DEEP ROLLING – THE PAST, THE PRESENT AND THE FUTURE

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ABSTRACT

The outstanding benefits of this classical mechanical surface treatment method for surface optimization are outlined in this paper. After a brief history of the deep rolling process, the current developments are adressed in detail. Among others, main topics of this contribution are typical applications of deep rolling for fatigue strength enhancement of various materials, typical features and advantages of deep rolling versus shot peening and other surface treatments and the mechanical and metallurgical effects of deep rolling. Special focus is put on future developments such as deep rolling at elevated temperatures and deep rolling of complicated geometries such as turbine blades and discs.

SUBJECT INDEX

Mechanical surface treatment, deep rolling, roller burnishing, fatigue, residual stress, high temperature deep rolling

INTRODUCTION AND HISTORICAL BACKGROUND

One of the most well known benefits of deep rolling as compared to other surface treatments is the great depth of the affected layer exhibiting alterations of the work hardening state (usually work hardening) and compressive residual stresses (Fig. 1). Another one is the generation of glossy surfaces with low roughness as compared to treatments like shot peening (Fig. 2). These three effects can significantly enhance the mechanical behaviour of metallic materials especially under cyclic/fatigue loading. It can be assumed that mechanical surface treatments of metallic materials have been used for thousands of years (e.g. hammering of swords after forging), but it was not until the first half of the last century that treatments like deep rolling or shot peening have experienced widespread industrial applications in mass production. In the U.S.A., deep rolling was applied already in the twenties of the last century as a surface treatment to strengthen axles of the Ford T and in the thirties, axles of trains were also deep rolled. Significant pioneer work in the U.S. in that field was carried out by Horger [1], in Germany, Föppl [2] and Thum [3] have debated about the causes of fatigue enhancement by deep rolling, probably inspired by materials failures in the oil industry. In the seventies, the basic effects of deep rolling on fatigue behaviour have been thoroughly investigated and the influence of notches and material hardness on fatigue strength enhancement of deep rolled components became clear [4,5,6]. In the eighties, deep rolling was already used in combination with thermal surface treatments such as induction hardening, especially in the automotive industry [7]. Certainly today, the most well known example for the application of deep rolling are deep rolled crankshafts, but this outstanding surface treatment has also found its way into other technical fields and applications, for example for surgical implants as well as for turbine blades in the power plant and aircraft industry among numerous others.

In all further elaborations, the terminology „deep rolling“ refers to a surface rolling treatment using rolls or ball-point tools with the purpose of inducing deep plastic deformations and residual stresses in near-surface layers in contrast to „roller burnishing“ which is usually applied with much lower forces or pressures and mostly aims to obtain a certain surface quality especially in terms of roughness.

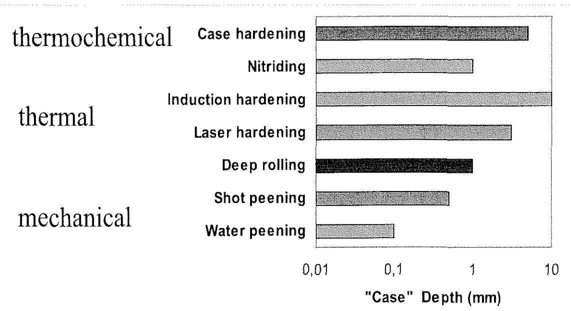


Fig. 1: Typical affected depth of different surface treatments [8]

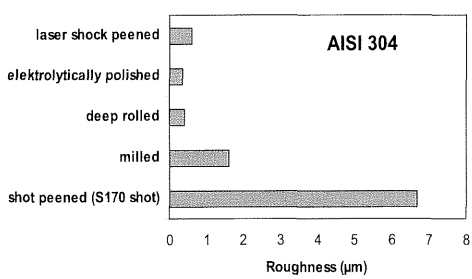


Fig. 2: Roughness R_Z of different mechanically surface treated AISI 304 samples

CURRENT STATE OF THE ART

Residual stresses and microstructure

A variety of parameters during the deep rolling process severely influences the near-surface residual stress state among which the rolling force or pressure is certainly the most important. It is known that only optimized rolling forces increase the fatigue strength, too low rolling forces have no pronounced effect on the fatigue behaviour anf too high ones may even aggravate it, for instance by inducing microcracks.

Fig. 3 exhibits schematically the influence of rolling force on the residual stress depth profile of a medium-hard metallic material (e.g. quenched and tempered steel). Typically, especially for hard materials, deep rolling leads to a subsurface maximum of residual stresses as expected by the Hertzian theory [9] predicting maximum equivalent stresses below the surface. It should be noted, that the position of the residual stress maximum not only depends on the rolling force, but also on the exact contact geometry of the involved workpiece and rolling tool. With increasing rolling force the compressive residual stresses also increase until a „saturated“ level of compressive residual stress is reached (usually determined by the yield strength or work hardening state of the material). However, a further increase of rolling force shifts the area of compression into greater depths and finally too high rolling forces can lead to subsurface compressive residual stresses but tensile residual stresses at the surface. Simultaneously, usually near surface hardness is also increased by work hardening effects (Fig. 4). In very hard material states (e.g. case-hardened steel) near-surface work softening by deep rolling can be observed. It should further be

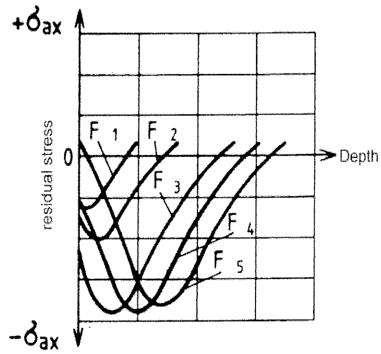
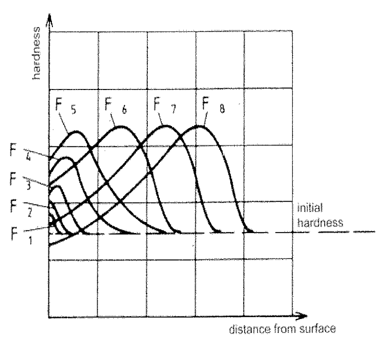


Fig. 3: Influence of rolling force on the residual stress depth profile (schematically [6])



Rolling force $F_8 > F_7 > F_6 > F_5 > F_4 >$
$F_3 > F_2 > F_1$

Fig. 4: Influence of rolling force on the hardness depth profile (schematically [6])

noted that for the assessment of the work hardening state hardness values can be very misleading, since they are also increased by compressive residual stresses [10]. Therefore the measurement of X-ray peak broadening yields more unequivocated information about the near-surface work hardening state.

The near-surface microstructures induced by deep rolling can be very manifold and depend strongly on the chosen process parameters as well as on the material itsself. Depending on the material deep rolling can result in the formation of dislocation cell-structures [11], nanocrystallites [12,13], twinning [14] or martensitic transformations [12]. As a typical medium strain rate surface treatment [15], deep rolling of „wavy slip“

materials such as plain carbon steels, usually leads to more cell-like dislocation arrangements than shot peening. In general, deep rolling produces high dislocation densities in near surface layers which are, however, lower than after shot peening [16]. Additionally, current results indicate that deep rolling is a very suitable method for near-surface nanocrystallization by plastic deformation. Nanocrystalline regions after deep rolling were detected so far in austenitic steels, magnesium and titanium alloys [17]. Fig. 5 depicts the nanocrystalline near-surface region in deep rolled Ti-6Al-4V. Typically, the created nanocrystalline regions are located directly at the surface and extend only a few microns into depth (typically 2-3 µm). In bcc metals such as plain carbon steel SAE 1045 the observed near-surface microstructures ressemble dislocation cell structures rather than nanocrystalline regions with high angle grain boundaries [16]. First results however, indicate that nanocrystallization can also be promoted by increasing the coverage and process temperature [18].

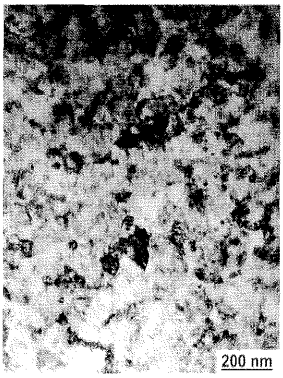


Fig. 5: Nanocrystalline layer in near-surface regions (depth 1 µm) of deep rolled Ti6Al4V

Effects on fatigue behaviour

The effects of a deep rolling treatment on fatigue behaviour depend very strongly on whether the fatigue process is crack initiation- or propagation controlled and it depends also very strongly on the yield strength of the material. In general, it can be stated that fatigue of smooth unnotched deep rolled components is dominated by crack initiation whereas fatigue of notched components is mainly crack propagation controlled. In the first case, the majority of the lifetime of the component is consumed by the crack initiation phase whereas in the latter case cracks initiate early and the crack initiation phase is negligible.

Figs. 6 and 7 show the influence of the 0.2%-yield stress on the endurance strength under rotation bending of various steels before and after a deep rolling treatment. It can be seen that for smooth specimens the effect of deep rolling is largest for very soft and very hard steels. For the material conditions exhibiting a low 0.2%-yield stress the fatigue strength enhancement by deep rolling is caused by near-surface work hardening, whereas for the material conditions with high 0.2%-yield stress compressive resifual stresses are assumed to be the main cause for fatigue strength improvement (mainly by preventing small cracks to propagate), since in the first case residual stresses partially relax and in the second case no significant near surface work hardening by deep rolling occurs. For an intermediate 0.2%-yield stress or -hardness both influences (residual stresses as well as work hardening) are claimed to cause the fatigue strength improvement, however recent results on a high strength titanium alloy indicate that also in the region around $R_{p0.2}$= 1000 MPa work hardening dominates the fatigue strength improvement more than residual stresses do if the surface is unnotched [19]. Fig. 8 shows that the fatigue life enhancement increases with rising work hardening in mechanically surface treated (deep rolled or laser shock peened) Ti6Al4V.

In the presence of notches the effect of mechanical surface treatments such as deep rolling is much more pronounced than for smooth specimens (Fig. 7) and it is highest for hard materials (several hundred percent of fatigue strength enhancement are not

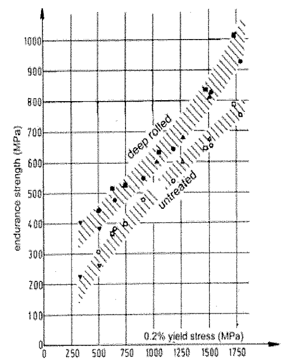


Fig. 6: Influence of the 0.2%-yield stress on the endurance strength of various steels before and after a deep rolling treatment [6]

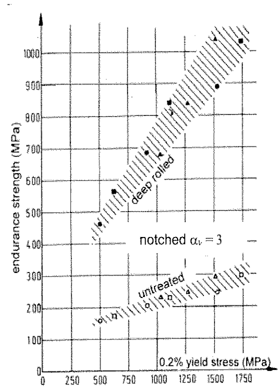


Fig. 7: Influence of the 0.2%-yield stress on the endurance strength of various steels before and after a deep rolling treatment for notched specimens[6]

a rare case !). It can be assumed that for notched components or specimens the fatigue strength enhancement is primarily caused by residual stresses regardless of the material hardness or 0.2%-yield stress since the fatigue damage process is now primarily crack propagation controlled and residual stresses mainly affect the crack propagation phase, but have little effect on the crack initiation phase [20]. Moreover, two other effects contribute to the extremely high lifetime enhancement in deep rolled hard materials: (i) the multiaxial stress state in the notch stabilizes the residual stress state and impedes residual stress relaxation (or a decrease of near surface work hardening in soft materials by cyclic plasticity) and (ii), the high hardness or yield

strength of the material leads to further residual stress stabilization. In addition, stress mechanical effects in notched specimens have to be accounted for.
As a general rule it can be stated that sufficient work hardening is much more important for deep rolled components than for shot peened components, since shot peened surfaces are always more or less notched by exhibiting high surface roughness therefore underlining the importance of compressive residual stresses there. In contrast, deep rolled surfaces are smooth and the fatigue process is mainly crack initiation and therefore work-hardening controlled.

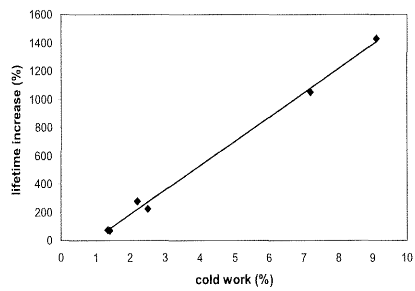


Fig. 8: Influence of cold work on the fatigue life improvement by deep rolling for the high temperature fatigued Ti-alloy Ti-6Al-4V (T = 250-450°C, σ_a = 460-550 MPa)

A closer look at the crack initiation and propagation phase is possible by performing stress-strain-hysteresis measurements of deep rolled specimens and by fracture mechanics methods, respectively. In the crack-free phase the cyclic deformation behaviour is altered characteristically by the deep rolling induced near-surface work hardening as can be seen in Fig. 9. In most metallic materials the increased dislocation density in near surface layers (sometimes assisted by additional hardening mechanisms such as strain-induced martensitic transformation) leads to a pronounced reduction of the plastic strain amplitude, if the affected layers are sufficiently deep. This in turn increases the fatigue life according to the Coffin-Manson law. The higher the rolling pressure or rolling force, the deeper the cases that are induced and the smaller the plastic strain amplitude or the larger the fatigue life enhancement, respectively (always on condition that the high rolling forces do not induce cracks at the surface already). Once a crack is initiated, its propagation is strongly controlled by the local residual stress state. Tensile residual stresses

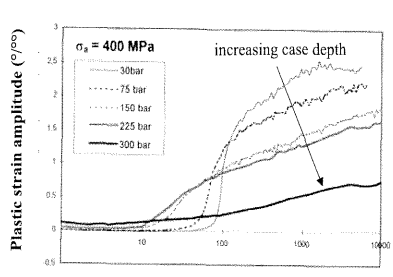


Fig. 9: Cyclic deformation behaviour of untreated and deep rolled SAE1045 in normalized heat treatment state for different rolling pressures

accelerate the crack growth, whereas compressive residual stresses deccelerate it or eaven lead to a complete crack arrest. Fig. 10 exhibits the crack propagation

behaviour of a crack in the notch root of deep rolled steel AISI 4140 (german grade 42CrMo4). Without compressive residual stresses the effective cyclic stress intensity factor increases continuously with rising crack length. However, in the deep rolled shaft the crack has to move through a maximum of compressive stresses below the surface. Since the cyclic stress intensity factor here consists of the loading stresses and the high compressive residual stresses it is reduced significantly and reaches values even below the threshold value for fatigue crack propagation of this material leading to crack arrest [21].
In nickel base alloys and titanium alloys, deep rolling can also compensate the effect of foreign object damage in turbine blade applications if the flaws are shallow and do not exceed the area of compressive residual stresses [22,23].

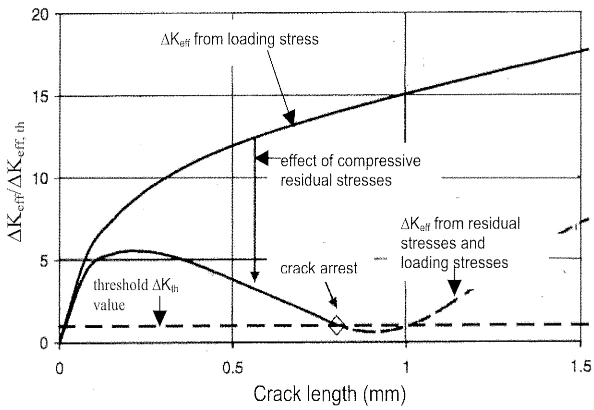


Fig. 10: Crack arrest in deep rolled AISI 4140 by residual stresses [21]

Corrosion and corrosion fatigue

Deep rolling is also a very effective means of mitigating corrosion fatigue damage at room temperature as can be seen in Fig. 11. Here, the corrosion fatigue performance of a Custom 450 stainless steel in acidic salt solution (3.5 wt% NaCl, pH 3.5) was investigated in an untreated and deep rolled condition and even in a notched predamaged (foreign object damaged) condition. Obviously, in the High Cycle (HCF) fatigue regime, the deep rolling treatment (here called „LPB") leads to a significant enhancement of the fatigue life and strength. Compared to the base line where the fatigue strength was 689 MPa, the foreign object damaged condition (0.25 mm indent) yielded a fatigue strength of only 69 MPa. After deep rolling the condition without foreign object damage exhibited a fatigue strength of 1102 MPa whereas the fatigue strength of the foreign object damaged condition reached 861 MPa [22].
Exemplary studies on the effect of deep rolling on the corrosion behaviour of magnesium alloys demonstrated that the corrosion behaviour of the magnesium alloy AZ91 (under sulphuric acid and water with added CO_2) is almost insensitive to the prior surface treatment (turning or deep rolling) whereas the opposite is the case for the magnesium alloy AZ31. Here, the mass loss inflicted by active corrosion was reduced by 70 % by deep rolling as compared to the turned condition which exhibited values of 40 % of the untreated and usually much more corrosion resistant AZ91 alloy. [24].

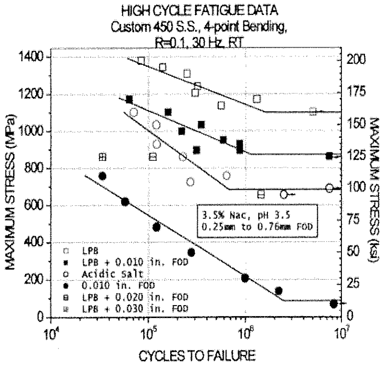


Fig. 11: Corrosion fatigue behaviour of untreated and deep rolled (LPB) Custom 450 stainless steel in acidic salt solution with and without foreign-object damage [22]

Modelling of the residual stress state

Considerable efforts have been undertaken to predict residual stresses after deep rolling just as for shot peening for a variety of rolling parameters and component geometries, but only a few literature sources document the modelling side of the deep rolling process [25,26,27]. As a simple approximation the Hertzian theory predicts the stress state close to the surface for rolling contact problems [9]. However realistic models of deep rolling should be capable of incorporating three dimensional, inhomogeneous and non-linear elastic plastic deformations. In addition, they should also be capable of describing the exact contact and friction conditions as a function of the rolling force. A limited number of finite element works have successfully predicted the sub-surface stress state in component-similar geometries by using either implicit or explicit Finite Element methods [25,26]. A comparison with experimental results have shown that the predicted stresses correspond well with the measured data and that developing times can be reduced significantly through using Finite Element methods on complex geometries (e.g. for fillet rolled crankshafts). Finite Element methods can also be helpful to assess stress and strain hardening redistributions after cutting deep rolled components, for example for X-ray measurement purposes [26].

Typical applications

Nowadays, surface rolling treatments are applied in many technical fields. Whereas roller burnishing (deep rolling with low forces/pressures) is mainly used to improve surface topography, deep rolling is used primarily to increase material strength. Typical examples can be found in the following fields:

<u>Automotive industry</u>
There are several mostly rotation-symmetrical components in the automotive industry that are highly loaded and deep rolled such as axles, shafts and especially steering knuckles. Since weight saving is especially attractive for components of the steering wheels or propulsion system, deep rolling is very efficiently used here. Applications range from cars to farm tractors. Sophisticated rolling tools enable machining of hardened components leading to further applications such as fretting fatigue loaded roller bearer steels. The combination of thermal and mechanical surface treatments

significantly enhances the fatigue strength leading to a pronounced reduction of weight. Fig. 12 exhibits deep rolling of a wheel flange as a typical example.

Aerospace and aircraft industry/power plant industry

Especially in the aerospace and aircraft industry weight reduction is a major aim of component designers. The optimization of near-surface properties by shot peening has been well established here. Since deep rolling offers a variety of economical and technological advantages, a lot of applications can also be found here. Typical examples are wheel rims of military aircraft, highly loaded screws and bolts as well as propulsion components such as turbine discs and compressor fan blades [28].

Medical applications

There are several examples in medical applications especially in the field of endoprothesis components that are higly loaded and must exhibit high cyclic strength. Typical examples are implants for artificial hip joints and the spinal chord. In order to guarantee long lifetimes, surface optimization is an absolute must. Moreover components of surgical instruments that are loaded cyclically in acidic and corrosive environment can be improved by deep rolling in terms of their stress corrosion behaviour.

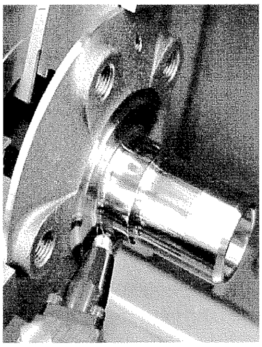


Fig. 12: Deep rolling of a wheel flange [29]

FUTURE DEVELOPMENTS

Deep rolling of complex geometries

Initially, the first major applications for deep rolling were geometrically simple and rotation symmetrical components such as axles for vehicles. The deep rolling tools were mostly mechanically operated and highly specialized for critical components such as crankshafts. Although, deep rolling today is still very often applied to mainly rotation symmetrical geometries and components, such as turbine shafts, turbine wheels, valves, cylinder liners, threads, pistons and small fillets, modern deep rolling tools today are designed for much more complex and also highly non-rotation symmetrical geometries. Especially the hydrostatic tools operated under full CNC-control allow to keep the rolling force or pressure constant during deep rolling of irregular surface topographies. Modern hydrostatic rolling tools are designed to fit into standard machine tools and the deep rolling process is fully integrated in the chip-forming production process chain in one setting. As a final step after conventional machining of the desired geometry it can even replace other surface finishing processes like grinding, superfinishing and honing. A typical example for a complex geometry are turbine blade surfaces that can be deep rolled partially along the leading edges or completely. Fig. 13 shows a double sided hydrostatic deep rolling tool for turbine blades. The deep rolling tool can be moved in a linear, meander-shaped trace in longitudinal or cross direction across the blade. The double sided rolling serves to avoid bending of the edges by the high rolling forces. Another example is deep rolling of dovetail slots which serve as connections between turbine blades and discs. Such dovetails slots are subjected to High Cycle Fatigue and Fretting Fatigue making them ideal candidates for mechanical surface optimization. Dovetail slots can be deep rolled by double sided hydrostatic tools or by hydrostatic multiple ball tools (Fig. 14). Thus all critical parts in the slot are covered by the balls.

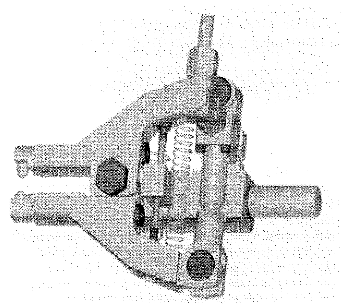


Fig. 13: Double-sided hydrostatic deep rolling tool for deep rolling of turbine blades [29]

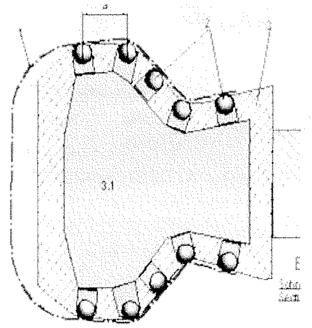


Fig. 14: Hydrostatic multiple ball tool for deep rolling of dove tails [29]

High temperature deep rolling

Recent investigations on several metallic alloys have clearly demonstrated that deep rolling can lead to even higher fatigue strengths and lives if the component or specimen is heated in a certain optimized temperature range during the deep rolling process itself, similar as it is the case for warm peening (shot peening at elevated temperatures). The principle effectiveness of such a treatment was confirmed for steels, aluminum and magnesium alloys [30,31]. We therefore call this treatment „High Temperature Deep Rolling" or „Thermomechanical Deep Rolling". The obtained fatigue properties by such a treatment are clearly superior to those of conventionally deep rolled or laser shock peened conditions.

Fig. 15 exhibits in an exemplary manner how high temperature deep rolling at 350°C affects the cyclic deformation behaviour of normalized plain carbon steel SAE 1045. For comparison, the cyclic deformation curves of the untreated (annealed) and conventionally (at room temperature) deep rolled condition are also included. It can be seen that high temperature deep rolling reduces the plastic strain amplitude in stress-controlled fatigue much more effectively than the conventional room temperature deep rolling treatment as compared to the untreated state. This reduction of cyclic plasticity leads to much higher fatigue lives and lifetime enhancements even in the low cycle fatigue regime, where the high stress/strain amplitudes render the conventional deep rolling treatment ineffective due to dislocation rearrangements [32]. The metallurgical explanation for this stunning fatigue life enhancement can be found in the formation of Cottrell clouds and formation of small carbide precipitates in the vicinity of dislocations before/after and during the deep rolling treatment, or in other words, in static and dynamic strain ageing, respectively [30]. High temperature deep rolling is also effective for AISI 304 steel (Fig. 16) and exceeds lifetime improvements by laser shock peening as well.

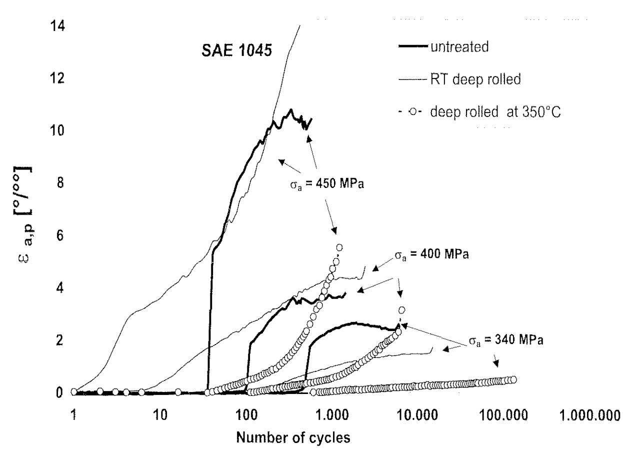


Fig. 15: Cyclic deformation behaviour of high temperature deep rolled SAE 1045

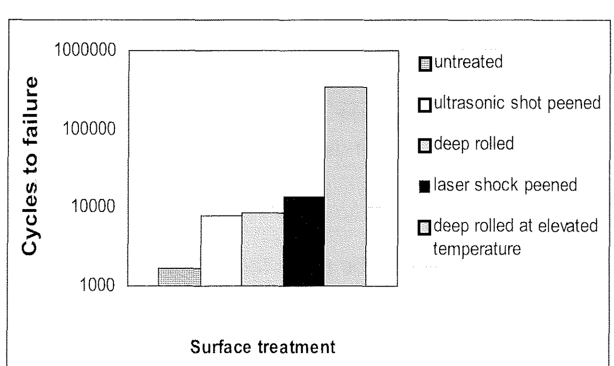


Fig. 16: Fatigue lifetime improvement for differently surface treated AISI 304 samples (σ_a = 350 MPa, f = 5 Hz, R = -1) [33]

CONCLUSIONS

Deep rolling is a very powerful tool for mechanical surface optimization and fatigue strength enhancement. On the basis of the well known mechanical and metallurgical effects it is continuously improved for even more complex as well as widespread applications and combined with other surface treatments. Its benefits range from classical fatigue strength enhancement to mitigation of stress corrosion, improvement of wear characteristics and superfinishing of surfaces for higher functionality. It renders production processes of structural parts more economical and contributes significantly to the proliferation of light-weight designs.

ACKNOWLEDGEMENTS

The author would like to express sincere thanks to the German Science Foundation (DFG) for financial support of the Emmy-Noether-group in Kassel, led by Dr. I. Altenberger, under contract number Al 558/1-2 and Al 558/1-3 and to B. Scholtes, I. Nikitin and P. Juijerm for fruitful discussions and experimental help.

REFERENCES

1. O.J. Horger, Journal Appl. Mech. 58 (1936) 91.
2. O. Föppl, Stahl und Eisen 49 (1929) 575.
3. A. Thum., W. Bautz, Forsch. Ing. Wesen 6 (1935) 121.
4. P. Strigens, Dr.-Ing. Thesis, University of Darmstadt, 1971.
5. H. Wiegand, P. Strigens, Draht 20 (1969) 189.
6. G. Berstein, B. Fuchsbauer, Z. Werkstofftech. 13 (1982) 103.
7. S. Gruber, G. Holzheimer, H. Naundorf, Z. Werkstofftech. 14 (1984) 41.
8. H.-W. Zoch, HTM 50 (1995) 207.
9. E. Broszeit, Z. Werkstofftech. 15 (1984) 416.
10. G. Zöltzer, I. Altenberger, B. Scholtes, HTM 56 (2001) 347.
11. I. Altenberger, B. Scholtes, U. Martin, H. Oettel, HTM 53 (1998) 395.
12. I. Altenberger. B. Scholtes, U. Martin, H. Oettel, Mater. Sci. Eng. A 264 (1999) 1.
13. I. Altenberger, R.K. Nalla, U. Noster, G. Liu, B. Scholtes, R. O. Ritchie, Mat. Wiss. u. Werkstofftech. 34 (2003) 529.
14. I. Altenberger, B. Scholtes, In: Surface Treatment V, WIT press, Southampton, 1999, p. 281.
15. I. Altenberger, In: Shot Peening, Wiley-VCH, Weinheim, 2003, p. 421.
16. I. Altenberger, B. Scholtes, Mater. Sci. Forum 347-349 (2000) 382.
17. I. Nikitin, I. Altenberger, H.J. Maier, B. Scholtes, In:7th International Conference on Nanostructured Materials, Wiesbaden, 2004.
18. I. Nikitin, I. Altenberger,University of Kassel, unpublished, 2004.
19. K. Röttger, G. Wilcke, I. Altenberger, In: DVM-Bericht 131 "Leichtbau und Betriebsfestigkeit", München, 2004, p. 293.
20. L. Wagner, Mater. Sci. Eng. A263 (1999) 210.
21. R. Schaal, C. Richter, C. Berger, Mat.-Wiss. U. Werkstofftech. 32 (2001) 477.
22. P. Prevey, M. Shepard, R.A. Ravindranath, T. Gabb, In: Proc. of ASME Turbo Expo 2003, Atlanta, Georgia, USA.
23. P. Prevey, J. Telesman, T. Gabb, P. Kantzos, In: Proc. 5th National HCF Conf, 2000.
24. H.K. Tönshoff, T. Friemuth, C. Podolsky, J. Winkler, H. Haferkamp, M. Niemeyer, V. Kaese, S. Janssen, Mat. Wiss. U. Werkstofftech. 32 (2001) 62.
25. U. Jung, B. Kaiser, K.H. Kloos, C. Berger, Mat. Wiss. U. Werkstofftech. 27 (1996) 159.
26. C. Achmus, J. Betzold, H. Wohlfahrt, Mat. Wiss. U. Werkstofftech. 28 (1997) 153.
27. C. Achmus, Dr.-Ing. Thesis, University of Braunschweig, 1999.
28. S. Mader, F. Klocke, 2005, this volume.
29. picture by courtessy of www.ecoroll.de
30. I. Altenberger, B. Scholtes, Scripta Mater. 41 (1999) 873.
31. I. Altenberger, I. Nikitin, HTM 59 (2004) 269.
32. U. Martin, I. Altenberger, B. Scholtes, K. Kremmer, H. Oettel, Mater. Sci. Eng. A 246 (1998) 246.
33. I. Nikitin, I. Altenberger, University of Kassel, unpublished, 2005.