of mechanically surface treated austenitic stainless steel AISI 304. Left figure: shot peened (Almen intensity 0.175 mmA, 100 % coverage), Middle figure: deep rolled (rolling pressure 150 bar), Right figure: laser shock peened (power density 7 GW/cm², 200 % coverage)

The stability of macro- and micro residual stresses in mechanically surface treated materials against mechanical (e.g. quasi-static or cyclic) loading is determined by the amount of plasticity during mechanical loading. It has been shown that residual stress relaxation can be directly correlated to the plastic strain amplitude during fatigue. Consequently, it is important to induce high work hardening and deep "cases" by mechanical surface treatments since both increase the cyclic compound yield strength of the surface treated component [6].

Several investigations have been focused on the thermal stability of macro- and micro residual stresses of differently mechanically surface treated materials [2,29,30]. The most notable finding is the observation, that thermal stress relaxation depends strongly on the material state, especially on the surface treatment induced dislocation density. Surface layers with medium dislocation densities (as created by water peening or laser shock peening, for example) showed enhanced thermal stability of residual stresses, whereas surface layers with extremely high dislocation densities (as induced by shot peening) exhibited poor stability against thermal loading [29,30]. This observations can be explained by taking into account the microstructural mechanisms for (macro) stress relaxation: Since stress relaxation is caused by thermally activated climb of edge dislocations, surface layers with severe work hardening are prone to easier stress relaxation by so called pipe-diffusion (with lower activation energies than in bulk diffusion) [31].

The thermal stability of near-surface microstructures can be studied in a direct manner by In-Situ-heating of cross-sectional TEM foils. Fig. 3 depicts the direct near-surface microstructure of deep rolled Ti-6Al-4V for different heating temperatures (holding time for each temperature: 5 min, heating rate: 100 K/10 min). After deep rolling a nanocrystalline grain structure was observed. Successive heating of this TEM-foil yielded vital information about the thermal stability of this surface treatment induced microstructure. It was found that these near-surface nanostructures were thermally quite stable and that -apart from some minor recovery- no visible recrystallization took place below temperatures of approx. 800–900 °C. This implies, that from a fatigue-point of view, near-surface microstructures in deep rolled Ti-6Al-4V are suitable for high temperature applications and serve to improve the fatigue behaviour of this alloy even at elevated temperatures way above the usual service temperature for this alloy in aircraft turbine applications.

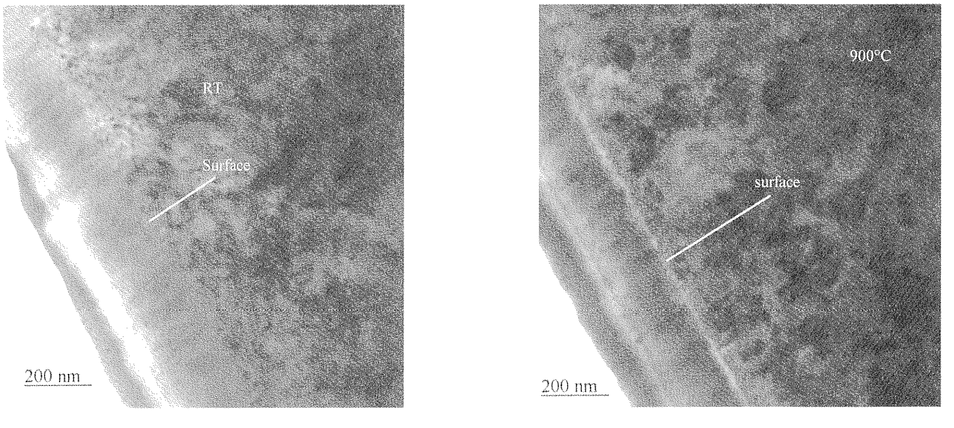

Figure 3: In-situ TEM micrograph of deep rolled (rolling pressure 150 bar) Ti-6Al4V surface regions before (left) and after (right) heating to 900 °C. (holding time 5min). Here, the observed nanocrystalline surface layer is thermally stable.

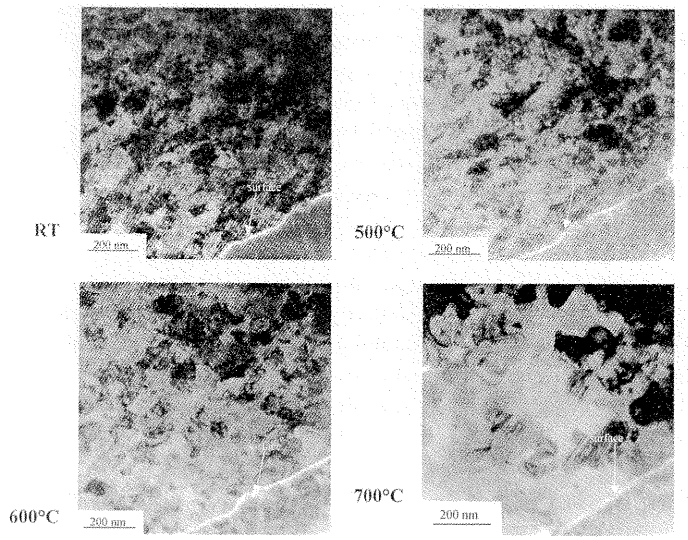

Figure 4: In-Situ TEM micrographs of deep rolled AISI 304 surface regions (rolling pressure 150 bar) heated to 500 °C, 600 °C and 700 °C (holding time 5 min) showing a nanocrystalline layer and recrystallization between 600 °C and 700 °C

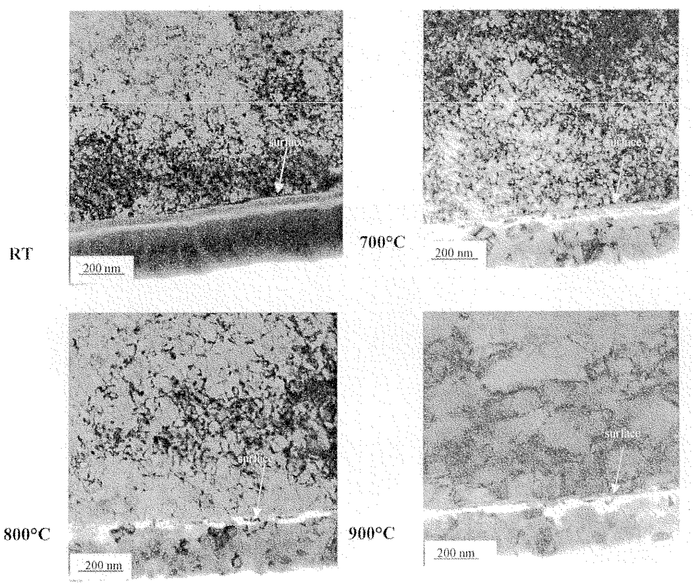

Figure 5: In-Situ TEM micrographs of laser shock peened AISI 304 (power density: 7 GW/cm², coverage: 200 %) heated to 700 °C, 800 °C and 900 °C (holding time 5 min). This near-surface microstructure exhibits higher thermal stability than the deep rolled surface condition.

In a second case the thermal stability of direct near-surface microstructures of deep rolled and of laser shock peened steel AISI 304 was investigated by the aid of In-Situ-TEM (Fig. 4 and 5). It was found that near-surface nanocrystals in deep rolled AISI 304 are thermally stable until approx. 600–650 °C when recrystallization sets in. As mentionend above, laser shock peening did not not induce any nanocrystals, but resulted in highly tangled and dense dislocation arrangements. These near-surface dislocation tangles were stable until even higher temperatures of about 800 °C. Both findings correlate with the excellent and enhanced fatigue behaviour of mechanically surface treated AISI 304 at test temperatures of 600 °C or lower [32].

4 Effects on Fatigue Behaviour

It is known that mechanical surface treatments affect all fatigue stages – from the first dislocation movements until macro crack propagation and final failure. Although a multitude of factors are known to influence the fatigue strength/life of mechanically surface treated metallic materials, three of these factors have been identified as especially influential: the residual stress state, the microstructure and the roughness [2]. More specifically, compressive residual stresses and work hardening improve the fatigue behaviour of surface treated materials significantly, however their effects are assumed to be different for crack initiation and crack propagation. According to [33], for shot peened and room temperature fatigued Ti-6Al-4V, it appears that residual stresses only influence crack propagation, but have little effect on crack initiation. Secondly, work hardening enhances the resistance against fatigue crack initiation, whereas it seems to facilitate crack propagation (table 2). Other investigations on the high temperature fatigue behaviour of deep rolled Ti-6Al-4V indicate, however, that work hardening retards crack initiation as well as crack propagation (Fig. 6 and [32]).

Table 2: Effects of mechanical surface treatment on crack nucleation and crack propagation according to [33]

	Crack nucleation	Crack propagation
Surface roughness	Accelerates	No effect
Cold work	Retards	Accelerates
Residual compressive stress	Minor or no effect	Retards

The fatigue mechanism in smooth mechanically surface treated samples (e.g. by deep rolling) is mostly initiation controlled, whereas it can be considered crack propagation controlled (damage-tolerant approach) in components with notches or rough surfaces such as in shot peened parts without subsequent polishing. In addition, it has been shown that residual stresses affect the fatigue behaviour of hard materials much more than of soft materials: Hard materials are much more *sensitive* to residual stresses than soft materials. Therefore, it can be summarized, that compressive residual stresses are the main influential factor on the fatigue strength/life for notched hard materials, whereas work hardening dominates the fatigue strength of smooth soft materials [34]. The following discussion shall confine itself to smooth-bar fatigue conditions and to materials with low and medium yield strength, therefore the effect of work/strain hardening will be treated more closely.

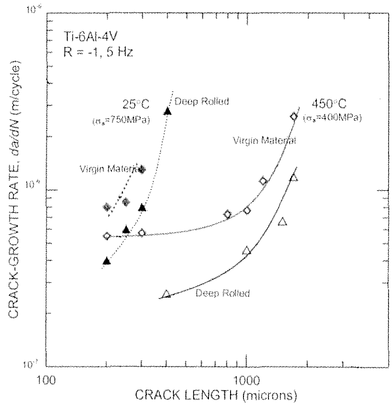

Figure 6: Crack growth rates from striation spacings measurements on fracture surfaces of untreated and deep rolled Ti-6Al-4V by different rolling pressures

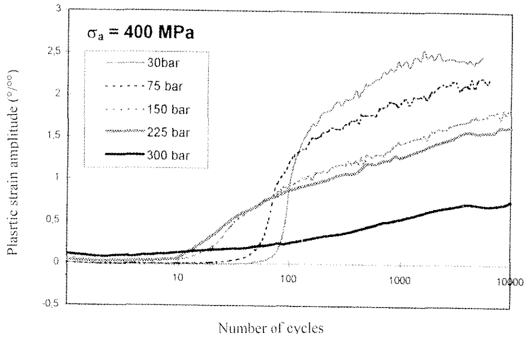

Figure 7: Cyclic deformation curves of deep rolled steel SAE 1045 for different "case" depths obtained

According to Coffin-Manson´s law the fatigue life in the finite life region is controlled by the extent of cyclic plasticity during fatigue: In a double-logarithmic plot the number of cycles to failure is inversely proportional to the plastic strain amplitude after half the number of cycles to failure. The higher the cyclic compound yield strength of a mechanically surface treated material, the lower the plastic strain amplitude. The cyclic compound yield strength depends on a) the volume fraction of the strain hardened regions as compared to soft core regions b) the cyclic yield strength of the work hardened surface layer (which can be determined by methods described in [35]), the cyclic yield strength of the untreated soft core material. Factors a) and b) can be influenced by the choice of mechanical surface treatment and by variation of process parameters (e.g. rolling force, Almen intensity etc.).

Fig. 7 shows cyclic deformation curves of deep rolled SAE 1045 with different "case" depths of work hardened material but identical residual stresses and FWHM-values at the surface. It can be seen that the plastic strain strain amplitude is systematically lowered and lifetime is systematically increased with increasing volume fractions of work hardened material.

Fig. 8 shows cyclic deformation curves of deep rolled and shot peened SAE1045 with identical "case" depths, but different FWHM-values and therefore different levels of work hardening. The shot peened material condition exhibited much higher dislocation densities than the deep rolled state [6,22] and shows superior cyclic deformation behaviour (lower plastic strain amplitudes) and a longer fatigue life as compared to the deep rolled condition.

The fatigue strength/life can therefore be increased by surface treatments which cause high work hardening (e.g. by high dislocation densities or by martensitic transformation) or by surface treatments which induce deep work hardened "cases". It could be shown that, for push-pull loading, deep rolled SAE 1045 specimens have to have at least 50 % greater "case" depths than shot peened SAE 1045 specimens in order to compensate for the lower near-surface work hardening. These implications are illustrated schematically in Fig. 9. It should be noted that Fig. 9

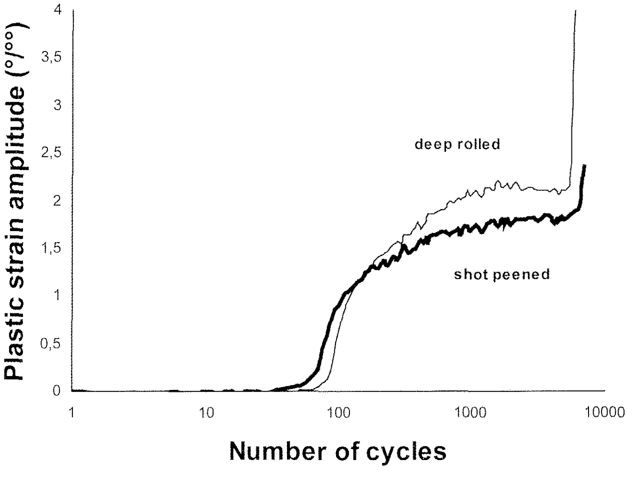

Figure 8: Cyclic deformation curves (σ_a = 400 MPa, R = −1) of shot peened and of deep rolled SAE 1045 push-pull specimens with identical "case"depths and residual stresses, but different levels of cold work

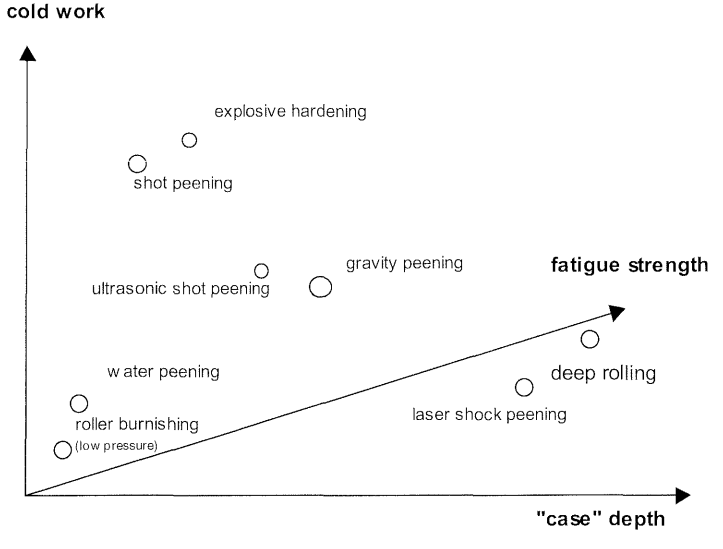

Figure 9: Cold work, "case" depths and fatigue strength for different mechanical surface treatments (schematically)

is expected to be only valid for push-pull loading of smooth samples with identical or very similar surface roughnesses.

Unfortunately, it does not seem to be possible to create "cases" with both maximum work hardening and maximum "case" depth. A good compromise, however, is deep rolling, since it delivers deepest cases and still quite high dislocation densities/work hardening (see also table 1). A practical example can be seen in Fig. 10. The superior high temperature fatigue behaviour of deep rolled Ti-6-4 as compared to laser shock peened Ti-6-4 could be correlated to significantly increased cold work in the deep rolled condition, since the stable residual stresses and the case depth were practically identical for both material states after half the number of cycles to failure [12].

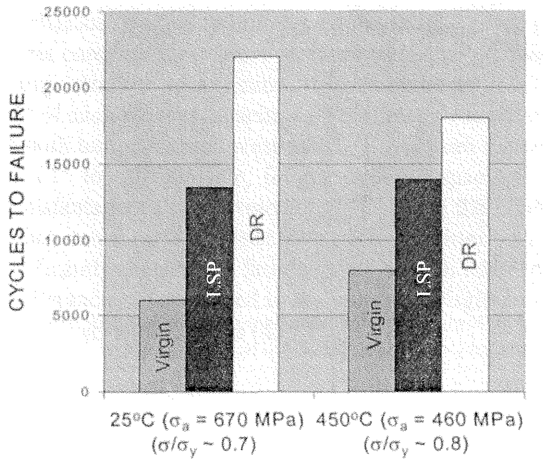

Figure 10: Fatigue lifetime enhancement of Ti-6Al-4V by deep rolling and by laser shock peening for test temperatures of 25 °C and 450 °C and stress amplitudes of 750 MPa and 400 MPa, respectively [32].

5 Conclusions

- Alternative mechanical surface treatments offer several advantages as compared to shot peening. Main advantages are better surface topography, deeper affected layers and higher thermal stability of surface layers.
- Since the strengthening mechanisms are quite similar than for shot peening the same fundamental principles for optimized fatigue life/strength improvement apply.
- A major difficulty in comparing different mechanical surface treatments is certainly the vast range of process parameters. Therefore, further standardization is needed also for alternative treatments.

6 Acknowledgements

Sincere thanks is expressed to Deutsche Forschungsgemeinschaft (DFG) and to the U.S. Airforce Office of Scientific Research for financial support, and to Metal Improvement Company, Livermore (CA), for the laser shock peening treatment. The author would also like to thank Prof. B. Scholtes, Prof. R.O. Ritchie, Dr. E. Stach, Mr. U. Noster, Mr. T. Ghwilla and Ms. G. Liu for helpful discussions and experimental support.

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