Influence of Shot Peening on Material Properties and the Controlled Shot Peening of Turbine Blades.

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Abstract

The change of surface properties and the metallurgical processes during shot peening treatment are studied in some detail. In addition, the influence of shot peening on the fatigue strength is explained using an austenitic steel and a ferritic 12% chromium steel as examples. The aim of the work was to investigate shot peening parameters which influence the fatigue strength of components. The presented results should lead to a better understanding of the metallurgical processes during shot peening and should thus allow the choice of the optimum peening parameters. It will also be demonstrated, how shot peening can be integrated into the production process of components and which measures, concerning the peening parameters and the quality control, have to be taken into account. New methods of quality assessment will be introduced.

1. Introduction

Highly stressed components such as turbine blades demand, in the development and concept phase, an optimum judgement of material, production and design based on the actual loading conditions (Fig. 1). The material surface plays an important role in components with vibrating loads because fatigue cracks usually start in the surface at notches, pores, fatigue slip steps and inclusions. In general, a turbine blade material has to fulfil several requirements:

- It has to satisfy the static and dynamic loading requirements.
- It has to satisfy the requirements in respect to wear, erosion and corrosion.
- It must allow easy manufacturing and processing.

Such a material that has to fulfil all these demands can in most cases only be produced by material combination or a composite design. In this respect, the various techniques for surface treatment are becoming more and more important. Three different procedures can be distinguished whereby the untreated substrate material can be improved (Fig. 2):

1. mechanical surface treatments.
2. surface diffusion treatments.
3. surface overlay coatings.

The shot peening treatment belongs to the group of mechanical surface treatments as do hammering, surface rolling, polishing, milling, turning, lapping and vibration grinding. All mechanical surface treatments that should improve the fatigue strength of components are based on the principle of preventing dislocation movement in the surface layer either by a local increase of the yield strength in the outer surface (mechanical hardening), the introduction of favourable compressive residual stresses or by reducing the surface roughness /1/.

For several decades shot peening has been successfully used as a surface treatment technique. After a correct shot peening treatment, dynamically loaded components can carry higher cyclic stresses, reducing the risk of fatigue fracture. On the other hand, the higher fatigue strength could also allow a reduction in component weight. It is found that shot peened components under corrosive environments can show significantly higher fatigue limits in comparison to untreated components.

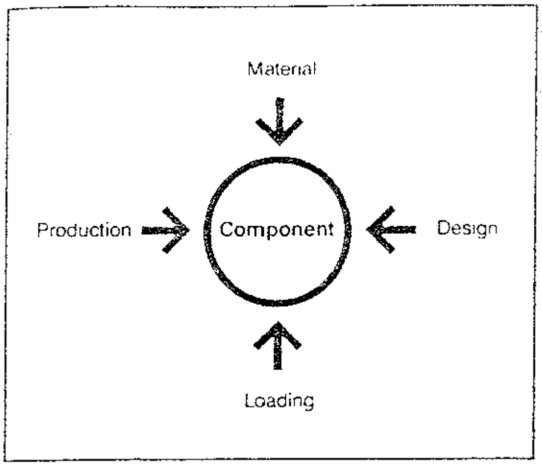


Fig. 1: Parameters that influence the quality of a component.

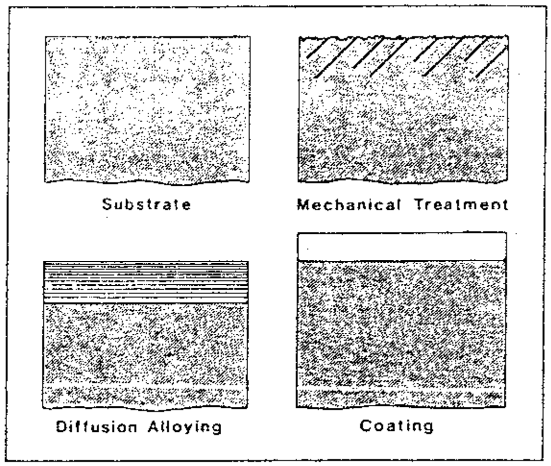


Fig. 2: Different methods of surface treatments (schematic).

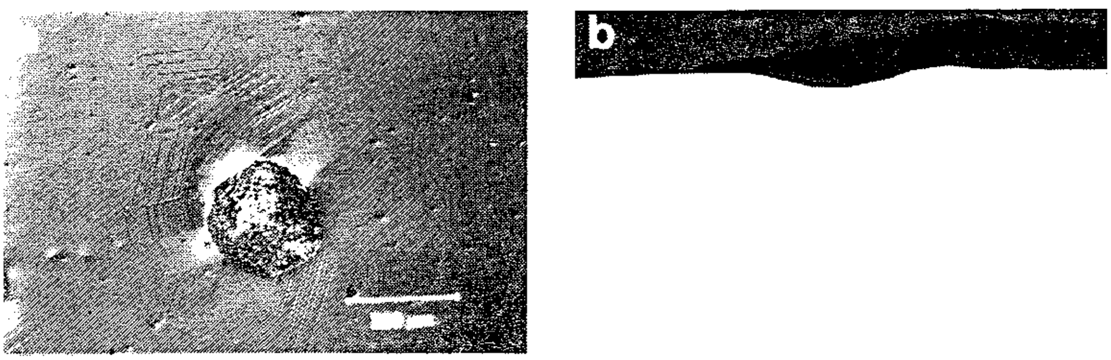


Fig. 3: Impact crater of a single steel ball, (d= 0,6 mm, v= 30 m/s, A286)

a) Formation of slip bands,

b) Cross section of an impact crater.

c) Impact crater, SEM.

What happens during shot peening and how does shot peening affect the material behaviour ?

The goal of shot peening is to plastically deform only the surface zone of a component. This is in contrast to peen-forming (which will not be treated here) whereby the fraction of plastically deformed zone in the cross section is large in order to cause a desired change in shape of a component. For shot peening, small steel balls are used which impact with high kinetic energy on the component surface. Each ball acts as a fine peening hammer under whose impact the surface zone is deformed. Upon impact, the kinetic energy of the shot is transformed into plastic deformation of the component surface and the shot itself as well as into a slight temperature increase of shot and component (lost energy). During the very short impact time, very high forces act locally. After impact, the shot is reflected from the component surface with the remaining kinetic energy.

In order to obtain the highest possible kinetic energy of the shot, the weight or the velocity of the balls can be increased. Using steel balls, for example, a higher deformation energy is obtained at the same impact velocity than with lighter glass or ceramic spheres. However, the maximum size of the balls is limited by technical restrictions: if the ball diameter is increased, the component surface roughness will become greater and there are certain machine operating restrictions. A ball size of 0.05 to 1 mm diameter is commonly used. The kinetic energy of the shot increases with the square of the velocity so that high deformation energies can easily be obtained by increasing the shot velocity. This can be accomplished by increasing the speed of rotation in centrifugal type shot peening machines or by increasing the air pressure in pneumatic type shot peening machines.

The shot peening treatment is characterized by the following:

- Shot material (grade, shape and hardness of shot; fraction of broken shot)
- Peening parameters (velocity of shot, nozzle diameter, mass-flow rate, peening time and impact angle)
- Intensity and coverage of components (depending on the peening parameters).

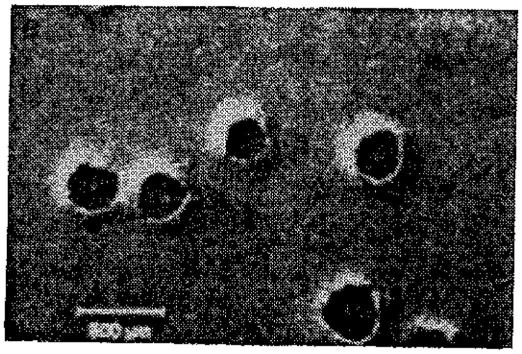
These parameters have to be controlled carefully in order to constantly guarantee top quality shot peened components.

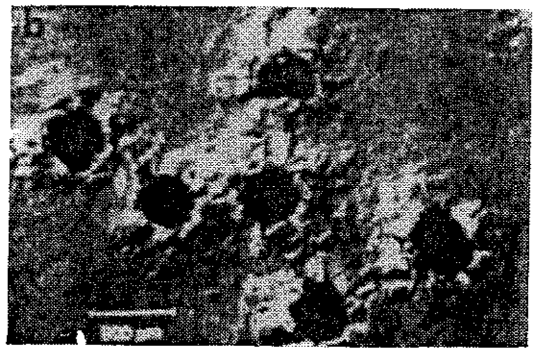
2. Mechanisms During Shot Peening

Upon impact of the shot, impact craters are formed on the component surface (Fig. 3). The component material is stressed far above its yield strength during impact so that plastic flow can occur with the formation of a hill and valley topography. Fig. 4 shows the impact craters of 0.6% carbon steel (Ck 67), a ferritic 12% Cr-steel (X 22 CrMoV 12 1) and an austenitic steel (A286). The austenitic steel shows the formation of slip bands and slip steps next to the crater edges (Fig. 3a). The 0.6% C-steel produces the most shallow impact craters due to its higher hardness and strength. This comparison should demonstrate optically that the microscopic deformation processes occurring in the component surface during shot peening are strongly dependent on the respective material properties such as strength, work hardening and ductility. In the first moment of shot impact tensile stresses are produced in the surface because the surface is trying to become plastically larger. As a reaction to the shot peening treatment a compressive residual stress is formed in the surface layer. These compressive residual stresses have to be balanced by residual tensile stresses in the entirely elastically deformed component interior /2/. The position of the maximum of compressive residual stresses depends on the peening intensity which is, at a given shot velocity, a function of the shot size. Using large steel shot it is often found that the maximum of the compressive residual stresses lies below the surface whereas the maximum lies directly on the surface when using small shot. In addition, this behaviour is strongly dependent on the material and its work hardening capabilities (Fig. 5).

With increasing shot peening time, deeper surface layers are plastically deformed, until a saturation is reached which depends on the energy of the impacting shot. The surface zone shows an increased dislocation density after shot peening. This increased dislocation density leads to an increased material strength in the surface zone. This work hardening of the surface zone can easily be proven by different techniques.

In the following sections it will be described how to determine the extent of the plastic deformation in the component surface after shot peening. An iron base superalloy, A286, is used as a model alloy. This material is an austenitic stainless steel that is precipitation hardened by gamma'-prime-particles, (γ', $Ni_3(Al,Ti)$). A286 is used for the production of forged gas turbine blades for turbomachinery. This material shows a different recrystallization response as a function of the preceeding cold deformation. At degrees of cold deformation between 25-90% recrystallization occurs with the formation of η-particles, (incoherent Ni_3Ti-particles). Interestingly, at deformation degrees between 90-95% the





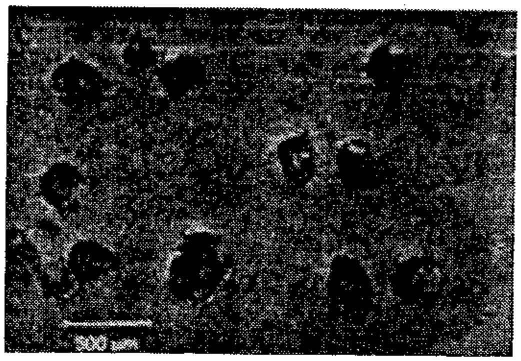


Fig. 4: Impact craters on polished substrate surfaces.

a) 12% Cr+(Mo,V)steel
b) A286 (peak aged)
c) 0.6% C-steel.

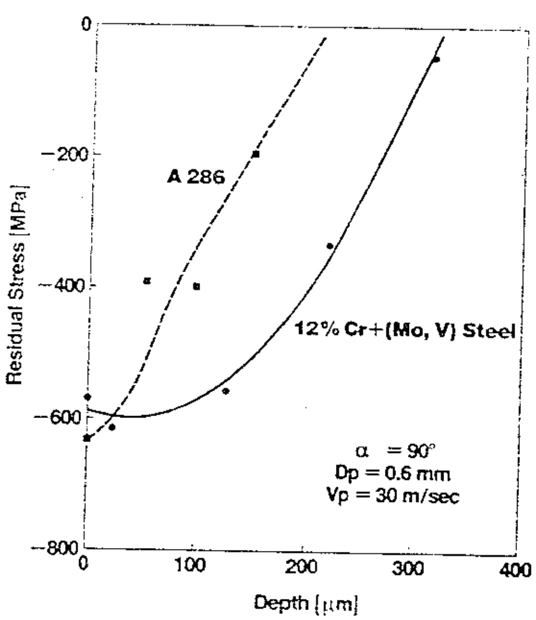


Fig. 5: Residual stress distribution of A286 and 12% Cr-steel after shot peening (S230).

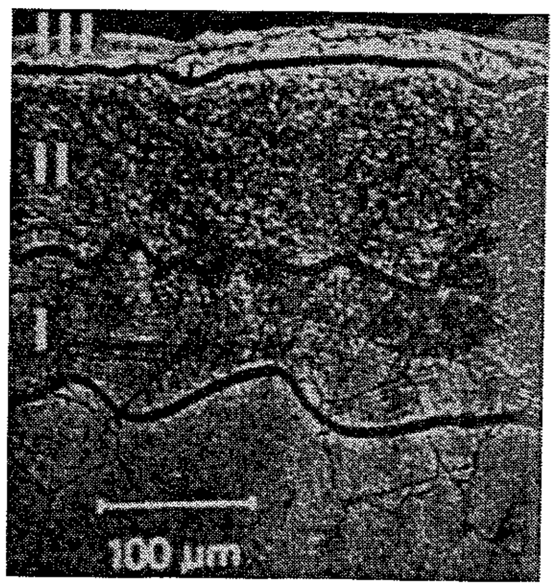


Fig. 6: Zones of different deformation after shot peening of A286, vissible after heat treatment: 24h, 820 °C.

recrystallization is prevented by the heterogeneous precipitation of finely dispersed gamma-prime-particles. At very high deformation, above 95%, the recrystallization occurs again. These different recrystallization mechanisms can be observed in shot peened samples after a suitable annealing treatment, for example 24h at 820°C. In Fig. 6, a shot peened A286 specimen with the three different recrystallization zones is shown in cross section. By this technique, it can be proven that a zone of more than 300µm depth is plastically deformed during shot peening. Moreover, it is obvious that shot peening must lead to degrees of cold deformation higher than 95% in the surface zone.

Two additional techniques were used to investigate the plastic deformation of the surface layer in A286 after shot peening. These were the hardness and the half width determined by an X-ray technique (a measure of the cold deformation and the dislocation density). Both were measured as a function of the degree of cold rolling. As a reference, part of the material was heavily strong cold worked up to a true degree of deformation of $\varepsilon=-4$ (Fig. 7a,b). The hardness and half width of shot peened specimens were measured as a function of the distance from the surface (Fig. 7c,d). In Fig. 7c, the measured hardness distributions for three different heat treatment conditions are plotted. Comparing the hardness of cold rolled and shot peened specimens, a maximum depth of deformation due to shot peening of up to 1000µm and a maximum degree of cold work of $\varepsilon=-3$ to -4 can be determined. However, for this comparison, one has to consider that the deformation of the shot peened surface zone is produced cyclically by the repeatedly impacting steel shot, whereas the cold rolling of the control specimens is a static deformation process. From the correlation with the half width (by X-ray technique) a depth of deformation due to shot peening of about 150µm can be determined for the aged condition of the tested austenitic steel (Fig. 7d). In comparison to the micro-hardness measurement, the measurement of half width is obviously less sensitive for this alloy. Comparing the half widths of cold rolled and shot peened specimens a maximum deformation degree of more than $\varepsilon=-1.5$ is found for shot peened surfaces. Although one has to be careful presenting quantitative values, it can be concluded from these experiments that the surface zones are heavily strong cold worked during shot peening. Fig. 8 shows a mobile X-ray diffractometer that can be used to measure residual stresses in samples, but also in turbine blades or large rotors.

The influence of impact angle on the surface deformation has also been studied using the above methods. At impact angles lower than 90°, even after very short peening times, a plastic flow of the surface zone occurs into the shot peening direction. Fig. 9 shows that the surface zone has

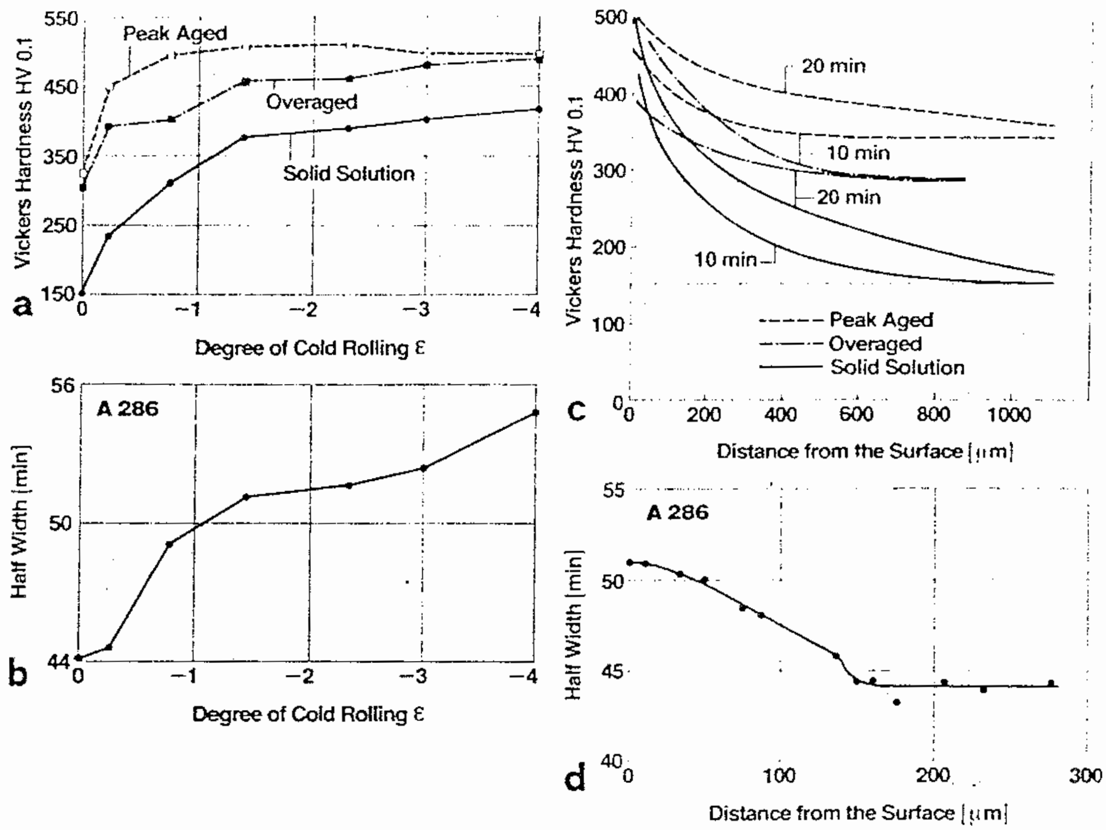


Fig. 7a: Hardness as a function of the degree of cold rolling (A286).
7b: X-Ray half width as a function of the degree of cold rolling.
7c: Hardness profile in the surface layer after shot peening for different peening times and for different material conditions.
7d: Half-width profile after shot peening.

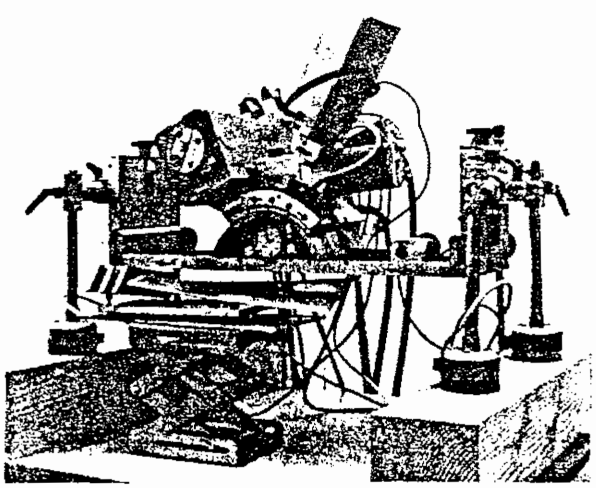


Fig. 8: Mobile X-ray diffractometer.

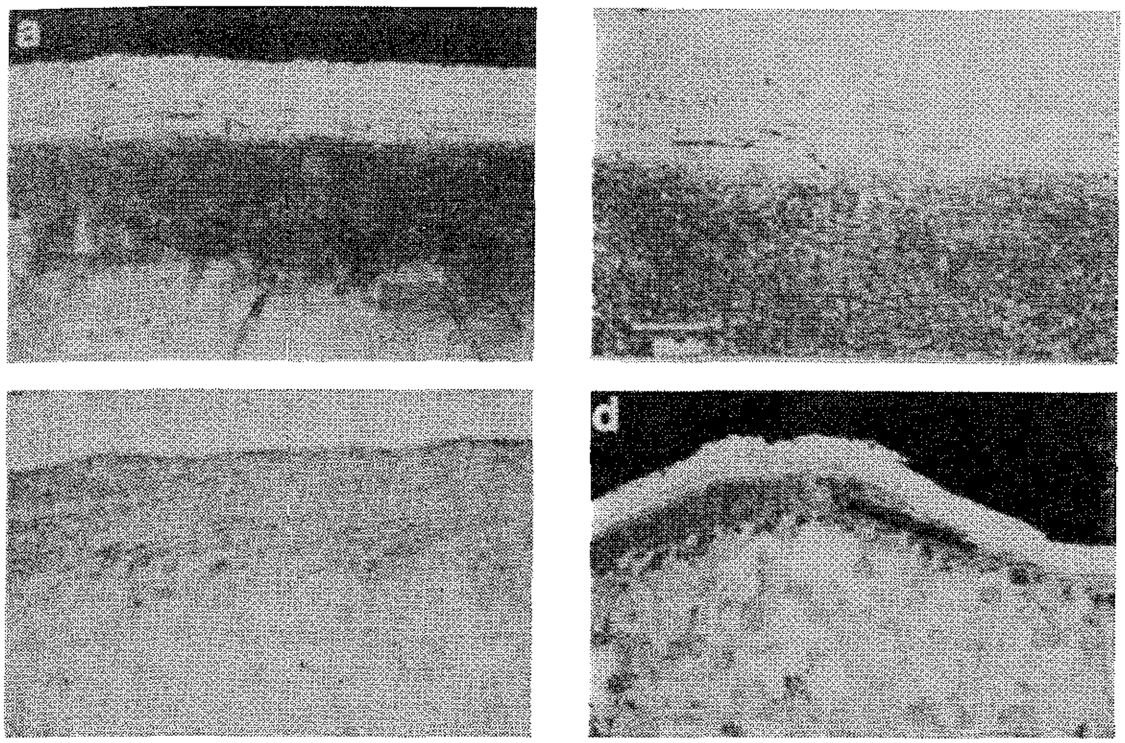


Fig. 9: Surface deformation after 10 minutes of shot peening.
a) and b) 90° angle, note subsurface cracks and turbulent flow.
c) 80° d) 30° angle, note deformation zone size.

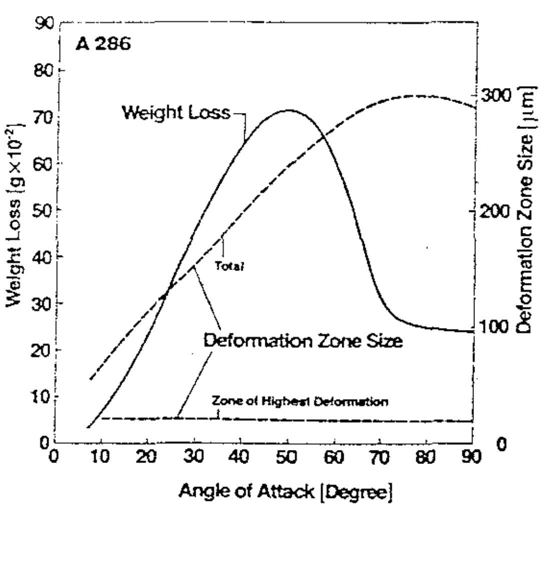


Fig. 10: Deformation depth and weigth loss as a function of angle of attack.

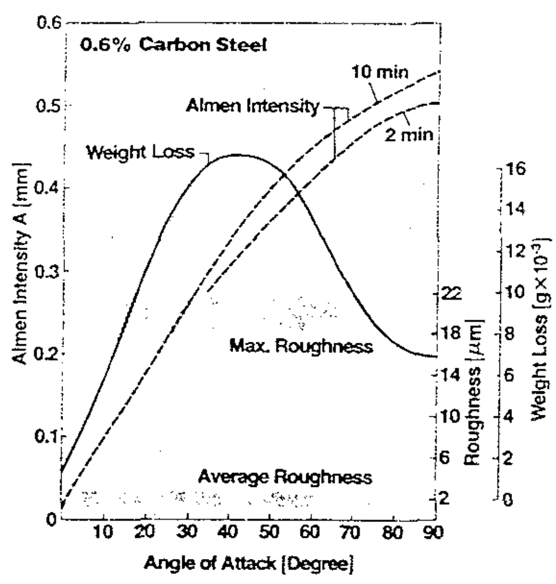


Fig. 11: Almen intensity A and roughness as a function of angle of impingement.

flowed up to a depth of more than 100μm in the peening direction. The recrystallized microstructure reveals that the total deformation depth diminishes with decreasing angle of impact (Fig. 10). The zone of maximum deformation (>95%), however, stays constant with a thickness of 20μm. The decreasing total deformation depth can be explained by the fact that the impact energy of the shot lessens with decreasing impact angle. The intensity of the shot peening treatment - the so-called Almen intensity, which is discussed later in more detail - is plotted in Fig. 11 as a function of the impact angle. As is to be expected, the Almen intensity strongly diminishes with decreasing impact angle.

The three investigated heat treatments of A286 showed a different influence of the peening time on the hardness in the surface zones. Whereas the hardness for the solid solution and the peak aged condition increases with increasing peening time (compare with Fig. 7c), it decreases for the overaged condition after longer peening time. This loss in hardness, however, is not due to cyclic softening with increasing peening time, as observed in titanium alloys, but is due to the damage of grain boundaries and the formation of grain boundary microcracks. In the overaged condition, large incoherent precipitates and precipitation free zones are formed along the grain boundaries. This results in the grain boundary embrittlement and facilitates crack initiation during shot peening.

3. Possible Negative Effects of Shot Peening

Whereas compressive residual stresses as well as increased dislocation density are introduced into the material surface with the purpose of improving the fatigue limit, the increase in roughness inherent during shot peening must always be considered as negative. At higher magnification overlaps, microcracks and areas with obvious turbulent flow can be found (see Fig. 9a,b). These overlaps can reach up to 30μm deep into the material interior. If the beneficial compressive residual stresses (or the dislocation density) are significantly reduced during the component service life due to thermal or mechanical conditions (see also Section 7), the fatigue limit could be lower than that of an untreated component with a smooth surface.

The surfaces of specimens shot peened for different periods of time (t=5s, 20s, 60s, A 286, shot peened with glass beads of 80μm diameter, v=30m/s, distance nozzle-specimen: 300mm, different impact angles) were investigated microscopically. The results are shown in Fig. 12. With increasing peening time the surface roughness increases as well. With decreasing impact angle the roughness stays constant despite a decrease in the total deformation depth (see Fig. 10,11). In addition, undesired side-effects occur in the shot

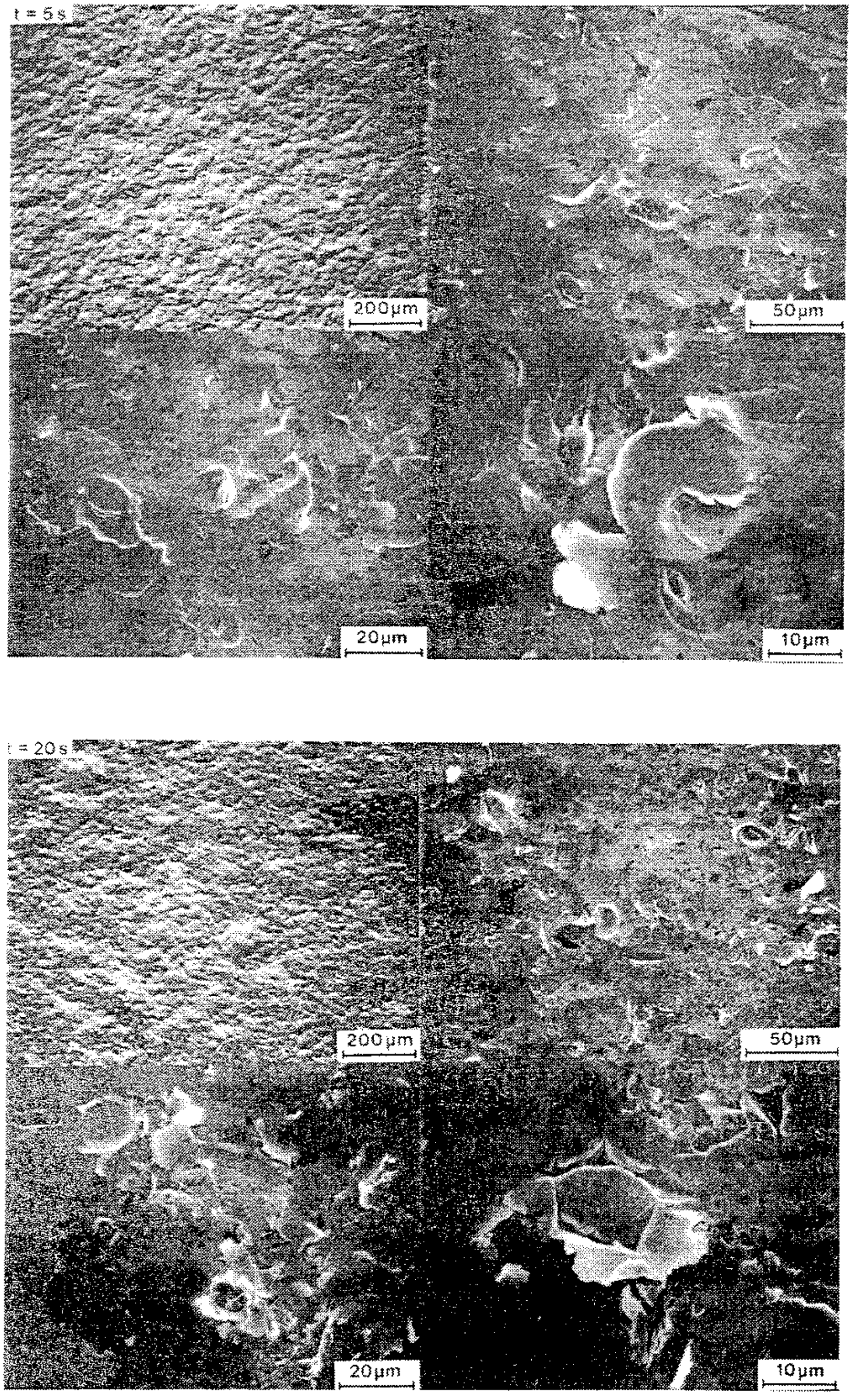


Fig. 12: Surface appearance after shot peening for different times.

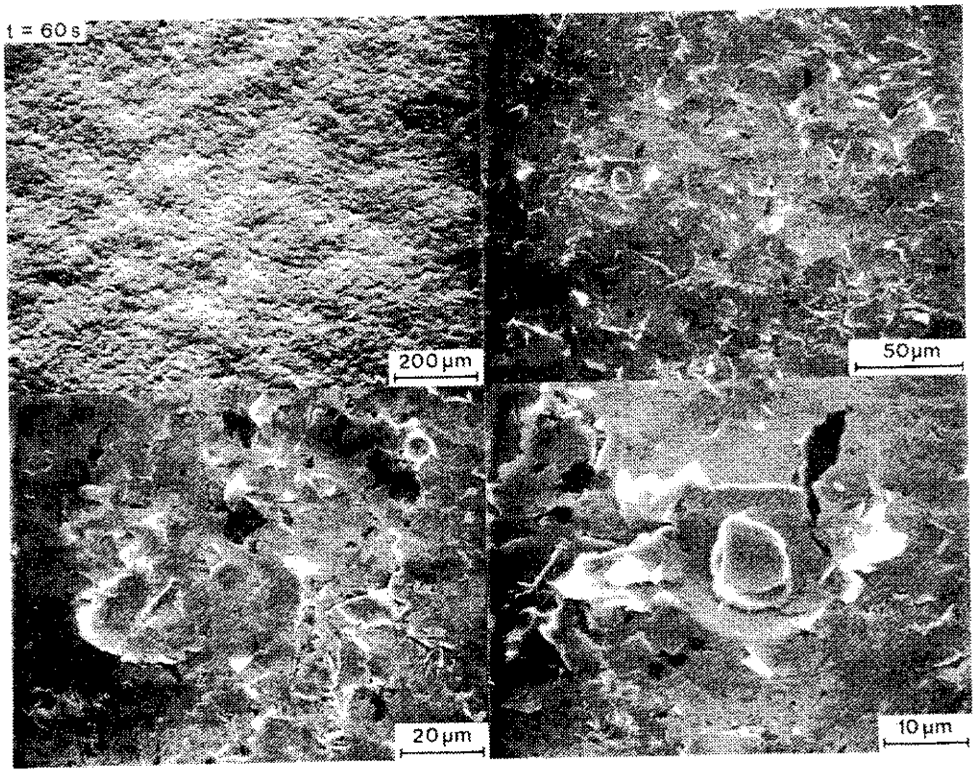


Fig. 12: Surface appearance after shot peening for different times.

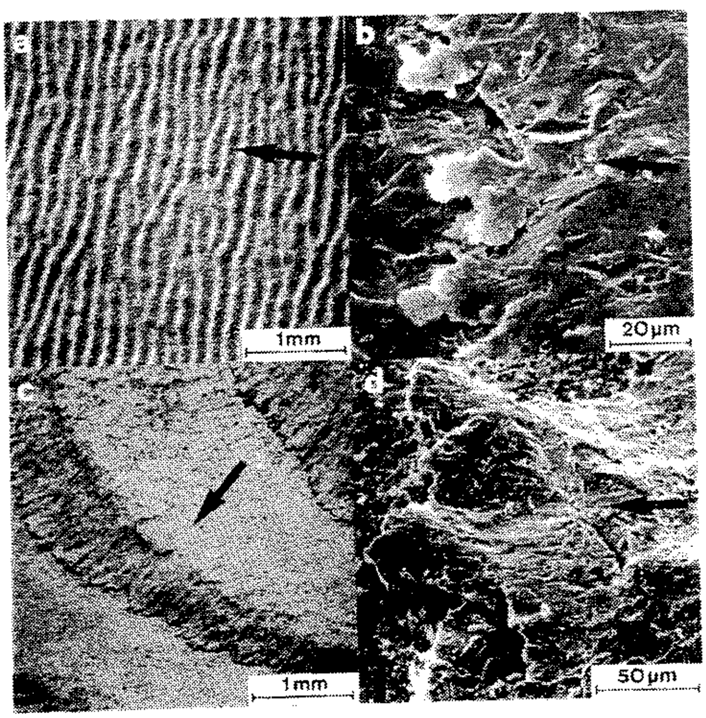


Fig. 13: Surface appearance after shot peening at 45° impact angles Formation of erosion platelets.

peened surface with decreasing peening angle: wavy and ripple-like surface morphologies are observed (Fig. 13). The distance between these waves depends on the shot diameter as well as on the shot intensity used. Owing to its regular structure, this effect may be used to produce optical or decorative effects; but for technical components like turbine blades this surface structure has aerodynamic disadvantages. Therefore, component areas that can be hit under smaller angles should be protected by covers. For all peening angles, thin platelets and overlaps with notches are formed as shown in Fig. 9 in a cross section. By exact weight and thickness measurement of shot peened specimens, it was noticed that after an initial weight acquired due to material transmitted from the steel shot, the specimens suffered a loss both in weight and in diameter. This loss in material has been plotted in Fig. 10 and is called erosion by solid particles, in this case, by the steel shot. As can be observed in Figs. 10 and 11, the material loss increases rapidly with decreasing peening angle and reaches a maximum at a peening angle of 20-30°. As is indicated schematically in the erosion diagram, the erosion loss is due to a fatigue and cutting process, which depends on the impact angle (Fig. 14). From Fig. 12 it can be seen that the material loss during shot peening already occurs after very short peening time. These specimens were further investigated in a scanning electron microscope (SEM) at magnifications of up to 10'000 times.

In these investigations thin platelets were found that had lost their contact to the substrate thereby leading to the observed weight loss. Under the peening conditions used, these platelets were usually between 5 and 30μm in size. For further investigation, these thin platelets were removed from the peened substrate surface by a so-called extraction replica technique (Bioden-replica) and analyzed in a transmission electron microscope (TEM) at magnifications between 10'000 and 300'000 times. This procedure has already been used by other authors for the investigation of erosion damage. In this technique, a thin polymer foil is glued on the shot peened surface for the purpose of letting the loose erosively damaged platelets adhere to it. The foil is then removed from the surface to be sputtered with carbon and subsequently dissolved in a solvent solution. The carbon replica with the erosion platelets stuck on it can then be investigated under the microscope. Fig. 15 shows the platelets removed by this technique (5 and 60 s peening time). In addition, thin splinters were found. They were analyzed by electron diffraction and EDAX-analysis and shown to be glass splinters from the glass bead shot used. The withdrawn platelets are so thin (< 0.1μm), that they are transparent to the electron beam.

As one can already conclude from the measurement of the hardness in the shot peened surface zone, there is a very high dislocation density in the top

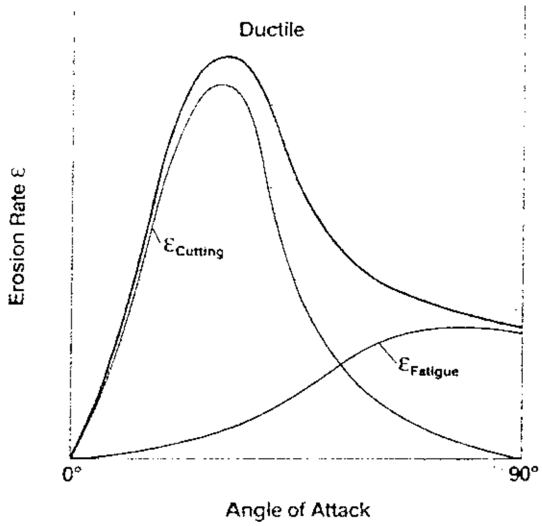


Fig. 14: Solid particle erosion as a function of the impact angle.

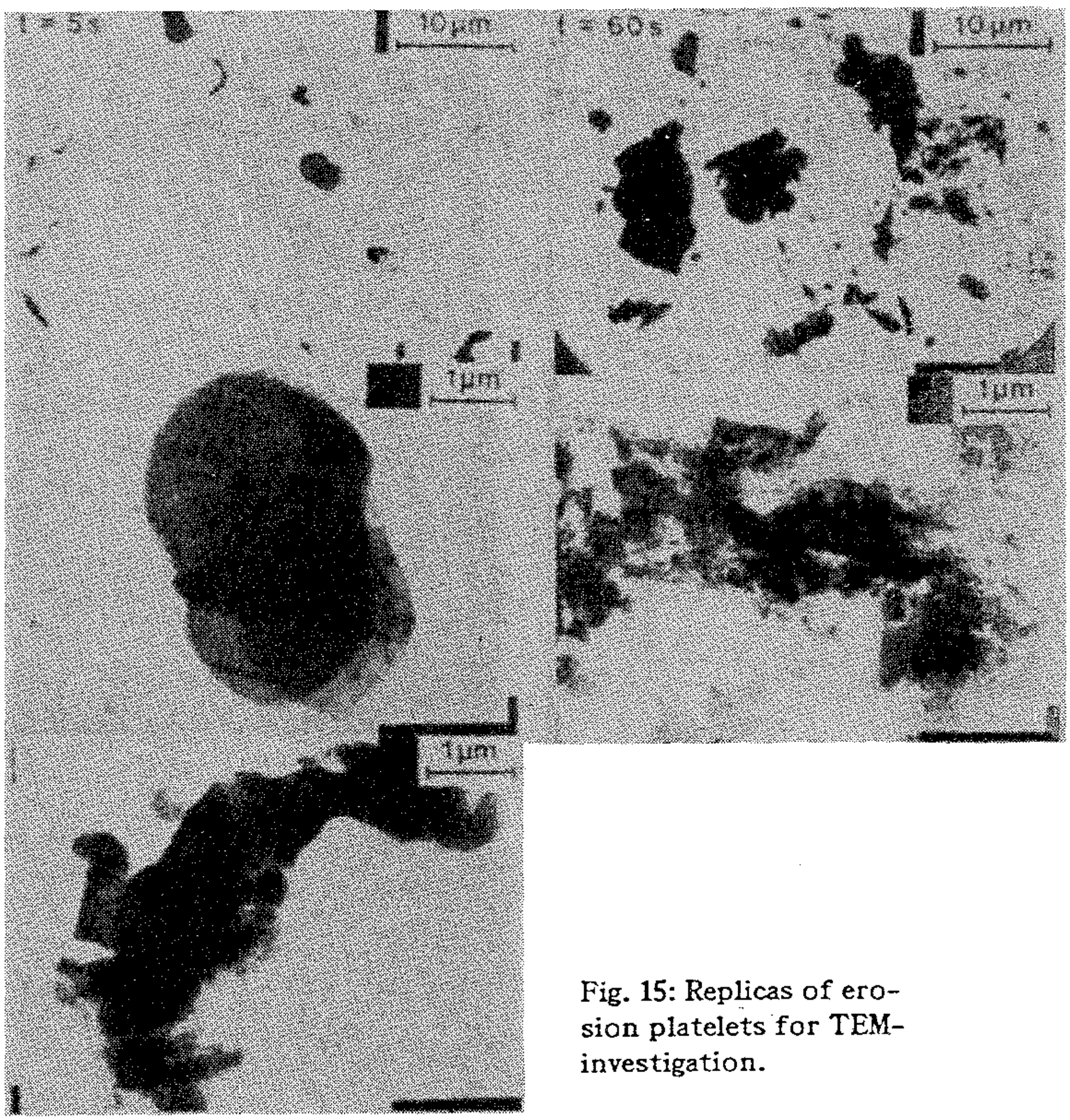


Fig. 15: Replicas of erosion platelets for TEM-investigation.

most surface zone. The dislocation density in the erosion platelets (Fig. 16) is so high that single dislocations can not be resolved. Furthermore, the diffraction patterns with concentric rings indicate the extremely high level of cold deformation of the surface zone (Fig. 16b,f). At a high magnification, a microstructure with subgrains or even recrystallized areas can be found in some platelets (Fig. 16c). This recrystallization cannot, however, be explained by a temperature increase during shot peening. Temperatures of more than 1000°C would have been necessary. Therefore, it is assumed that these recrystallized areas are artifacts due to the very thin platelets.

It has often been asserted that during shot peening extremely high temperatures can occur and that these are responsible for the erosive loss of surface material /3/. However, our TEM-investigations of material platelets from the top surface zone have shown no traces of molten areas. Further, these investigations confirm the above mentioned measurements of hardness, degree of recrystallization and half width. Such a high plastic deformation occurs in the component surface during shot peening that the observed overlaps as well as the erosively formed platelets can be produced. These platelets become detached from the substrate surface because the deformation capability and ductility of the material are exhausted. At degrees of deformation higher than ε=-1.5 crack initiation and crack propagation occur and hence a detachment from the substrate material must also occur. The erosive weight loss is strongly dependent on the component material. For the 12%Cr-steel the erosion loss is very high, higher than for Ti-6Al-4V, A286 or for an austenitic 18/8 steel. For A286 it could be shown further, that the erosion loss depends also upon the heat treatment condition (Fig. 17).

When components of titanium are peened with glass beads or steel shot, a strong spark formation, depending on the peening angle, is observed as is well known (Fig. 18). From this effect, it often was concluded that the impact energy of the shot was sufficiently high to liquify thin surface films. In order to study this phenomenon in more detail, the replica technique was used once more. Again the thin, heavily cold worked platelets without any sign of melting (see Fig. 16e,f) were found in the titanium surface. The observed spark formation, however, can be explained by an oxidation process of small titanium platelets and particles which are removed from the surface by erosion and abrasion. This fresh titanium surface of the erosion platelets is very reactive and oxidizes immediately. The steel shot reflected from the titanium substrate and the sparks formed are collected with an adhesive tape. In addition to the thin erosion platelets, also molten, rapidly solidified titanium particles in the shape of spheres with a diameter of 2-15μm are found. Using micro-analysis, it can be

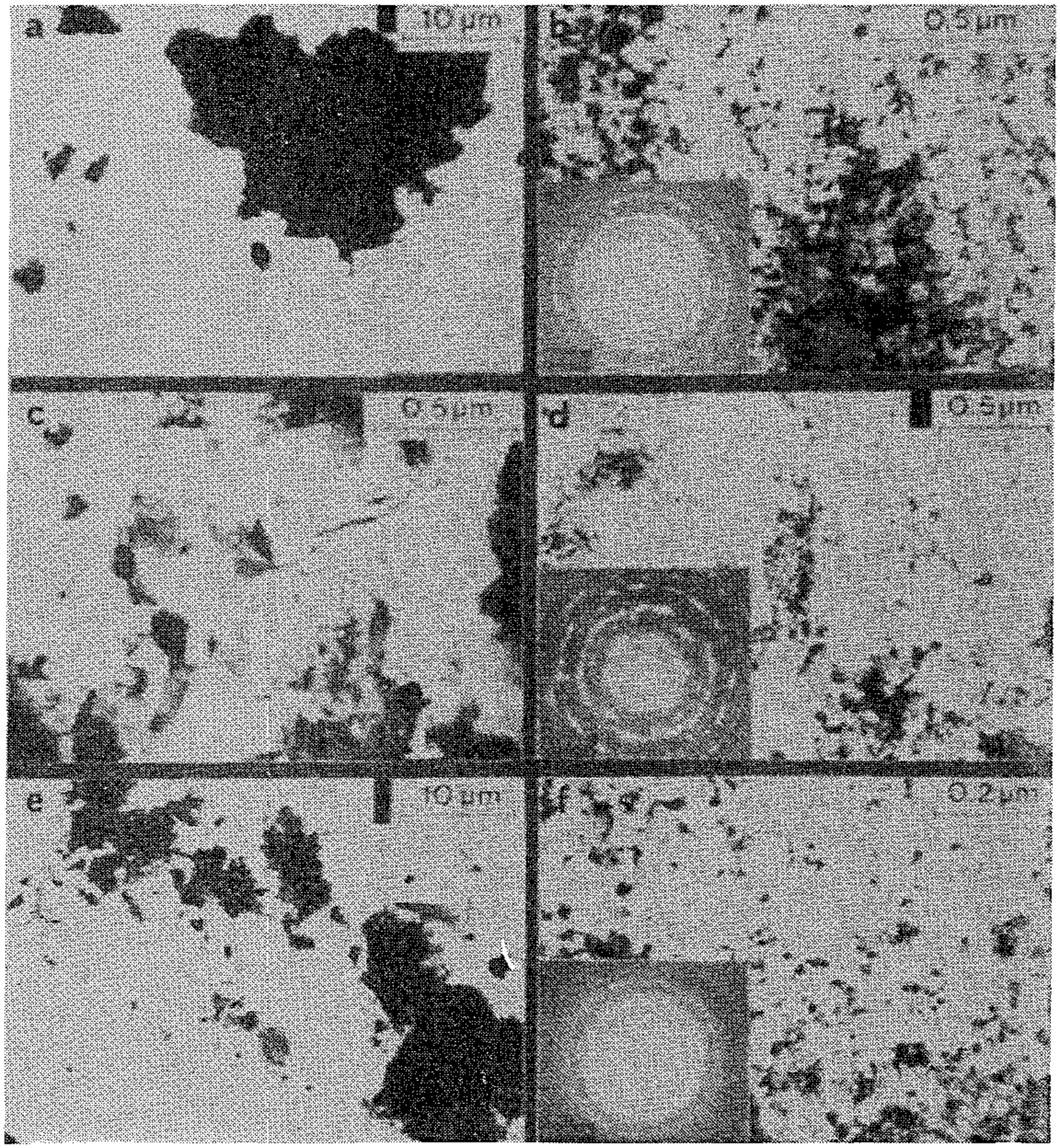
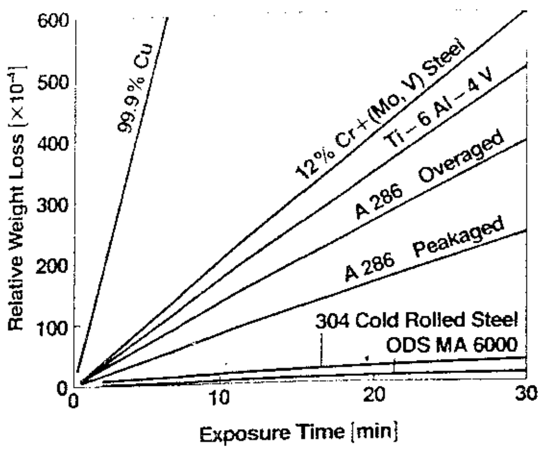


Fig. 16: Transmission electron microscopy of erosion debris and cold rolled material.
a-d) A286.
e-f) Ti-6Al-4V.



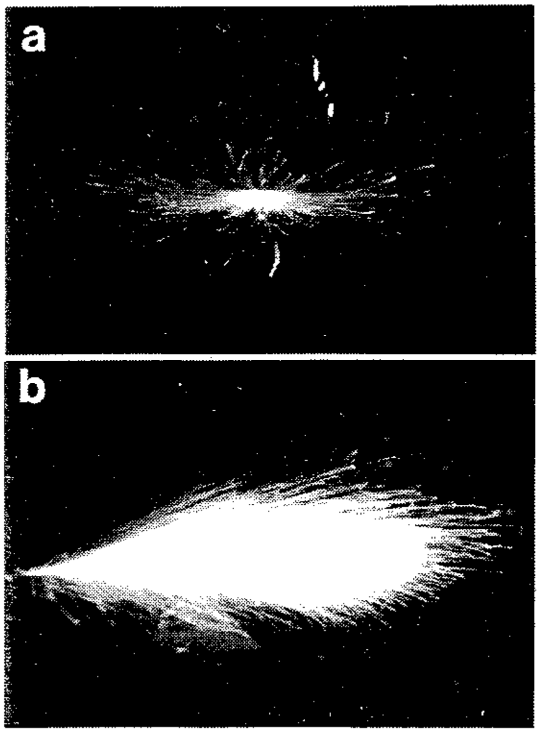


Fig. 17: Erosion weight loss for various turbine blade materials.

Fig. 18: Shot peening of titanium at a) 90° and b) at 30° impact angles (Exposure time 2 min.)

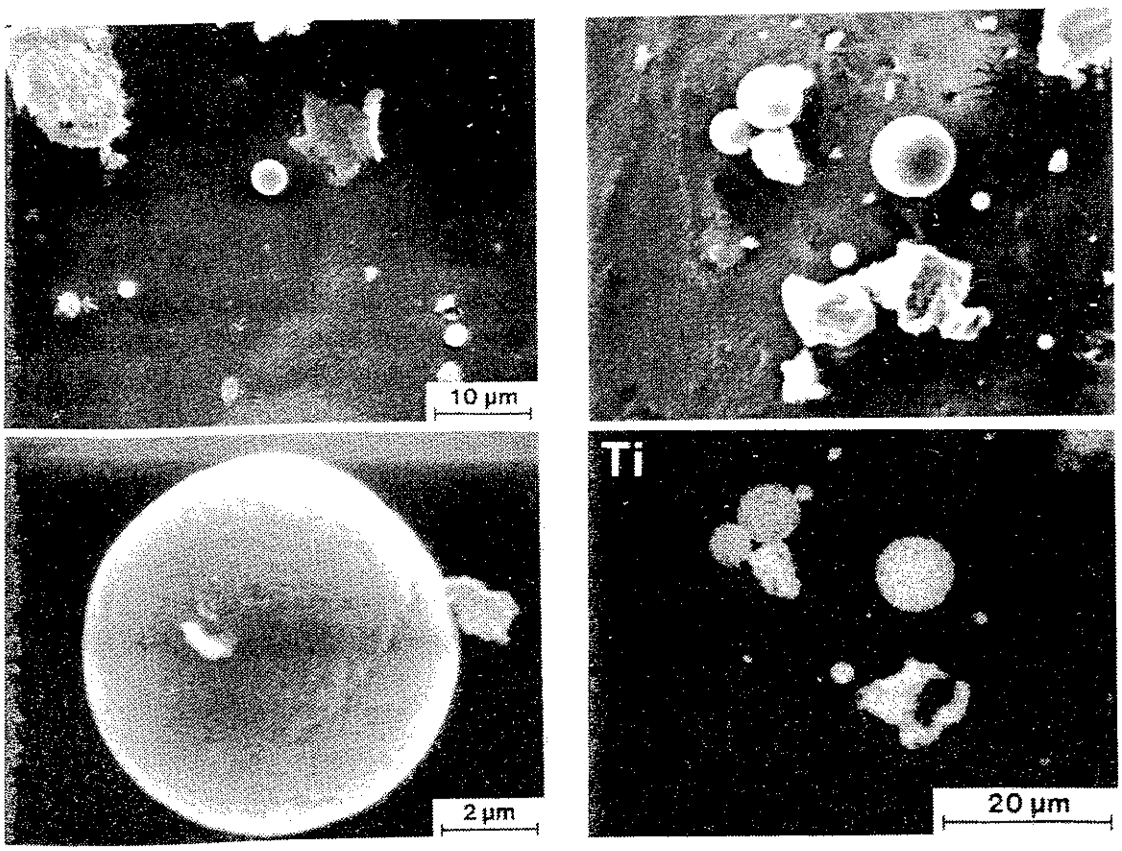


Fig. 19: Ti droplets and platelets after shot peening

proven that it really is titanium material (Fig. 19).

Besides the notches and overlaps, additional negative effects are produced by shot peening. For example, material from the steel shot can be transmitted to the component surface. If these impurities are not removed, undesired corrosion mechanisms can occur. In order to avoid contamination of titanium compressor blades with steel (galvanic local element iron-titanium) such components are either peened with glass beads only or peened over with glass beads for cleaning purpose after the peening with steel shot. However, as shown before, residues from the glass beads can also remain in the component surface (see Fig. 15). These residues from the peening shot, together with dirt from the shot peening machine, are embedded in the component surface. Therefore, a regular cleaning of the complete peening machine, the removal of dust and dirt as well as of broken, sharp shot particles from the peening process, is by all means necessary.

4. Fatigue Behaviour of Untreated and Shot Peened Specimens

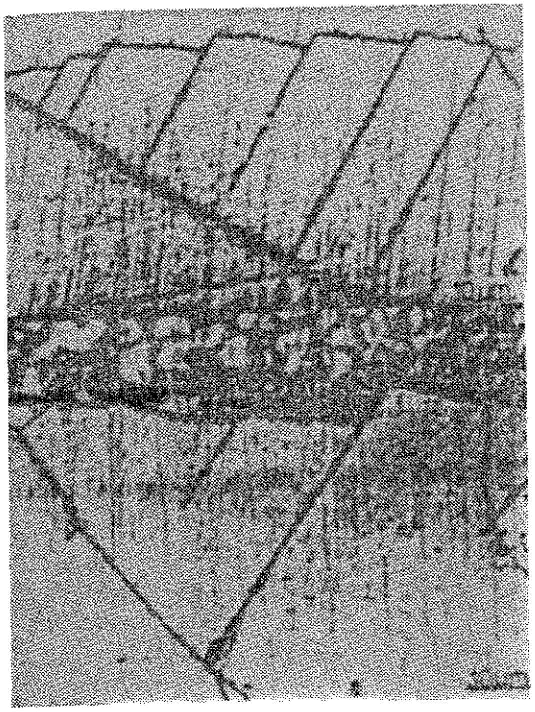
4.1 Influence of the Shot Peened Surface Zone

The total fatigue process of materials can be subdivided into 5 phases: cyclic hardening and/or softening, fatigue crack initiation, microcrack propagation, propagation of large cracks and final fracture. The number of cycles to failure, N_f is the sum of N_o, the number of cycles until the first crack appears (crack initiation), and the number of cycles N_p (crack propagation) up to final fracture. In the investigated model alloy A286 the first fatigue cracks were initiated at all stresses after less than 10% of the total number of cycles to failure N_f. More than ninety percent of the fatigue life is determined by the propagation of small microcracks in the surface. The fatigue cracks are formed at high, sharp slip steps in the surface (Fig. 20). Therefore, the shot peening treatment should be very promising for such a material because the initiation and propagation of small cracks can be strongly retarded by surface hardening and surface compressive residual stresses respectively. By microscopic investigations of fatigued specimens the following observations of the shot peened surface were made:

a) Significantly fewer fatigue cracks initiate than in the untreated substrate (Fig. 21).

b) The high fatigue slip steps do not occur (Fig. 22).

c) The cracks now form at overlaps or surface notches produced by



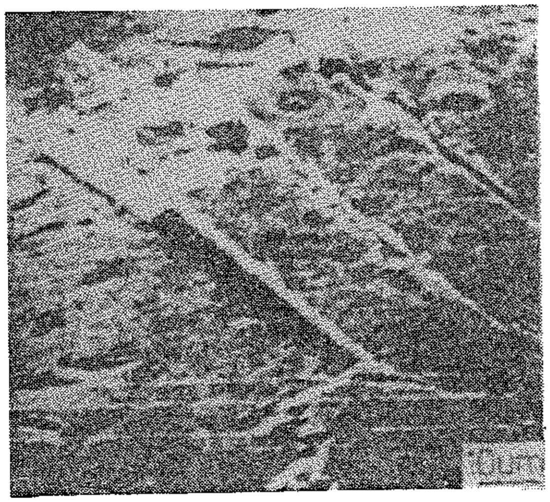


Fig. 20: Formation of fatigue cracks at high, sharp slip steps in the surface (electrolytically polished condition).

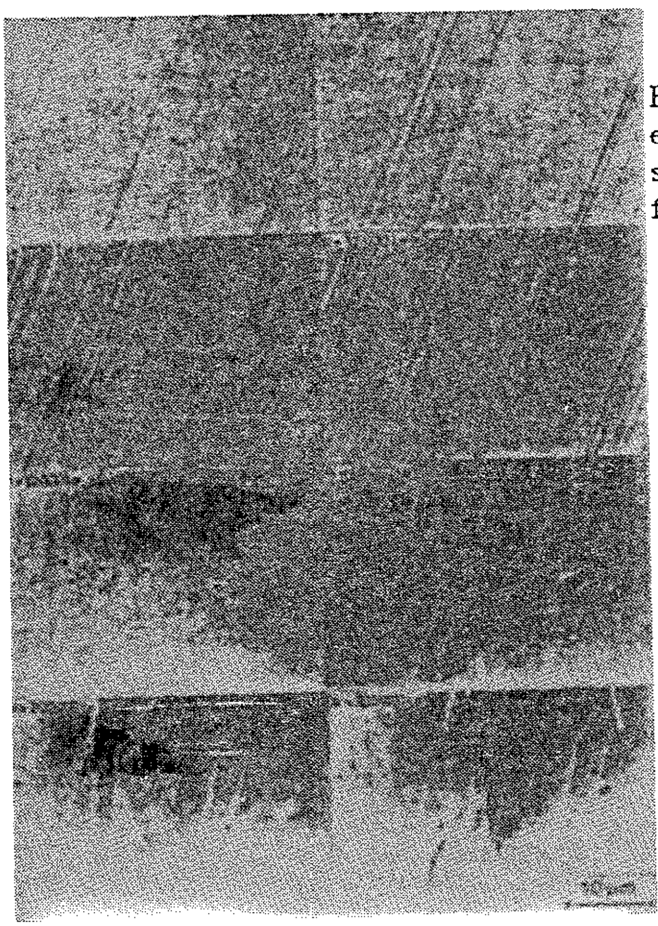


Fig. 21: Appearance of fatigued, electrolytically polished and shot peened surfaces after different numbers of cycles.

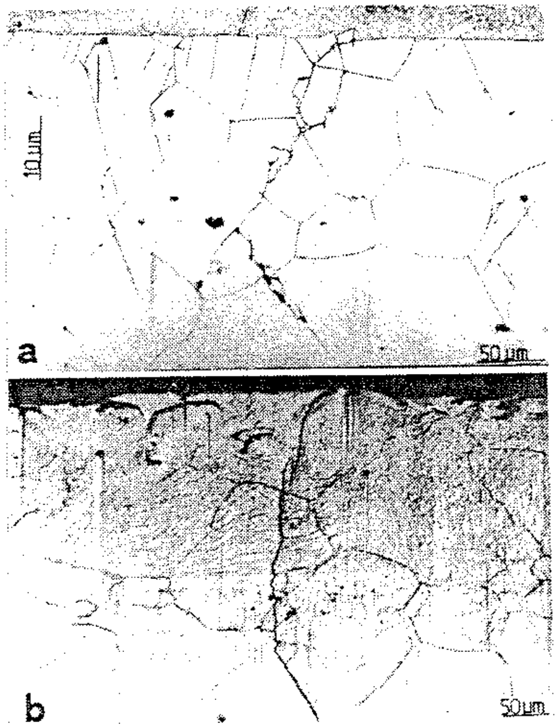


Fig. 22: Fatigue slip bands in a
a) electrolytically polished surface.
b) shot peened surface

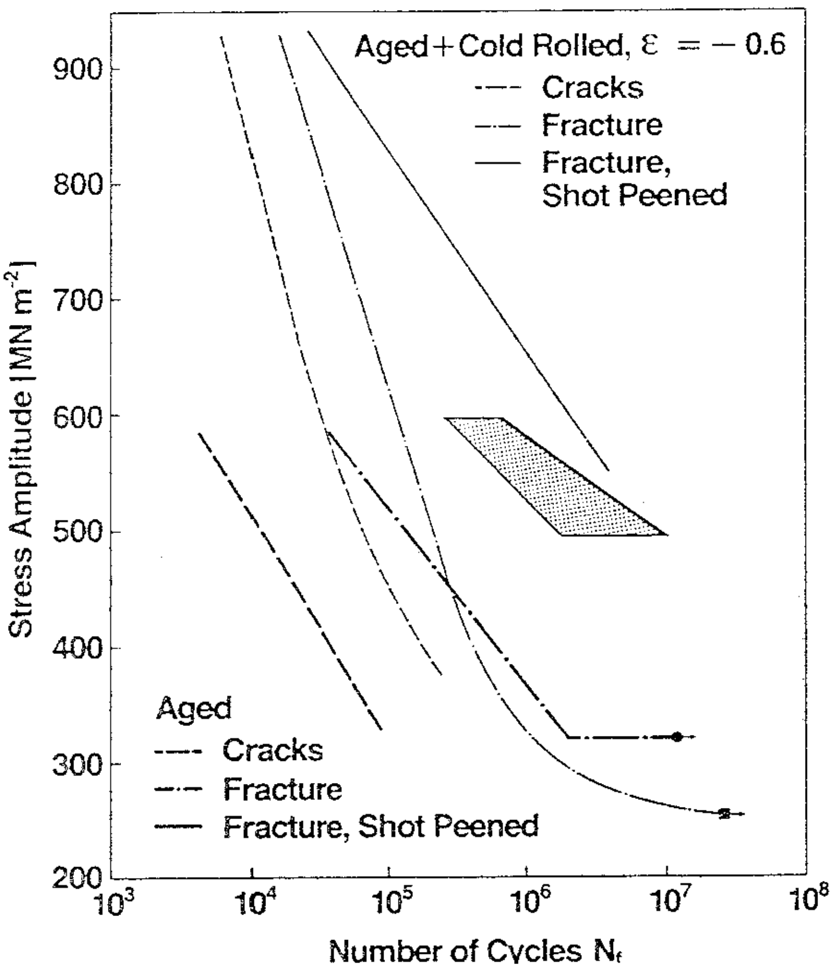


Fig. 23: Influence of cold rolling and shot peening on the fatigue strength of A286.

shot peening.

d) The number of cycles, N_O, until the first fatigue crack (>100 μm) is observed, is 50-80 times larger than in the untreated condition (depending on the stress). The number of cycles during crack propagation is about 30 times higher. Also, after the shot peening treatment the crack propagation determines the larger part of the total fatigue life.

e) Shot peening has a stronger effect under corrosive conditions for inhomogeneously deforming materials (materials with low stacking fault energy like austenitic steels, materials with high slip steps generated by dislocation pile-ups after cutting of precipitates) because the protecting passive films can no longer be damaged.

Based on these observations, the effect of the shot peening treatment on the fatigue strength of materials with medium strength and inhomogeneous slip distribution can be explained as follows:

By shot peening a high plastic deformation is produced in the substrate surface. In the outermost surface zone a degree of deformation of more than 95% is observed in A286. This degree of deformation reduces to zero at a depth of about 300μm in the untreated material depending on the shot intensity. This highly cold worked surface zone shows a more homogenous deformation behaviour under fatigue loading than the untreated material. The fatigue slip bands pile-up now against the cold worked surface zone from underneath and react with it. Therefore, the originally very inhomogeneous slip distribution becomes more uniform. High slip steps are prevented and thus no high notch stresses can occur. Because of the reduction of fatigue slip steps, the crack initiation is strongly retarded. However, if a crack is still formed in the surface, it can propagate only slowly or not at all due to the high compressive residual stresses /4/. These compressive residual stresses act like a shift of the mean stress level and therefore reduce the stress ratio R to lower values /5/. As is well known, the propagation of the fatigue cracks is mostly slower at lower R-values than at higher R-values. In addition, the threshold value ΔK_{th}, below which no fatigue crack growth occurs, is normally raised by the reduction of the R-value. This depends to a great extent on crack closure and mean stress effects.

The microscopic investigations show that the fatigue crack formation in a shot peened, cold worked surface starts later than in the inhomogeneously deforming, untreated surface. Therefore, it is logical not only to harden the surface but also to produce a cold worked, homogeneously deforming microstructure across the whole cross section. This idea is investigated later in more detail. In comparison to the inhomogeneously deforming untreated specimens, a strong increase of the number of cycles until first crack initiation is found due to the homogenization of deformation (comparison at the same cyclic stress amplitude, see Fig. 23). Now the cracks no longer form at high slip steps but at inclusions in the surface (Fig. 24). Although the number of cycles until final fracture is higher at high and very high stress amplitudes (due to increase of the yield strength by cold rolling) than in the untreated materials, the fatigue strength limit is lowered. This effect can be explained by the assumption that the few cracks formed in the cold rolled material have a higher stress intensity compared to the many cracks formed in the untreated material and that the crack propagation rate of the homogeneously deforming, cold rolled material is higher. This is demonstrated in Fig. 25. The crack propagation rate da/dN was measured on fracture mechanics specimens (SEN-specimens, Single Edge Notched) and plotted as a function of the stress intensity range ΔK. With increasing degree of cold rolling, and accordingly increasing homogenization of the slip distribution, the crack propagation rate increases strongly at the same ΔK-value. (Aged condition = inhomogeneous : cutting of γ'-particles. Overaged condition = by-passing of γ'-particles. Aged and cold rolled = homogeneous: sharp slip steps are no longer formed due to the many active slip systems). Whereas the inhomogeneously deforming condition shows a very fissured fracture surface, the surface of the homogeneously deforming specimens is very smooth (Fig. 26). The slower crack propagation rate of the aged condition can be explained by the model of Hornbogen and Zum Gahr stating that a given number of dislocations can slide back during each cycle (slip reversibility) in those sharp slip bands, thereby reducing the overall crack growth rate /6/.

Based on these results the microstructure of a component with optimum fatigue strength can be defined as follows:

a) A homogeneously deforming (cold worked by shot peening) surface zone with retarded crack formation.
b) Compressive residual stresses, to drastically reduce the faster crack propagation rate of the homogeneously deforming surface zone.
c) Inhomogeneously deforming, undeformed condition, in the component interior with the corresponding lower crack propagation rate due to the slip reversibility.

When untreated and cold rolled specimens are shot peened, both material conditions reach about the same fatigue limit. Due to the shot peening in the cold rolled condition, the crack propagation rate is more retarded by the compressive residual stresses. In comparison, the crack initiation is

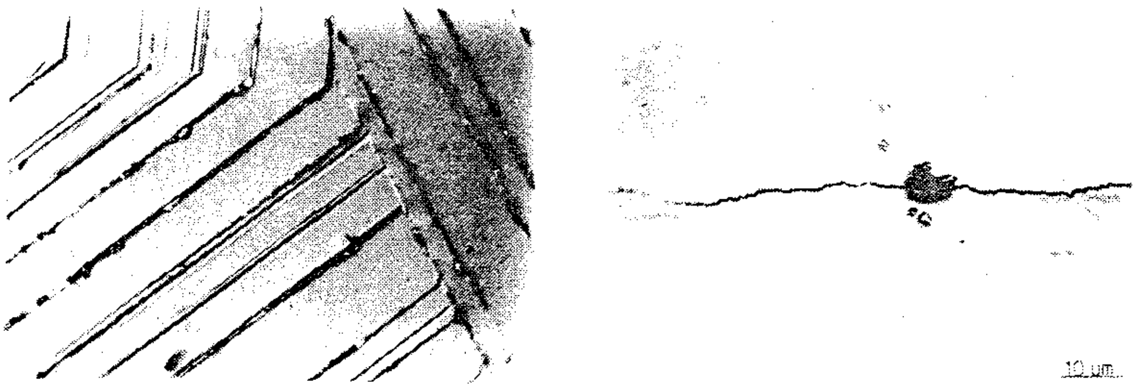


Fig. 24: Fatigue crack initiation of A286 in a
a) polished surface (at slip steps).
b) cold rolled surface (at inclusions).

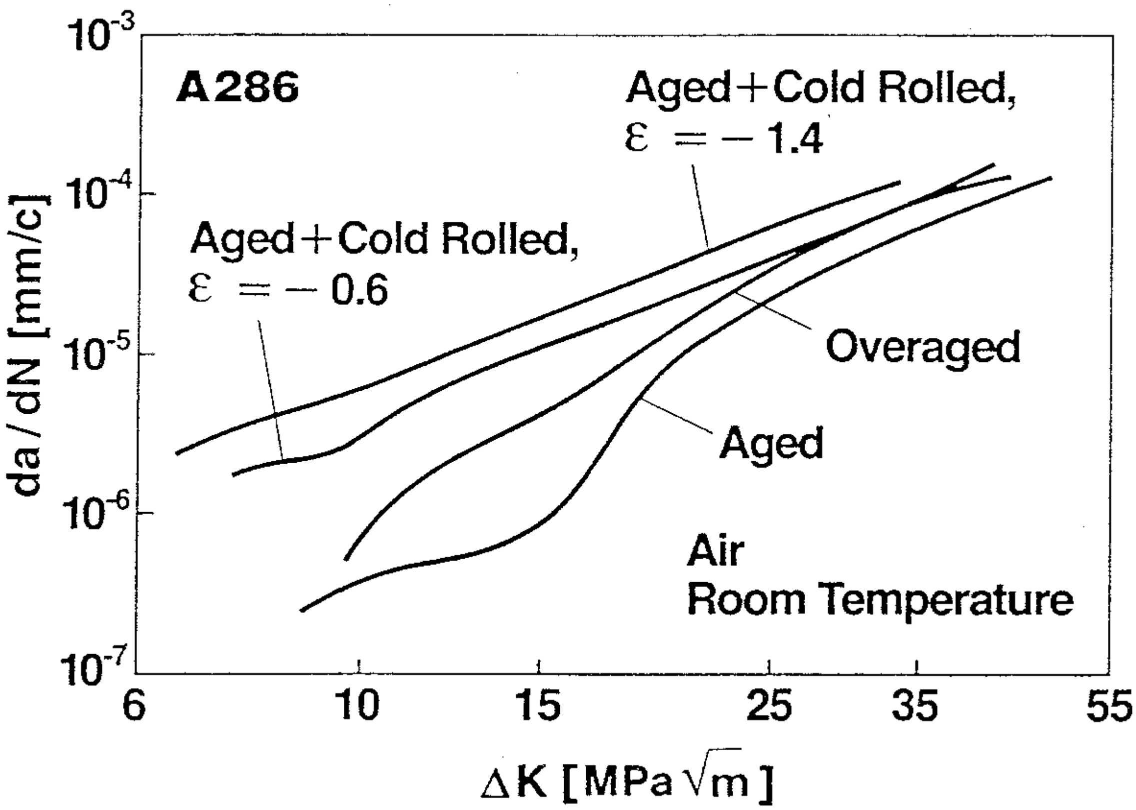


Fig. 25: Fatigue crack propagation rate for different conditions of A286.

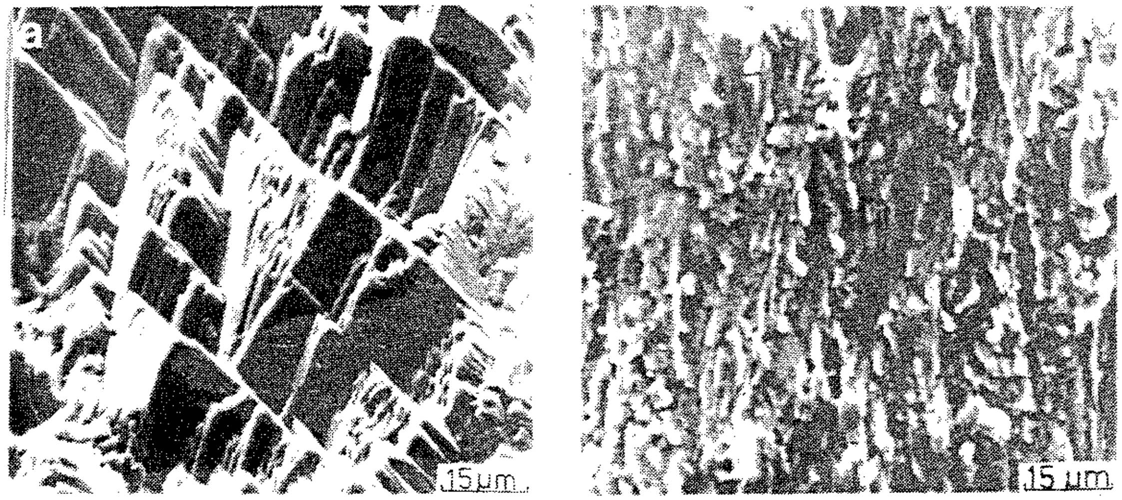


Fig. 26: Fracture surfaces of fatigued A286.
a) homogeneous slip distribution (overaged).
b) inhomogeneous slip distribution (aged).

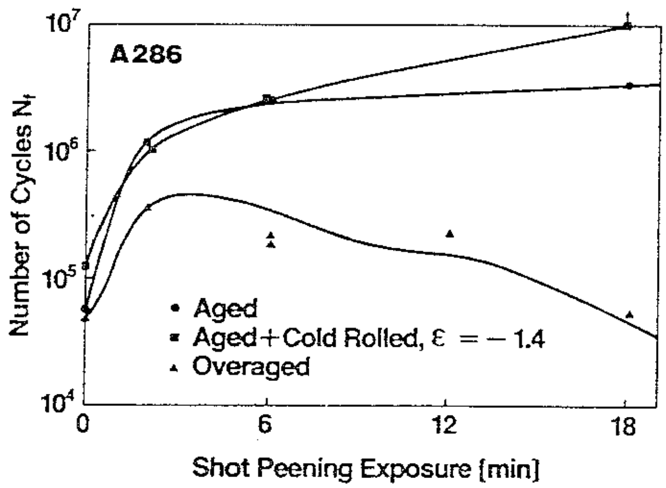


Fig. 27: Influence of shot peening time on the fatigue life of A286 (σ_a= 550 MPa; f= 25 Hz; air).

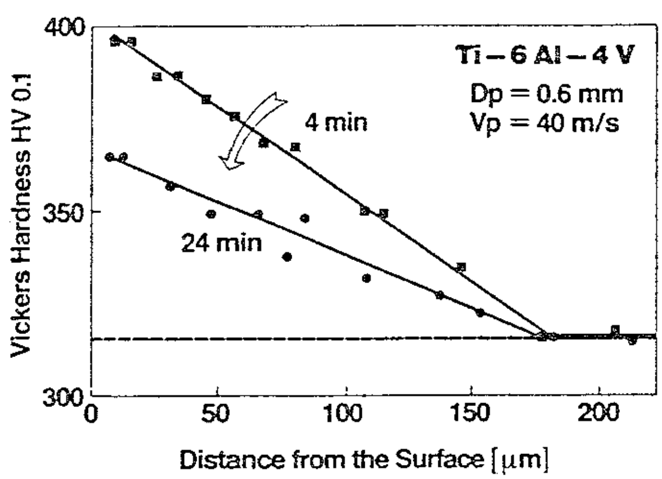


Fig. 28: Microhardness profile in the surface layer after shot peening for different peening times /17/.

more retarded by the homogenization of surface slip behaviour in the untreated condition.

Quite a number of experiments have been carried out in order to separate the influence of cold work vs. residual stresses. Such experiments are complicated by the fact that the residual stresses can be reduced by the cyclic loading, particularly for higher stacking fault energy materials (easy cross slip of dislocations) and applied test stresses /7-10/. Generalizing, it can be concluded for shot peening that the acquired fatigue strength for steels with lower strength can be almost exclusively attributed to the work hardening; for steels with medium strength, equally attributed to work hardening and compressive residual stresses; and for high strength steels, exclusively attributed to the compressive residual stresses /11/.

It is often observed for shot peened components that during fatigue loading, cracks are formed beneath the surface. In this case, surface micro-cracks cannot propagate due to the high compressive residual stresses and an early crack initiation occurs in the region of tensile residual stresses (about 300μm below the surface). In this region below the surface the local fatigue limit of the material is exceeded and thus crack initiation and crack propagation can occur. This mechanism is observed when neither a steep stress gradient nor a corrosive medium favours the crack initiation and propagation from the surface /12,13/. The crack propagation starts on the one hand in the direction of the shot peened surface zone, that is a zone with increasing compressive residual stresses, and on the other hand, in the direction of the component interior towards falling tensile residual stresses. Until the moment the crack reaches the surface the crack propagation in the material occurs under vacuum conditions. For some applications such a shift of the crack initiation location under the material surface can therefore be favourable for the complete fatigue life of components because the crack propagation rate in vacuum can be several orders of magnitude lower than in corrosive medium (or air).

4.2 Overpeening Effect

The negative effect of excessively long peening times on the fatigue strength (overpeening) should be discussed. By overpeening, the fatigue strength decreases with increasing shot peening-time /14-16/. In Fig. 27 the number of cycles to failure is plotted as a function of the shot peening-time. In order to study the mechanism in detail, very long peening times were used. The fatigue specimens (A286) were investigated in rotating bending fatigue tests (σ = 550 MPa, f = 25Hz, air). Three different heat treatments, that showed about the same yield strength and the same fatigue strength in the untreated condition were compared . The aged and the aged plus cold rolled condition show a strong increase in the number of cycles to failure which goes into saturation after 6 minutes of peening. In the overaged condition (400h, 775°C), however, the fatigue limit decreases with increasing peening time. Metallographically, it was noticed that embrittled grain boundaries were cracked by the shot peening treatment so that a damaged surface zone with microcracks was present after peening. For materials showing the overpeening effect, that is for materials in which damage is induced by shot peening, the peening parameters have to be carefully selected. Possible damage mechanisms leading to the overpeening effect are: crack initiation at grain boundaries, crack formation at brittle carbides and inclusions in the surface zone, as well as softening of the surface zone in materials (titanium, hardened steels) that show cyclic softening (Fig. 28) /17/.

On the other hand, it becomes clear from these experiments that the cracks generated can propagate only slowly and thus, despite the damage, a small increase in fatigue life in comparison to the untreated material can be observed. However, for notch sensitive materials the fatigue strength of shot peened specimens can be lower than in the untreated condition if the damage by deep surface notches or cracks is larger than the beneficial effect of work hardening and compressive residual stresses together.

4.3 Surface Finish After Shot Peening

In many cases, a so-called vibration grinding is used in practical application in order to reduce the average roughness and to remove the roughness peaks. To fulfil the aerodynamic demands of shot peened turbine and compressor blades, the vibration grinding is quite often indispensable if the blades are not also protected by corrosion resistant coatings. During vibration grinding, the shot peened parts are abrasively smoothed by ceramic grinding cones in vibrating containers (Fig. 29). The surface peaks are removed and are to some extent squeezed into the roughness valleys (Fig. 30). Although the average roughness is hereby reduced, the fatigue strength is not necessarily increased but can even be decreased due to additional overlaps and flaws. In no way can the deep surface notches (up to 30µm deep), overlaps and furrows be removed. Thus the influence on the fatigue strength of the blades has to be checked from case to case.

In addition, the effect of subsequent electrolytic polishing on the fatigue life of shot peened specimens of A286 was investigated. By electrolytic polishing, the notches, overlaps and roughnesses produced by peening are removed. This removal of surface material occurs not abrasively as in vibration grinding but totally deformation-free by the electrochemical reactions in an electrolytic solution. As shown in Fig. 31, after about

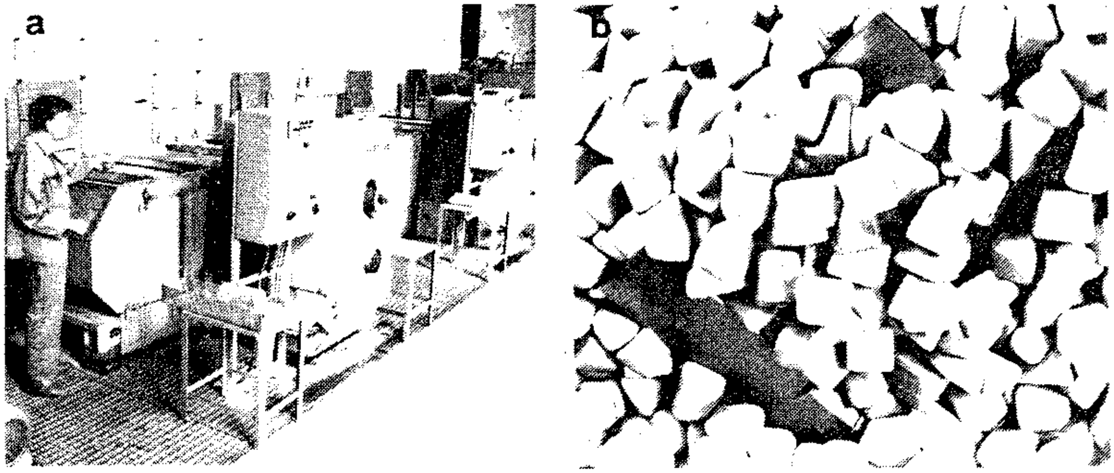


Fig. 29: Vibration grinding
a) facility.
b) ceramic grinding cones and blades.

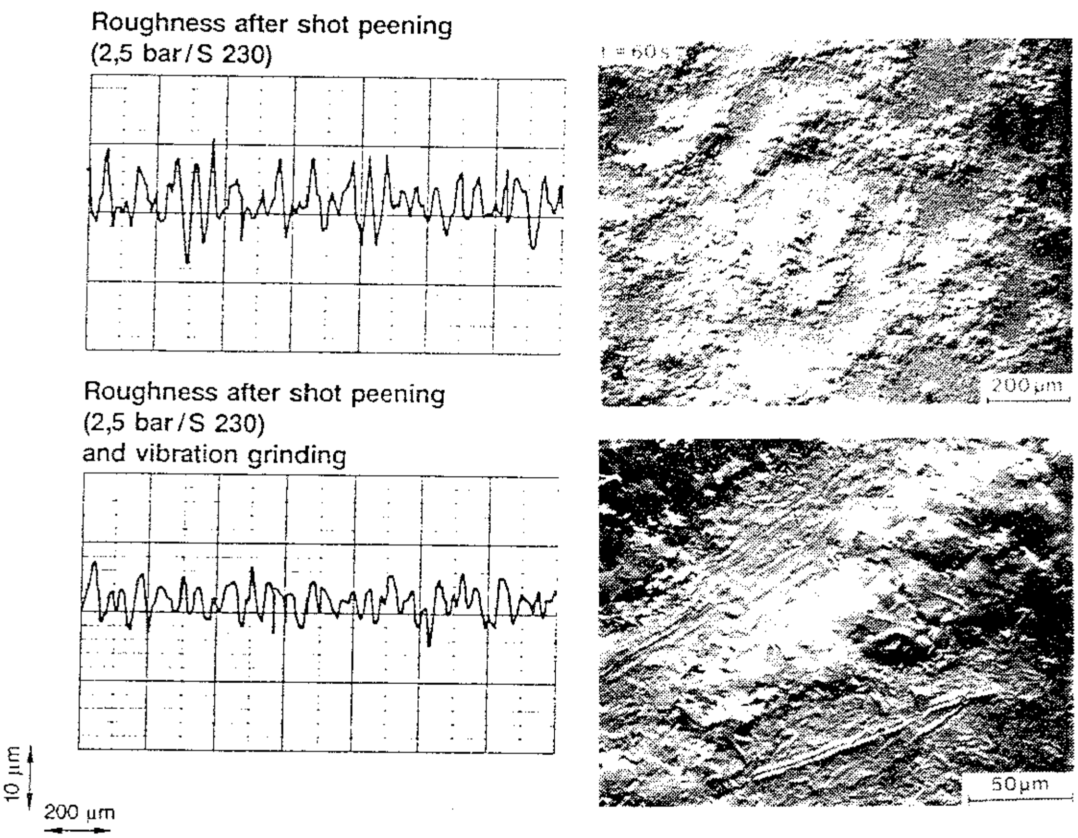


Fig. 30: Influence of vibration grinding on the roughness of a shot peened surface.

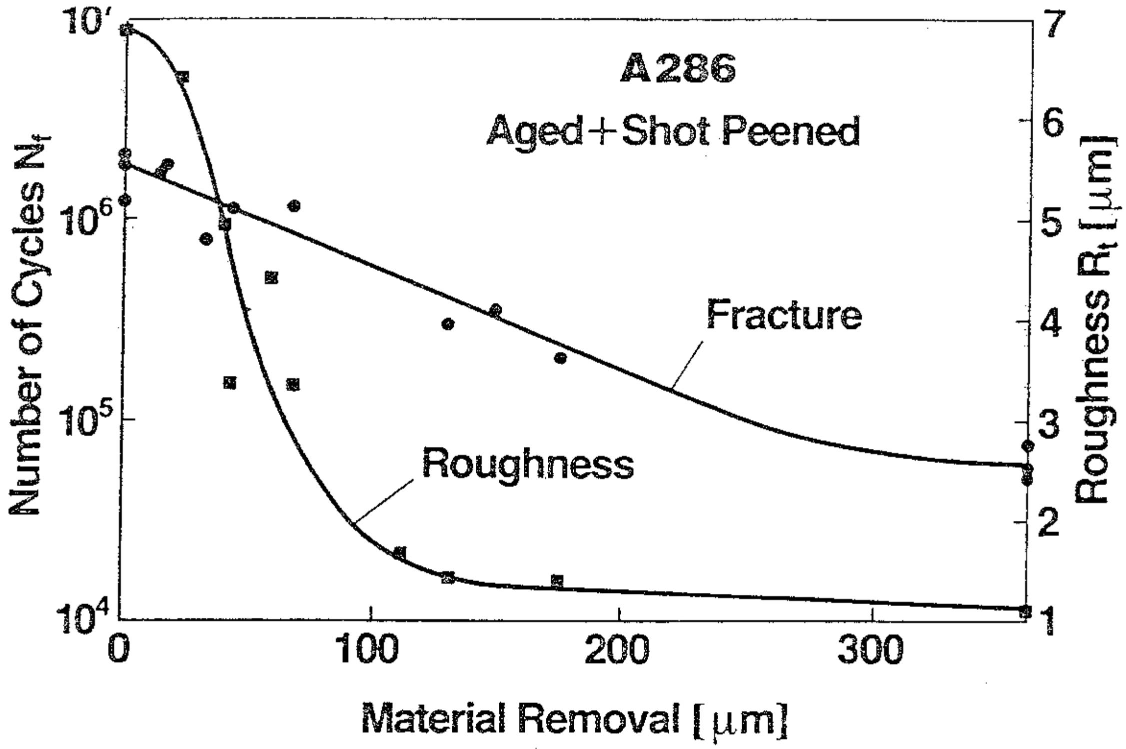


Fig. 31: Influence of surface material removal on the roughness and number of cycles to failure of shot peened A286 (σ_a= 550 MPa, f= 25 Hz, air, R= -1)

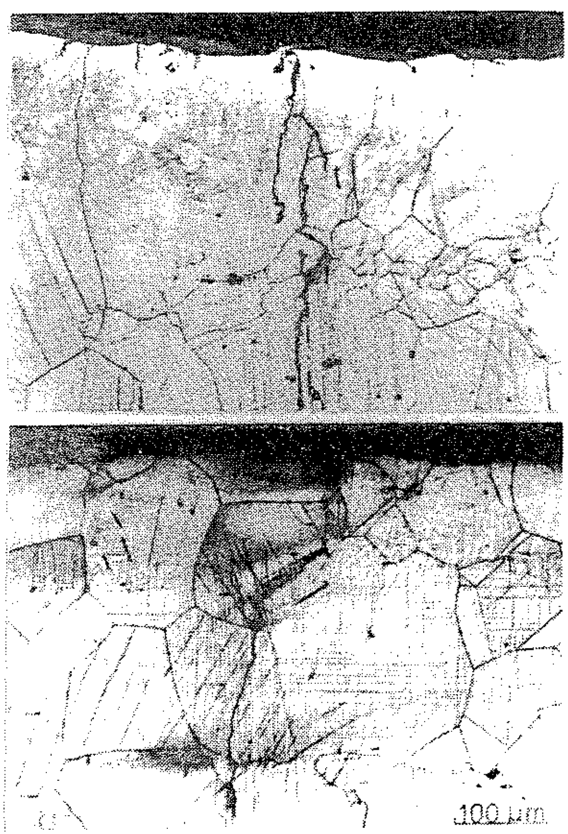


Fig. 32: Influence of material removal on the deformation behaviour of shot peened surface layer (A286)

100-200μm material removal, the roughness of the unpeened condition is reached again. Against this beneficial effect stands the fact that already after removal of 100-200μm material the work hardened zone is removed to such an extent that the fatigue slip bands for the austenitic material tested can reach the surface again and lead to sharp slip steps (Fig. 32). After polishing away only 50μm material the roughness increase from shot peening is reduced to half whereas the number of cycles to failure at the same stress level decreases only from about $2x10^6$ to $9x10^5$ cycles (unpeened $9x10^4$ cycles). In the literature it was reported for Ti-6Al-4V that after removing 20μm material a higher fatigue life was measured because on the one hand the damaged surface notches and overlaps (crack nuclei) are removed and thereby the maximum compressive residual stress (about 20-50μm below the shot peened surface depending on the peening conditions) is shifted out to the surface /17/. The electrolytic polishing can have a beneficial effect for example for medical implants, for turbine blades and other parts with critical surface demands, because not only roughnesses and notches but also embedded foreign material like dirt, glass or steel particles from the shot as well as the erosively formed thin platelets can be removed (Fig. 33).

For shot peening of critical components where surface contamination and embedding of shot material should be avoided there is a new technique evolving: shot peening with water droplets. As is indicated schematically in Fig. 34 the impact by solid shot leads on the positive side to improved fatigue properties and on the negative side to solid particle erosion as discussed above. The negative effect of liquid impact is well known for example as rain erosion on aircraft wings or as water droplet erosion in steam turbine blades. However, it is only recently that the positive effect of liquid impact has drawn attention /18/. In Fig. 35 a typical water droplet erosion curve is plotted: the erosion starts after a material and velocity related incubation period and then continues with a constant material loss rate. During the incubation period, however, compressive residual stresses are produced by the impacting droplets. Upon impact of a liquid drop (Fig. 36) shock waves with a high velocity (proportional to the acoustic wave velocity in water) are produced at the contact area. The short high pressure pulse, known as "water hammer pressure", is sufficient to cause local plastic deformation thereby generating compressive residual stresses upon impact. The details of liquid impact are described in the article of J.E. Field and I.M. Hutchings /19/. There are two practical possibilities for water jet peening: either a high pressure water jet is chopped into many droplets or short water cylinders /18/ or, single water droplets are accelerated by compressed air /20/ or by a centrifugal wheel to high velocities. It was shown that water jet peening for 60s duration increased the fatigue life of ferritic steel samples significantly /18/. Water droplet peening tests with the MIJA (Multiple Impact Jet Apparatus) showed that

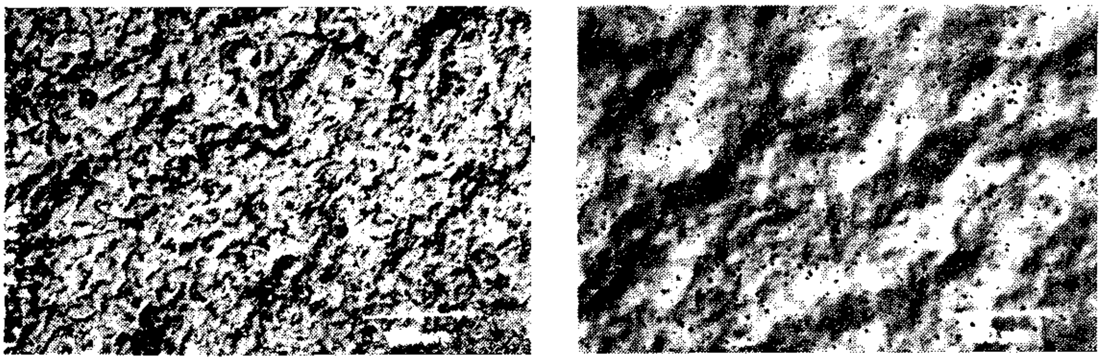


Fig. 33: Appearance of shot peened surface after material removal by electrolytical polishing (5 µm and 20 µm).

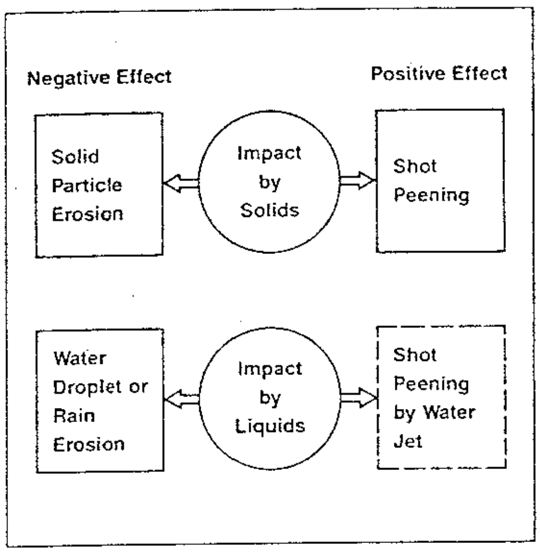


Fig. 34: Positive and negative effects of solid and liquid impact.

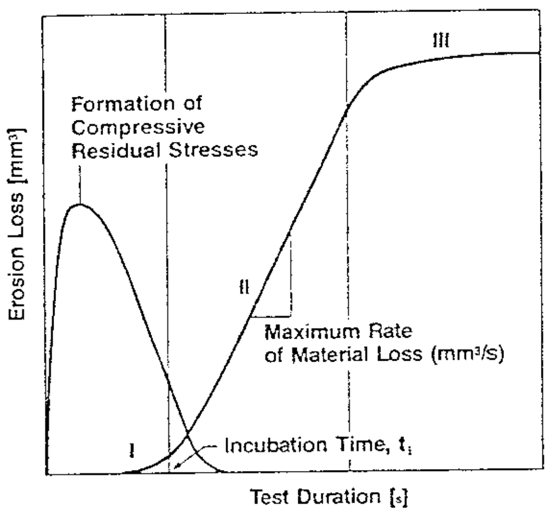


Fig. 35: Water droplet erosion and formation of compressive residual stresses.

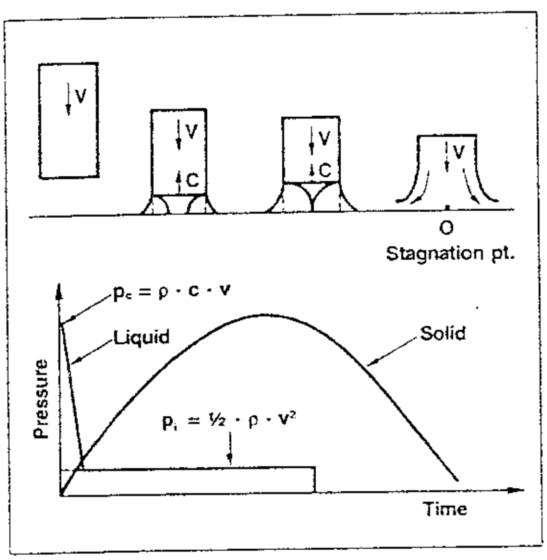


Fig. 36: Basic mechanisms of water droplet impact of high velocity, after J.E. Field /19/.

compressive stresses can be produced at impact velocities above 700 m/s /21/. Water peening with pressures of 300 to 2400 bar did not produce beneficial effects if a continuous water jet was used. Further research work and practical testing is necessary for this new technique. An additional aspect in favour of using water is that it is a clean, cheap and healthy working media that can easily be recycled and reused.

4.4 Numerical Approach

Other service-related questions on the optimum shot peening treatment of components that contain surface flaws and microcracks will be discussed briefly. Important components like turbine blades are examined before the shot peening treatment by ultrasonic, eddy current and dye penetration techniques in order to detect existing cracks, forging defects or grinding cracks. However, it has to be assumed that defects may not be detected or that micro-cracks exist with a length below the resolution of non-destructive testing. Therefore, using a two dimensional model the stress intensity factors that build up at potential crack tips were determined under the applied external stress and the existing internal compressive residual stress /22/. In a 12%-Cr steel, two different distributions of residual stresses by different peening conditions were produced: for the residual stress profile I the maximum value of compressive residual stress was located on the surface, whereas for profile II a broader profile is produced by a higher peening intensity, with a maximum about 50μm below the shot peened surface (Fig. 37). Fig. 38 shows how the range of the stress intensity factor ΔK increases with increasing crack length. However, due to the compressive residual stress profiles, the effective intensity factor at the crack tip is strongly reduced. With these stress intensity factors the number of cycles for the fatigue growth of a small crack were calculated by integration of the crack propagation rate/stress intensity amplitude curve (Paris-law). It was found that the increase in fatigue life due to the compressive residual stresses is very high. Owing to the compressive residual stresses a 150 or 6'000 times higher fatigue life is obtained for profiles I and II respectively. As is obvious from Fig. 39, at small crack lengths a profile I with the maximum compressive residual stresses at the surface of a cracked component is more beneficial than a profile II with the maximum compressive residual stresses below the surface. For longer cracks a broader profile is more beneficial. Therefore a most intensive peening treatment with a maximum compressive residual stress below the surface would be recommended for components in which cracks or small surface flaws must be assumed. These imperfections can be production defects as well as non-detectable or overlooked cracks. This is also true for service-exposed turbine blades which are to be reconditioned after fixed service intervals and have to be shot peened again. For

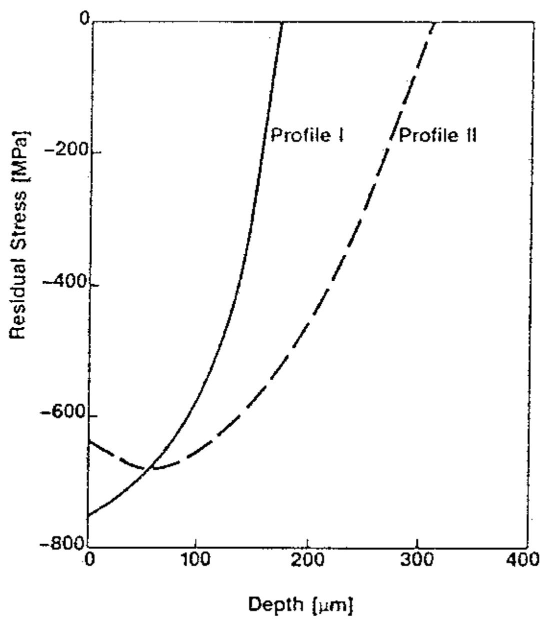


Fig. 37: Different simulated residual stress profiles in the surface layer.

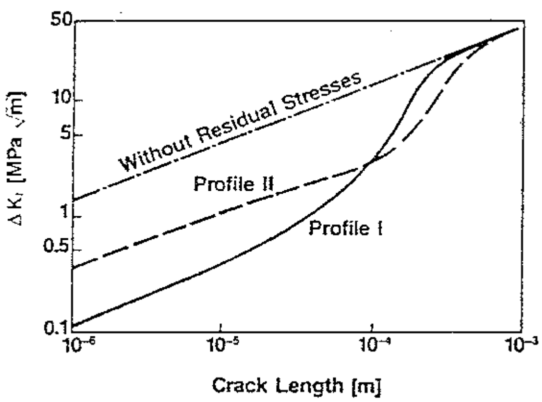


Fig. 38: Dependence of calculated ranges of stress intensities ΔK on simulated residual stress profiles.

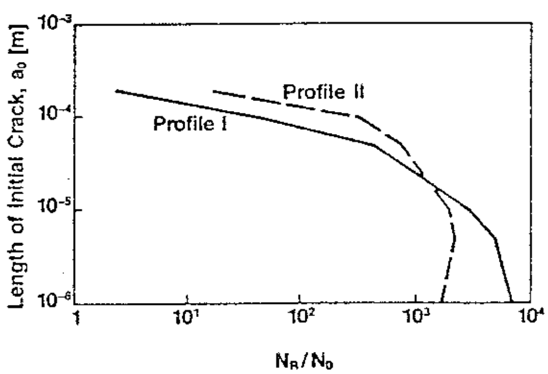


Fig. 39: Increase in fatigue life as a function of starter crack length and the residual stress profile.

NR: fatigue life with residual stress.

NO: fatigue life without residual stress.

crack-free components, however, the shot peening treatment should be chosen in such a way that the maximum compressive residual stress can be produced on the surface. For this case Fig. 40 shows how the stress intensity range increases with depth of penetration for a constant mean stress of 300 MPa and two values of stress amplitudes, namely +/- 75 MPa and +/- 150 MPa /23/. These ΔK values are compared with the threshold value (ΔK_{th}) which would be expected at different locations below the surface of peened and unpeened specimens. The threshold ΔK_{th} is independent of depth in the unpeened samples and also at a depth above 0.4 mm in the peened condition. However, ΔK_{th} increases below the surface of peened samples as a result of the compressive residual stresses which reduce the mean tensile stress arising from the centrifugal force on the blade.

However, the numerical approach to the propagation of surface cracks under this influence of superimposed internal and external stresses is not used to the design shot peened components because the numerical model uses many simplifying assumptions deviating from reality. For example, all calculations were conducted for a plate with a microcrack assuming linear-elastic behaviour. The validity of the Paris-law for the calculation of the crack propagation rate of surface cracks at low ΔK-values is an additional assumption that had been made to obtain a rough estimation of the fatigue life. From many publications, however, it is well known, that cracks with low ΔK-values and especially small surface cracks show a different crack propagation rate that cannot be described with the Paris-equation found with long cracks /24,25/. Small-crack-propagation has to be measured since it cannot be calculated from long-crack-data. In addition, the fact that the crack propagation rate in cold worked material (without residual stresses) increases, was not considered /26/.

5. Influence of Corrosive Environment on Shot Peened Components

As already mentioned in chapter 4, after shot peening of materials with originally very inhomogeneous deformation behaviour a more homogeneous deformation behaviour in the surface zone and therefore a reduction of the rupture of passive layers is found. Due to this effect, the corrosion resistance under static loading of a component (stress corrosion cracking) as well as under cyclic loading (corrosion fatigue) is improved /27-30/. In Fig. 41 is an example showing the improvement due to shot peening of the fatigue strength of a duplex steel. While the fatigue strength in air increases only about 7%, an improvement of about 70% is found in a corrosive NaCl-solution in comparison to the untreated, electrolytically polished condition /31/. In Fig. 42 the effect of a shot peening treatment in tests under corrosive environment is shown schematically.

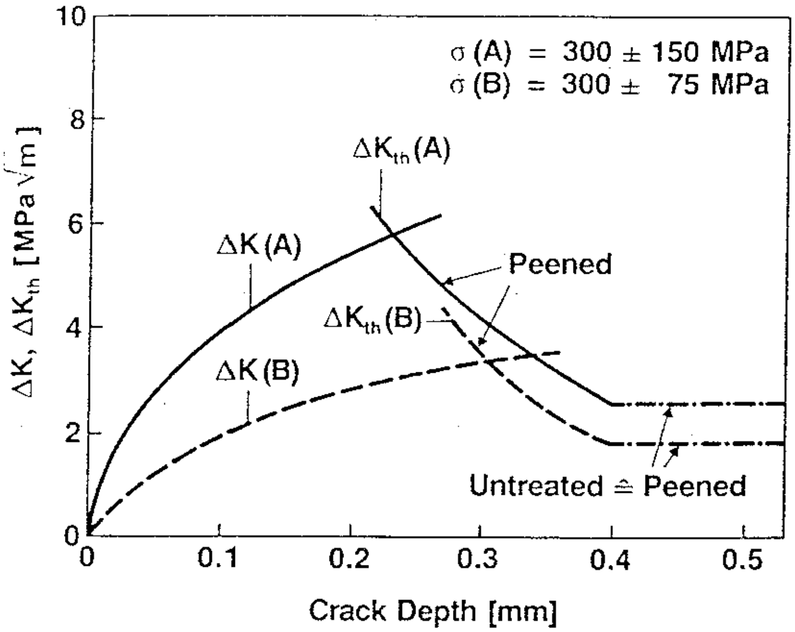


Fig. 40: Stress intensity (ΔK) and threshold stress intensity values (ΔK th) for shot-peened and untreated samples as a function of crack depth.

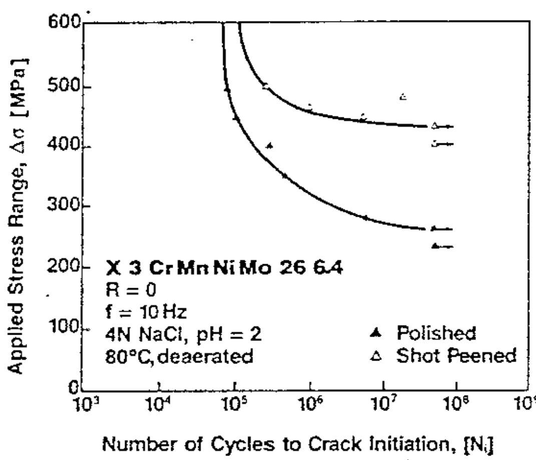


Fig. 41: SN-curves for polished and shot peened specimens tested in corrosive environment

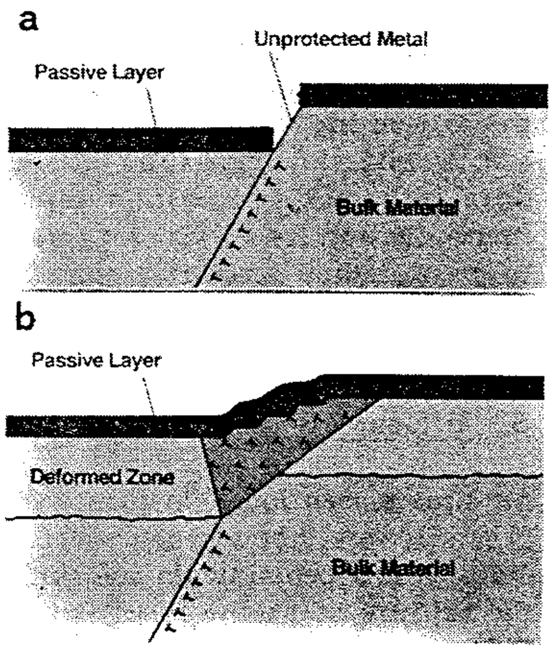


Fig. 42: Influence of shot peening on corrosion fatigue crack initiation (schematic)

a) unpeened: passive layer rapture
b) shot peened: finer slip distribution

An improvement of fatigue life, however, is only observed if during *corrosion fatigue* loading the damage occurs along slip band cracks. Often another type of corrosion occurs in steam turbine blades or compressor blades in gas turbine. That is the formation of so-called etch pits (pitting corrosion). At the intake of a compressor, for example, condensate can be formed with impurities from the surrounding air. This kind of corrosion cannot be prevented by shot peening. It can in contrast rather be accelerated because the etch pits can form preferentially at imperfections in the surface such as notches, scratches and overlaps. For a 12%Cr-steel in hot, oxygen-enriched salt water no detectable increase of the fatigue strength could be obtained, see Fig. 43 /32/. As shown in Fig. 44, the etch pits grow in depth through the surface zone and a crack tip formed would lie in the region of tensile residual stresses. The electrochemical dissolution process is thereby accelerated further. This kind of corrosion can only be prevented by protecting the shot peened blades with a corrosion resistant coating. Nickel-cadmium or aluminium-containing coatings are used. Aluminium coatings act as a sacrificial material and dissolve preferentially if any damage of the corrosion resistant coating occurs. Under severe pitting corrosion conditions the 12% Cr-steel is often replaced by less susceptible titanium alloys.

In addition, the effect of shot peening under hydrogen embrittlement conditions has been investigated. Material damage can occur by external hydrogen gas, for example in hydrogen cooled generators, or by internal hydrogen gas via cathodic charging from electrochemical reactions. Steels and nickel alloys are known for this embrittlement mechanism that often is difficult to detect. Under the influence of hydrogen, a grain boundary embrittlement and an intercrystalline fracture with strongly reduced ductility is observed. When untreated and shot peened nickel specimens are charged with hydrogen, no improvement due to shot peening is found in tensile testing. The grain boundary fracture still occurs. However, in high cycle fatigue (HCF) tests it was found that the compressive residual stresses lead to a strong increase in fatigue life for specimens under the effect of external and internal hydrogen /33,34/. At an applied stress of 180 MPa in a hydrogen atmosphere the untreated specimens failed after about 2'000 cycles whereas the shot peened specimens lasted more than 800'000 cycles (Fig. 45). However, if the tests were conducted under fatigue conditions with high plastic strain amplitudes (LCF-test), the beneficial compressive residual stresses would be easily reduced by the high plastic deformation and no improvement of the fatigue life by shot peening could be obtained.

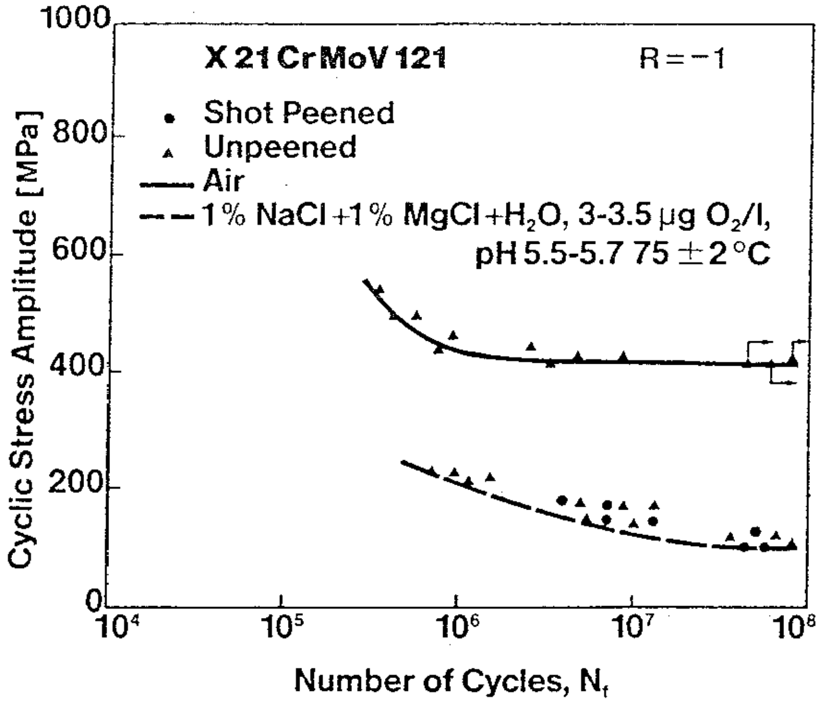
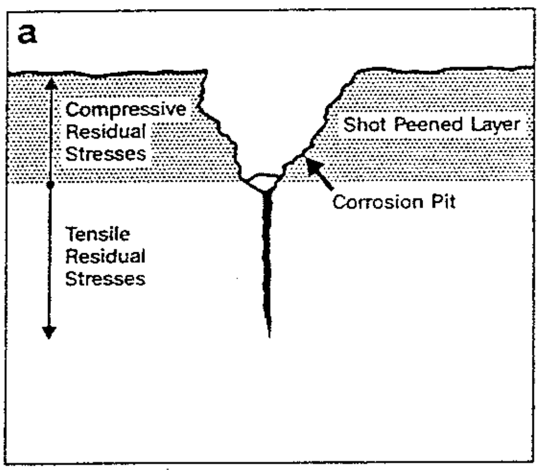


Fig. 43: SN-curves for shot peened and unpeened specimens tested in air and in a corrosive environment.



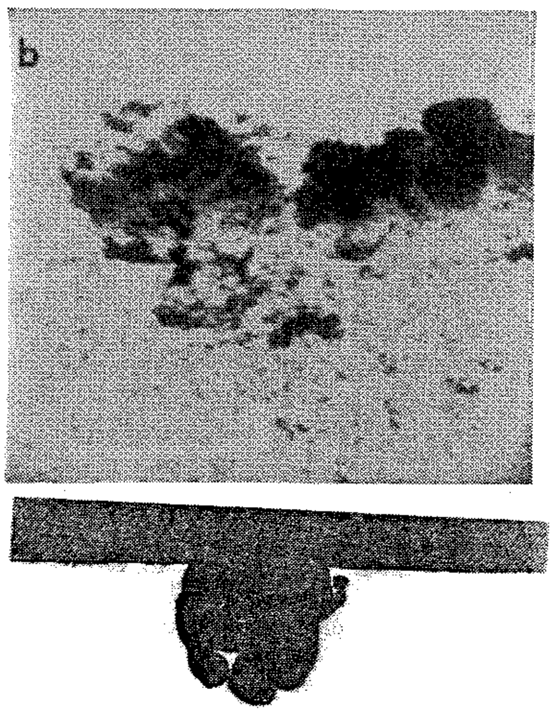


Fig. 44 a: Stress corrosion failure nucleating from an etch pit in a shot peened surface (schematic).

44 b: Etch pit (pitting corrosion) in a surface layer.

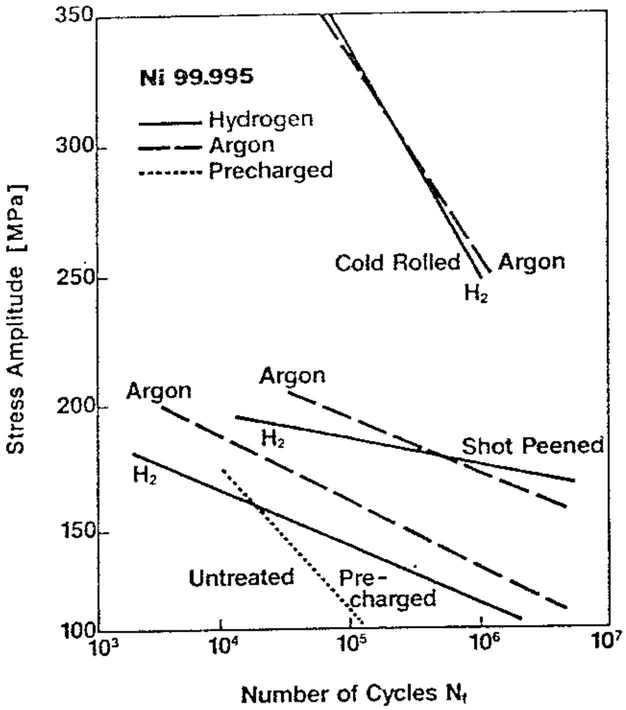


Fig. 45: SN-curves for different treated specimens, tested in different environments.

Maximum Service Temperatures of Shot Peened Materials

Material	Temperature (°C)
Steel	180–260
Cr-Ni-Steel	550
Aluminium Alloys	100
Titanium Alloys	330–420
Nickel Base Superalloys	450–750

Fig. 46: Maximum possible service temperatures for different shot peened materials (estimates).

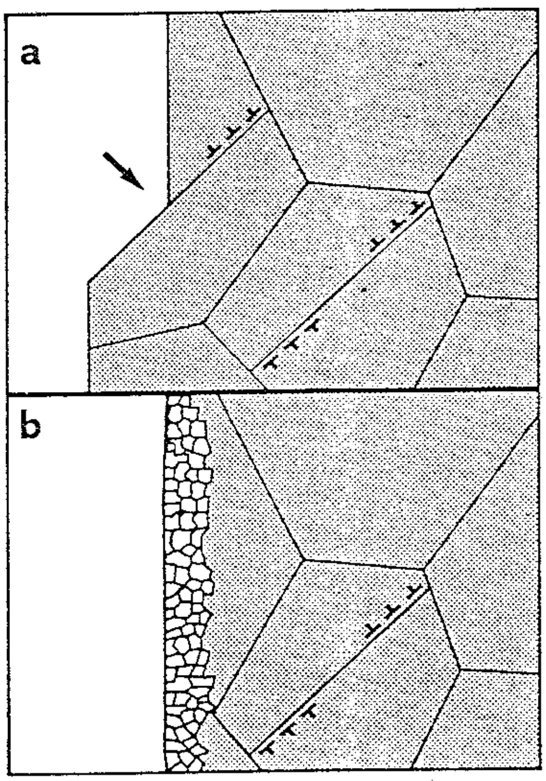


Fig. 47 a: Formation of slip bands in an untreated surface.
b: Cross-section of a shot peened and recrystallised surface layer (schematic).

6. Extended Application Areas for Shot Peening

The application of shot peening (see also next section) depends on the service temperature of the component to be shot peened. It must be guaranteed that a thermally induced decay of compressive residual stresses does not strongly reduce the effectiveness of shot peening in respect to fatigue strength. In table I (Fig. 46) the maximum possible service temperatures for different materials is given (estimates). The higher the service loading (plastic strain amplitude, temperature), the smaller the improvement in fatigue life by shot peening - in some cases even a deterioration is found - due to the mechanically and/or thermally induced decay of compressive residual stresses.

At very high temperatures, above 75% of the melting point, another mechanism occurs: the recrystallization of the cold worked surface zone with the formation of subgrains and new grains with a very fine grain size. This fine grain size is the result of the high amount of cold work in the surface zone, whereby the grain size increases with increasing distance from the surface. A grain size of 2-5μm can be obtained. In order to produce the fine-grain zone, the shot peened components have to be heat treated for a short duration at a sufficient temperature, the specific recrystallization temperature of the material. Undesired grain growth in the substrate material will not start under the given heat treatment conditions. However, it must be guaranteed that the substrate material strength is not excessively reduced due to tempering effects. Such a fine grain zone can be advantageous in many cases, for example, in the preparation of welds in superalloys to prevent the formation of cracking in coarse grained zones, in the optimal bonding preparation for plasma sprayed coatings or for the formation of an homogeneous deforming surface zone in large grained turbine blades for the improvement of fatigue life. This mechanism is shown in Fig. 47 schematically. Bending fatigue specimens of A286 with a shot peening induced fine grain size zone show a 80 times higher fatigue life at a test temperature of 840°C /35/. This beneficial effect remains up to those temperatures at which the fine grain size layer is preserved in the surface zone. In a recent investigation, shot peening and subsequent re-crystallisation was also applied on Ti-alloys to modify the surface microstructures. This surface treatment resulted in an improved elevated temperature HCF-fatigue strength /36/. This method could open new application areas.

7. Shot Peening as a Production Process

Before the shot peening can be applied to components and the peening specifications can be determined, the component specific conditions have to be analyzed. Therefore:

a) the exact demands to the product have to be defined
b) the process parameters have to be specified
c) the possibility of sufficient quality assessment and quality control have to be checked.

Depending on the product demands, a decision is made whether it is really judicious for a component/product to incorporate shot peening in the production process. The product demands are determined by the service loading and the material behaviour of the specific component. Under service conditions the mechanical loadings under corrosive environments and the thermal loading, for example in steam turbine blades or gas turbine compressor blades have to be taken into account. The temperature influence should be discussed in more detail.

An important question for the engineer is whether due to the service temperature a reduction of the compressive residual stresses produced by shot peening can occur. It is of special interest to know to what extent the residual stresses are reduced as a function of temperature and time because the positive effect of shot peening can be lowered due to the decrease in residual stresses or the peening treatment might even lead to an overall reduction in fatigue life if the reduction of residual stresses is too high. In this case, the increase in surface roughness associated with shot peening can have a negative effect on the fatigue properties of turbine blades.

Therefore, the following questions have to be answered :

- Up to what temperature can the shot peened component of a given material be used without showing a considerable decrease in residual stresses (< 30%) during the complete component life time of about 100'000h?

- At what service temperature of a component is shot peening useless (the residual stresses decrease after a short service time for example to 40%)?

In order to answer these questions, it is necessary to determine experimentally the thermal residual stress decrease for the used material. For this, two different experiments can be used: the isochronal and the isothermal annealing of shot peened strips whereby the change in the deflection of shot peened strips corresponds to a change in residual stress. In the isochronal experiment a shot peened strip is annealed at different increasing temperature steps (e.g. 100, 200, 300°C) for a relatively short time internal (e.g. 4 h). In the isothermal tests the test strips are annealed at a constant temperature and the decrease in deflection is measured after constant time intervals (times between 500 and 1'000 h). The decrease in deflection is thereby a measure of the decrease in compressive residual stresses.

The analysis of such experiments results in a diagram like the one shown in Fig. 48 for the material X21CrMoV121 (12% Cr-Steel) /37/. For all desired temperature/service time combinations the decrease of residual stresses can be seen as a percentage. The different slopes in the curves result from a change in the microstructural mechanisms responsible for the decreasing residual stresses at temperatures above 300°C. The activation energy at higher exposure temperatures has about the same magnitude as the activation energy for self diffusion so that it can be concluded that the residual stresses are decreased by diffusion-controlled dislocaton motion (climbing of dislocations) /38,39/. However, the thermally induced residual stress decrease at low temperatures is based on logarithmic creep with much lower activation energies. The extrapolation of the experimental results to times up to 100'000h relies on the knowledge of the activation energies for these two decay mechanisms. In addition, it is assumed that a longer annealing time at a lower temperature can be substituted by a shorter annealing time at higher temperature. However, this is only true for the temperature regime in which the same mechanism is active. To confirm this extrapolation some isothermal experiments were conducted up to annealing times of 10'000h.

If there are no other problems encountered besides the mechanical and thermal loading conditions (for example problems due to the component geometry), then the decision can be made to shot peen the component. In this case, the peening parameters have to be optimized to obtain the desired improvement of fatigue strength. Therefore, additional tests are performed with specimens to determine the optimum process as a function of the shot used, the machine parameters and the materials properties. The peening treatment is optimized in accordance with X-ray measurements of residual stresses and the residual stress profile and the measurement of the hardness profiles as well as the surface roughness profiles. The peening result should then be checked by HCF-tests with specimens and, if possible, with real components. Thereafter, the peening conditions can be fixed. This procedure is shown in Fig. 49 schematically /40/.

In order to guarantee a reproducible peening process, some values that characterize the shot peening process have to be controlled regularly, for example the Almen intensity, or the coverage.

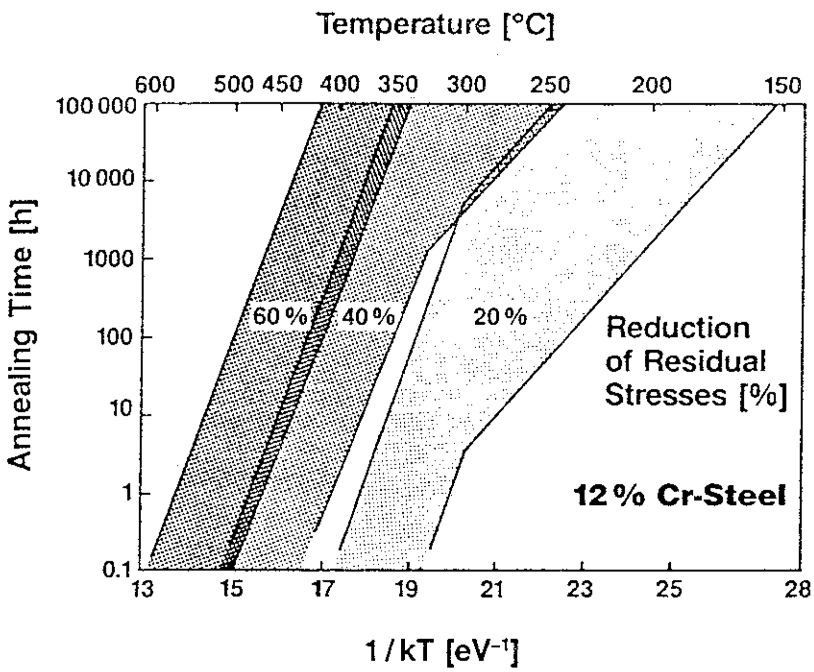


Fig. 48: Prediction of the residual stress relief as a function of annealing time and temperature.

Fig. 50: Shot peening machine with numerically controlled nozzles.

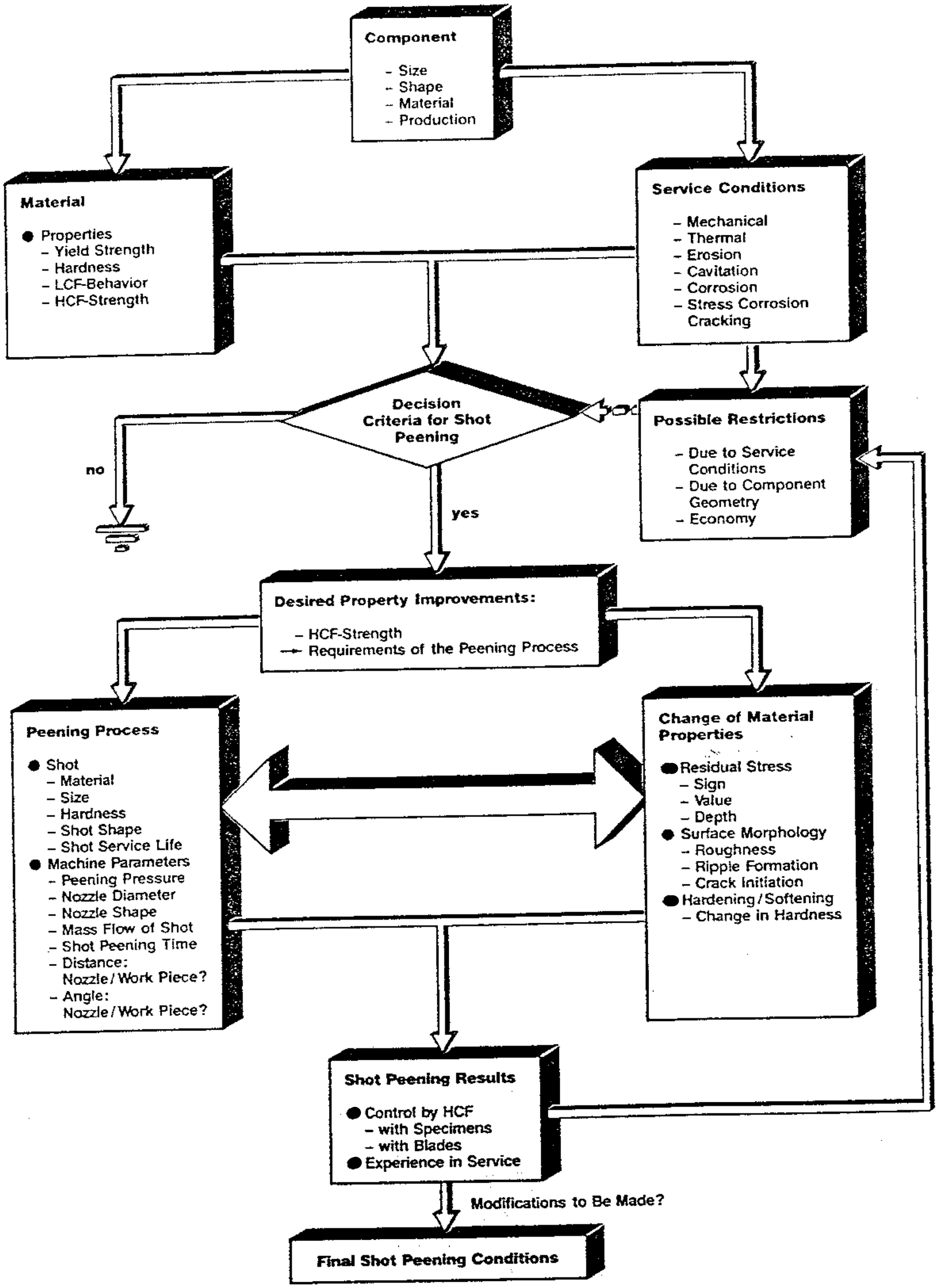


Fig. 49: Procedure to fix the peening conditions (schematic).

8. Quality Assessment and Quality Control

8.1 Shot Peening Machine

For shot peening, various machines are used which work with different principals:

- injector peening machines
- compressed air machines
- centrifugal wheel machines

The principle as well as the optimum application areas of these machines are thoroughly described in the literature /41,42/. The machines differ mainly in the way in which the shot is transported in the machine and how it is then accelerated onto the workpiece. ASEA BROWN BOVERI uses machines of the compressed-air type with numerically controlled nozzles (Fig. 50). These machines are best suited for the demands of controlled shot peening of complicated components (e.g. fir-tree roots of turbine blades) as centrifugal wheel machines show peening patterns with different peening intensities (Fig. 51). The machine control allows peening with different programs that are suited for the different blade types.

The main parts of a peening machine are:

- the peening cabin
- the shot feeder system and the shot separating system
- the machine control system.

The shot feeder system allows a continuous shot flow whereby the pressure, the flow rate and the nozzle motion are continuously controlled during the process and corrected as required. In addition, the desired size of the shot used is controlled and adjusted by a chain of sieves in the shot transportation system. Dust particles are sucked out of the process. Besides the size, the shape of the shot is also periodically controlled during operation, in a special unit, in order to minimize the fraction of broken shot.

8.2 Shot

The purchase of the steel shot used is made in accordance with international standards /43/. Depending on the application field the shot has to fulfil demands in respect to hardness, chemical composition, microstructure, density, shape and size distribution. Upon purchase a

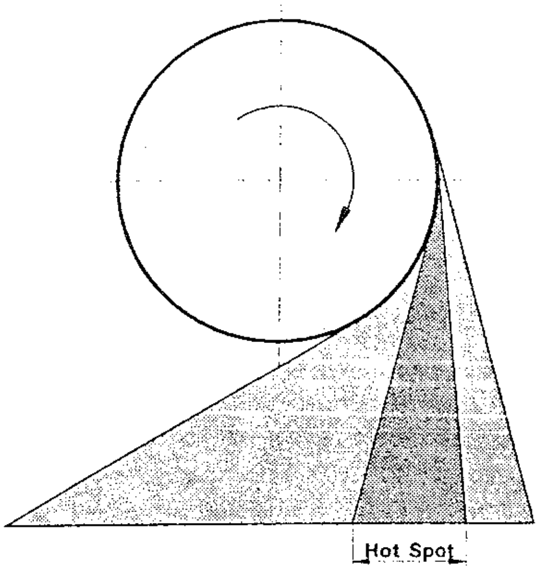


Fig. 51: Peening patterns of a centrifugal wheel machine (schematic).

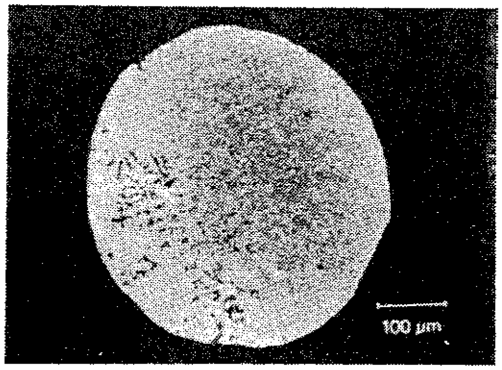


Fig. 52: Micro-section of a steel shot.

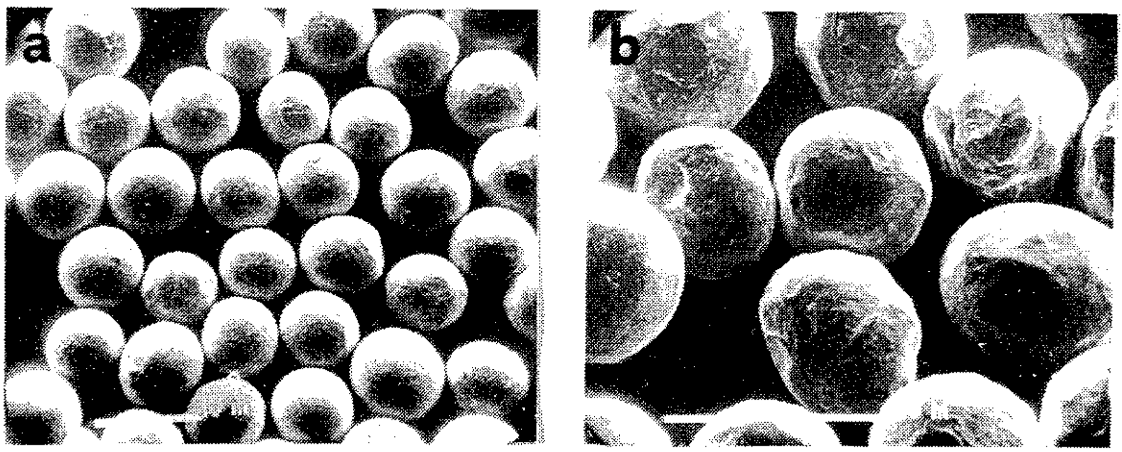


Fig. 53: Steel shot.

a) new.
b) used.

sample from every delivery of shot is tested and a test certificate is issued. Fig. 52 shows steel shot in a micro-section at high magnification. Upon delivery of the shot another representative sample is taken in the inspection to check if the specified demands are fulfilled. If the results are positive the material is cleared for production. In Fig. 53 new and used steel shot are compared in the scanning electron microscope.

8.3 Control of Shot Peening Conditions

The most important parameter of the shot peening treatment is the intensity of the shot. A simple measure to characterize this peening parameter is given by the so called Almen intensity. In order to determine the peening or Almen intensity a thin steel strip from a standard steel is fixed with four screws onto a metal block and is then peened with the same peening conditions as the component (Fig. 54). Due to the peening of one side only the thin plate will show a deflection after being removed from the metal block. This deflection is an integral measure of the resulting compressive residual stress-field as a function of the peening parameters used. The Almen intensity, given in deflection height, is now used in practical applications to control the machine parameters such as shot velocity, peening time, flow rate and shot size. The Almen value does not depend on one parameter, but gives an integral value for a given peening treatment. These Almen values are used by the engineers to define the intensity of the desired peening treatment of a given component. If the Almen strips are shot peened at constant peening pressure for various peening times and the Almen intensity is plotted as a function of time, a characteristic curve for the shot peening process is obtained (Fig. 55) /44/. This curve is usually correlated with the coverage of the peened strips. A degree of coverage of 98% is by definition given as that peening time at which doubling the peening time leads to an additional increase of the Almen intensity by 10%. The characteristic curve basically serves to monitor the influence of the most important machine parameters.

Some aspects of the measurement of the Almen intensity will be discussed briefly. The Almen intensity is usually measured with a standard steel, Ck 67. It is clear that the material of the component will show a different deformation behaviour than the material of the Almen strip, so that different compressive residual stress values and different deformation depths are found in the component. Therefore, the Almen intensity may not be used to obtain an indication of the increase in component fatigue strength. The same Almen value, for example, can lead to an optimal fatigue strength in steel components and to overpeening in titanium alloys. Therefore the optimum peening conditions have to be determined for the actual component material (fatigue strength as a function of the peening

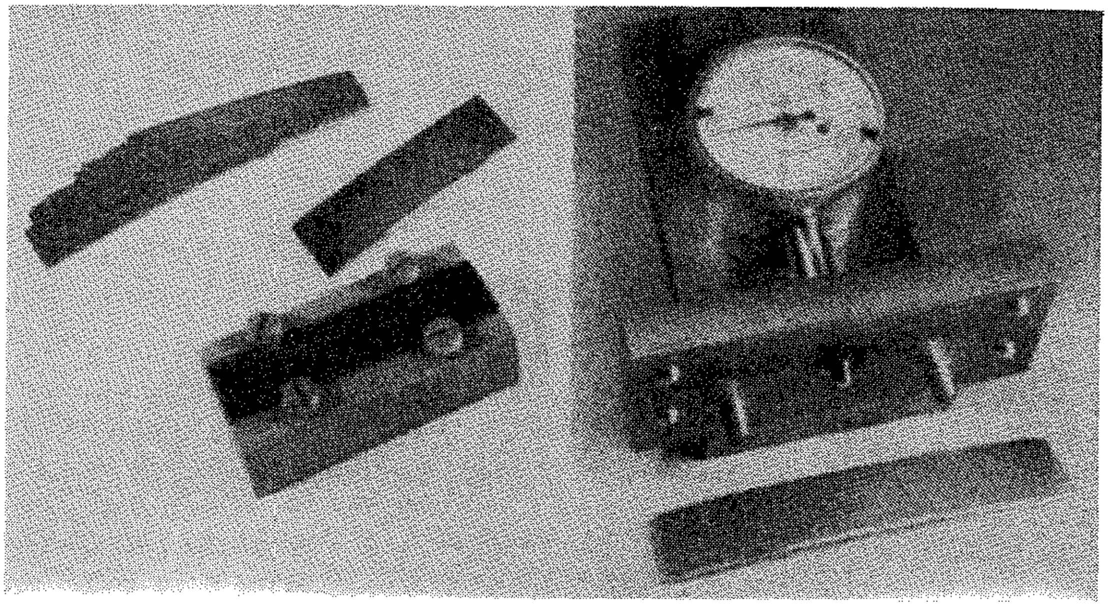


Fig. 54: a) Almen test strips and fixture.
b) Measurement of the archeight of shot peened Almen test strips.

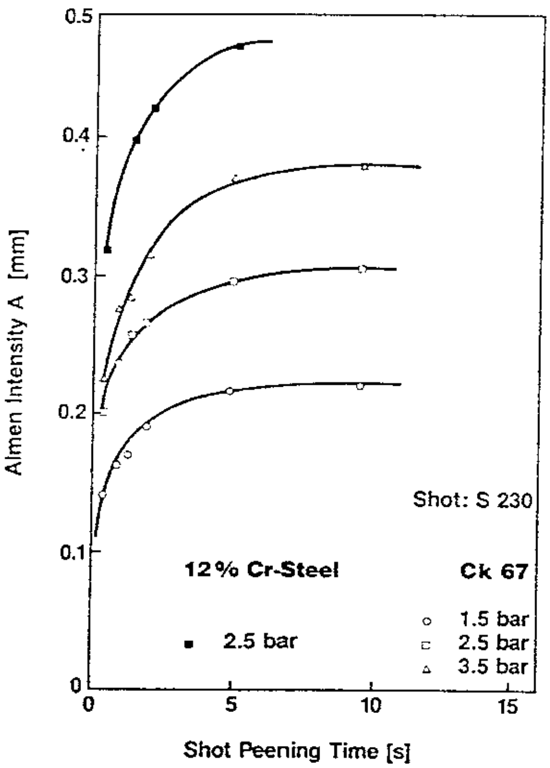


Fig. 55: Almen intensity as a function of shot peening time for constant. peening

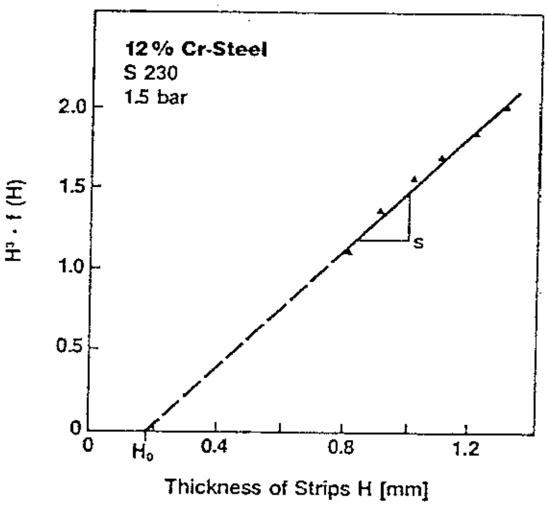


Fig. 56: Plot of deflection data against plate thickness. The Ho-value and the slope s can be used for calculating a rectangular or a parabolic stress profile

σp= 4/3 x E/l2 x s/Ho with
Ho: average depth of stress profile
σp= average strength of the residual stress.
l: length of plate.

time, peening velocity, shot media) leading to the optimum fatigue strength. In Fig. 55 the Almen intensities are plotted as determined with Almen strips from the standard material and the 12% Cr-Steel. The 12% Cr-steel shows a higher Almen intensity. Depending on the peening parameters, saturation may already be found after 2 minutes peening time. That means a longer peening time would lead to only a slight increase in compressive residual stresses.

A higher Almen intensity can be obtained more economically and easily by increasing the peening velocity. However it has to be considered that metallurgically different mechanisms take place in the surface zone and the parameters: peening time/peening velocity or peening velocity/shot size cannot be freely exchanged even though the Almen intensity might have the same value in both cases. Shot peening itself is comparable to a fatigue process for the surface zone. The number of impacts corresponds to the number of cycles in a fatigue test, the impact velocity corresponds to the applied cyclic stress. For some alloys this correlation with the fatigue behaviour has been established directly. For titanium alloys, for example, it is known from fatigue experiments that they are prone to cyclic softening at higher test stresses, because the strengthening precipitates are destroyed /45/. This mechanism of softening can also take place during shot peening after longer peening times. The hardness of the shot peened surface zone is then reduced with increasing peening times /46/. Also in a hardened steel a lower strength in the surface zone than in the substrate material was measured in such an investigation, because this zone was cyclically softened. This effect occurs also in heavily cold worked materials. In order to avoid this overpeening effect, the exact material behaviour must be determined. In measuring and controlling the so-called degree of coverage, it should be enssured that on the one hand a 100-120% degree of coverage be obtained by shot impacts, but that on the other hand material softening due to overpeening is avoided. As can be seen from the above examples, a more effective method is to produce Almen strips from the component material and to determine the peening times for 1 or 2 times coverage. In addition, one obtains information concerning whether or not the material would show the overpeening effect after longer peening times and/or higher peening pressures.

Because the Almen intensity gives no information on the height and depth of the compressive residual stresses, a simple measuring technique has been developed that can deliver better information on both values. In this technique - which is used for quality assessment - Almen strips with different thicknesses are shot peened with typical production parameters. This so-called plate-method /47,48/ has been patented by ABB. The plot of deflections of the plates against the plate thickness (Fig. 56) gives the penetration depth of the induced residual stress and with the slope of the curve the average height of the compressive residual stresses can be calculated. In contrast to the Almen intensity measurement this technique gives, therefore, additional information on the profile of the residual stresses. The agreement of the relative average heights and depths distributions of residual stresses with the corresponding profiles measured by the X-ray technique is quite good as is shown for the example of the 12% Cr-steel (Fig. 57). For alloys where the X-ray measurement of residual stresses is difficult, this procedure offers, in a slightly modified version, the possibility - besides quality control - of approaching and predicting the distribution of residual stresses by a parabolic function /49/.

The usual control of the degree of coverage is to observe the surface of the peened component under a stereomicroscope at magnifications of 20-50 times and to compare it with shot peened standard test pieces. For a documentation the surface can be photographed. This fast and easy quality assessment can easily be incorporated into the production process. However, a complete control of the coverage of large components is only possible practically, if the so-called peen-scan technique (patent of MIC in USA, West-Germany and France) is used for coverage control /50/. The component to be shot peened is coated with a fluorescent varnish that defoliates during shot peening only at those points where the steel shot impacts. In the subsequent blade control under UV-light very small, incompletely covered areas can be recognized due to residues of the varnish. In this technique, the lacquer must have the property of not spalling-off at unpeened locations in order to avoid misjudgements during coverage inspection. The disadvantage of this method lies in the additional steps such as applying and drying the lacquer as well as on the extra cost associated therewith.

9. Shot Peening Procedure for Turbine Blades

Gas turbine compressor blades and steam turbine blades at ABB are mainly made out of the 12%Cr-steel (X21CrMoV121) or the titanium alloy Ti-6Al-4V with only a few exceptions. For these materials there is considerable experience with respect to the optimum shot peening conditions as well as some decades of service experience. These blades operate world wide under various climatic conditions. If the decision is made to shot peen a particular turbine blade type the shot peening parameters are determined.

The desired distribution of residual stresses is chosen depending on the steel shot. This distribution is characteristic of the component material upon shot peening. However, not only the material behaviour during shot

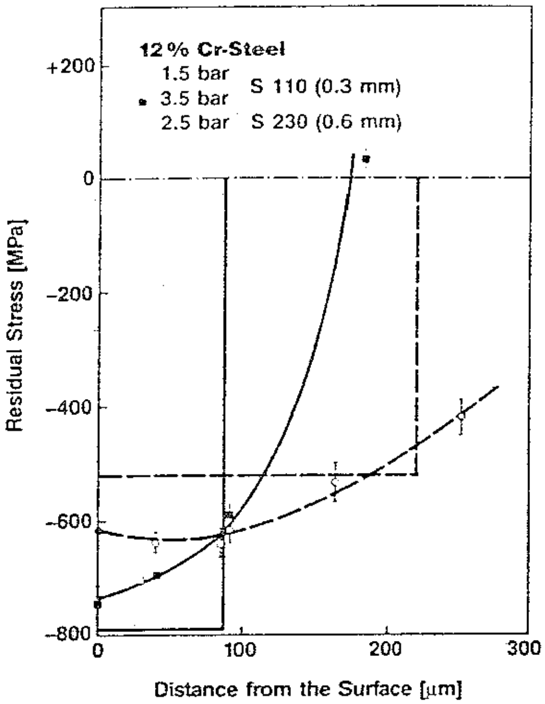


Fig. 57: Comparison of measured residual stress profile and calculated rectangular stress profiles.

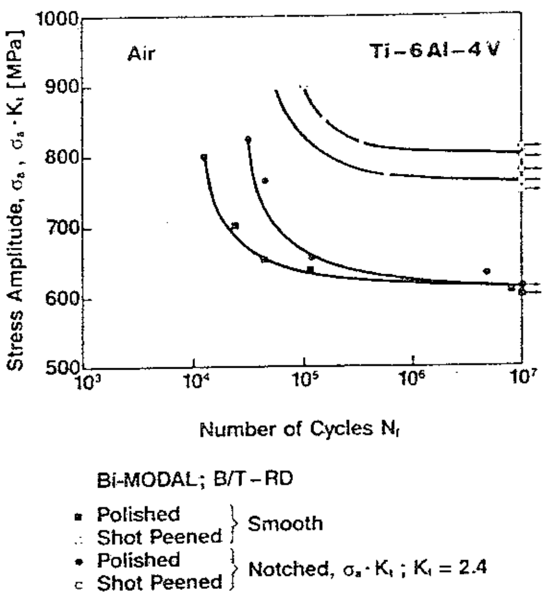


Fig. 58: SN-curves, influence of shot peening on the fatigue limit of notched and unnotched specimens (Air, R= -1, RT).

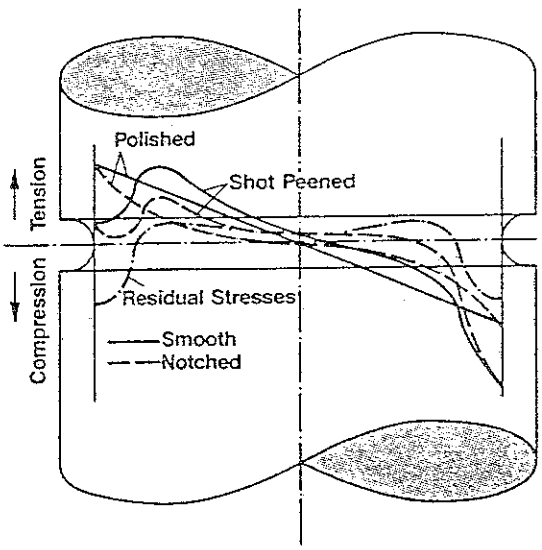


Fig. 59: Superimposition of applied stresses (bending) and residual stresses (shot peening treatment) for a notched and an unnotched specimen (schematic).

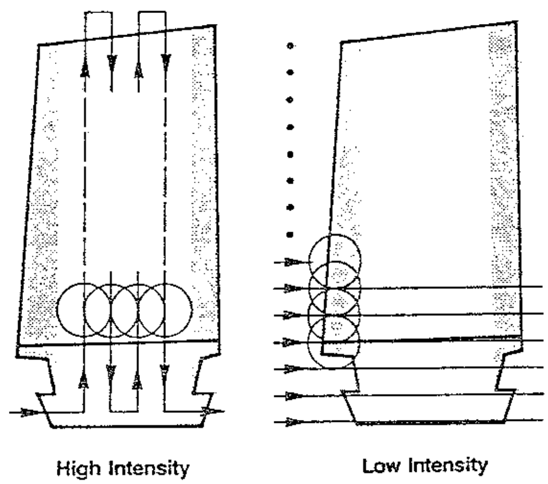


Fig. 60: Shot peening of thin blades (schematic).

peening of components is important, but it has to be checked in a second step whether the chosen residual stress distribution is compatible with the geometric conditions. Practically speaking this means for a turbine blade: consideration of the smallest radius in the blade root or transition between airfoil and root. Experiments with notched specimens have shown that shot peening of notches has a beneficial effect only if the notch radius to be shot peened is several times larger than the diameter of the shot used. Otherwise, there is an obstruction of the steel shot resulting in an insufficient peening treatment in the notch root. If notched specimens or notched components are shot peened with the right shot and the right intensity the improvement of fatigue strength obtained is higher than for smooth specimens or smooth sections of components at the same load (Fig. 58). For example, investigations with several microstructures of the titanium alloy Ti-6Al-4V have shown /51,52/ that the increase in fatigue strength in this alloy after shot peening depends more on the retardation or prevention of propagation of surface microcracks due to the compressive residual stresses than on the prevention of crack initiation as is the case for austenitic alloys. If a notch is present this crack retardation effect is even more pronounced due to the stress gradient /53-55/. Fig. 59 shows schematically the load profile of a notched and a smooth bending specimen after shot peening treatment. For the same maximum stress at the surface a significantly lower tensile stress profile is found in the notched specimen by superimposing the residual stress profile with the bending stresses in the surface zone which is the important zone for preventing the propagation of small surface cracks /56/. The higher the stress gradient (depending on the notch factor) the more likely is the possibility that cracks might form in the surface, but cannot propagate (so-called non-propagating cracks) /57/.

The size of the steel shot to be chosen is also determined by the thickness of the blade areas to be shot peened. Thin trailing edges may not be peened with too high a peening intensity (also depending on the steel shot), because there is the danger of component deformation. Therefore, thin blades are initially only peened in the middle airfoil section and the root section with high intensity and subsequently the complete blade, including the edges, with low intensity (Fig. 60). Therefore the roughness of the blade section firstly peened with higher intensity will be slightly reduced. Not only due to the negative effect on the fatigue strength, but also for aerodynamic reasons the surface roughness cannot be neglected as long as the blades are not coated after peening. Fig. 61 shows that the roughness increases with increasing peening pressure, shot velocity and with increasing shot size /44/. The roughness values measured with specimens correspond quite well with shot peened turbine blades. It is well known that a larger steel shot diameter results in a higher surface roughness R_a at

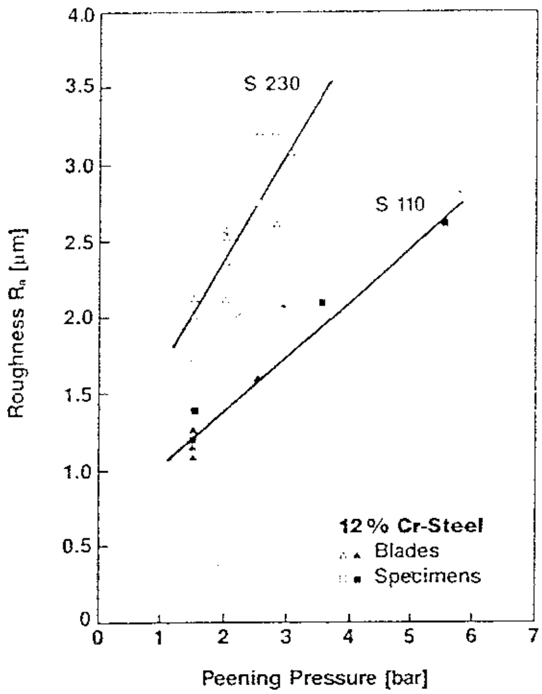


Fig. 61: Surface roughness as a function of peening pressure for shot peened blades and specimens.

Fig. 62: LP-Steamturbine blades with Almen-strips.

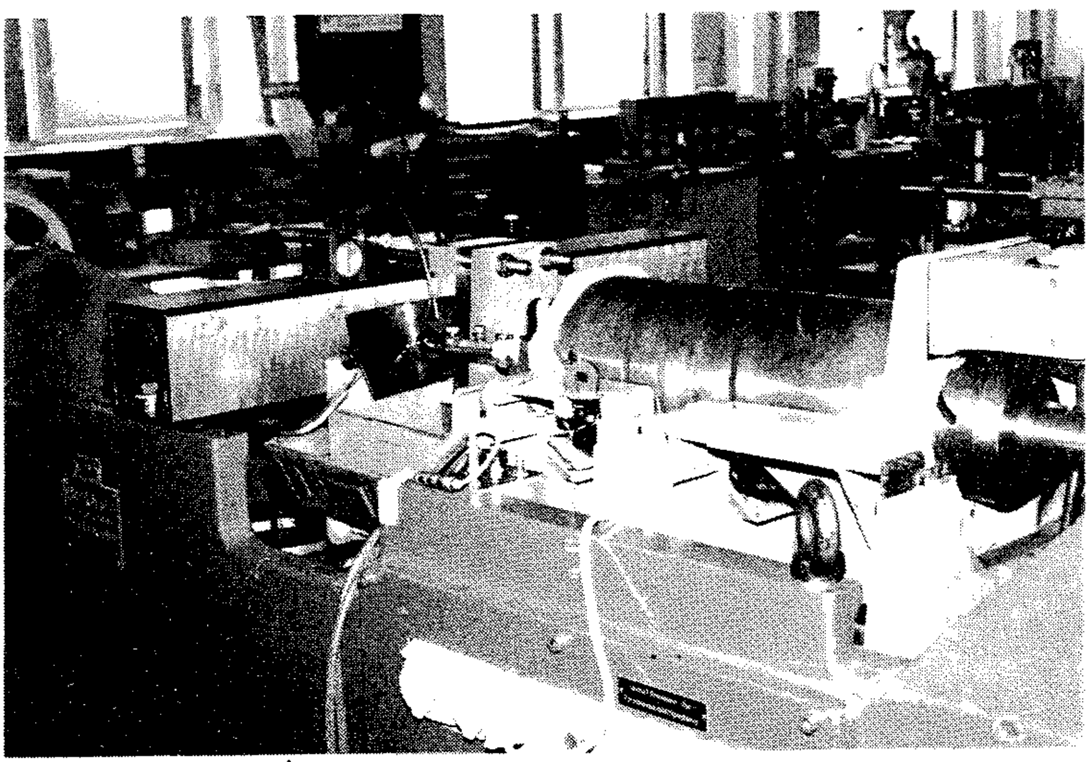


Fig. 63: Test arrangement for fatigue testing of compressor blades.

constant Almen intensity. Finally the Almen value is determined for the chosen peening treatment and is given together with the desired degree of coverage and the indication of blade sections to be shot peened on the blade drawing. Subsequently a model of the blade type to be shot peened is fitted with Almen test strips (Fig. 62) and is then shot peened with the desired peening and machine parameters. The resulting Almen values have to fulfil the specified drawing values in order to obtain the release of the blade type for controlled shot peening.

Because the fatigue of blades compared to specimens is much more complex (geometry, loading profile), such complicated, shot peened blades are investigated in the laboratory before being cleared for service. Besides measurement of residual stresses, roughness and hardness at different blade sections the blades are cyclically loaded under the service loading conditions. These tests should guarantee that the peening parameters optimized using specimens are completely transferred to the peening of the blades and that the same increase in fatigue strength is obtained as with specimens. Fig. 63 shows a fatigue test machine for cyclic loading of compressor blades. The blades are fixed in a resonance fatigue tester so that gas loads occurring during service are transferred on a calculated loading point by a piston which acts simultaneously as a measuring device. Compared to unpeened, ground blades the fatigue strength of shot peened compressor or turbine blades is between 15 to 35% higher, depending on the alloy used. Using FE-calculations it was found that the areas of highest stresses and risks of fatigue crack initiation are located close to the blade leading edge. In fact, in these areas the fatigue cracks were initiated (Fig. 64). Different blade types from the investigated 12% Cr-steel show the same fatigue strength values. This indicates a good transfer of laboratory results from specimens to components and also a good reproducibility of the shot peening treatment. In many cases the fatigue crack initiation is moved from the surface by the shot peening induced compressive stresses towards the blade interior where the highest tensile residual stresses exist (Fig. 65). In corrosive environments the effect of shot peening is still enhanced if the crack initiation point is not moved towards the surface again by an aggressive environment.

10. Conclusions

In this investigation, the effect of shot peening on the surface zone and the resulting fatigue behaviour have been studied in detail. With metallographic techniques (measurement of hardness, X-ray analysis of half-width and residual stresses and roughness measurement as well as scanning and transmission electron microscopy of the surface and surface replicas) it can be shown that by shot peening plastic deformations of

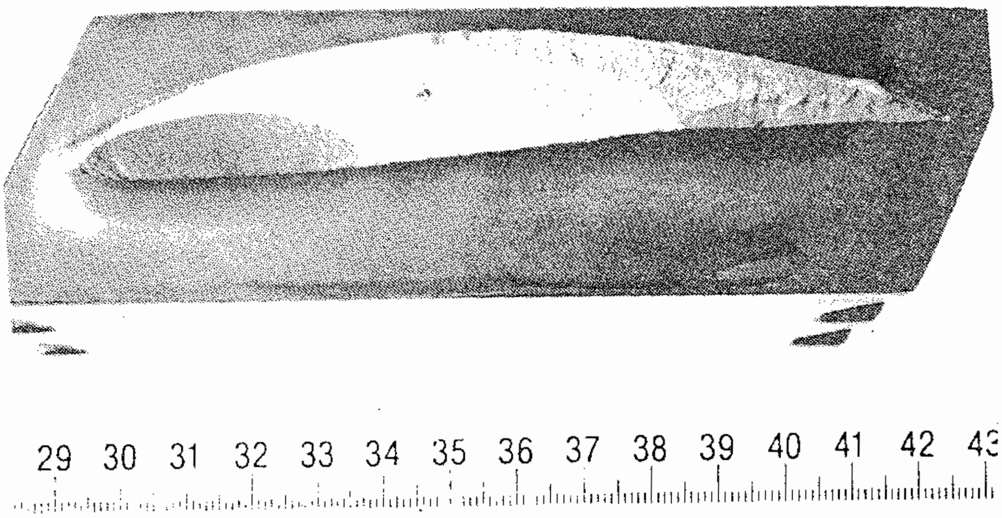
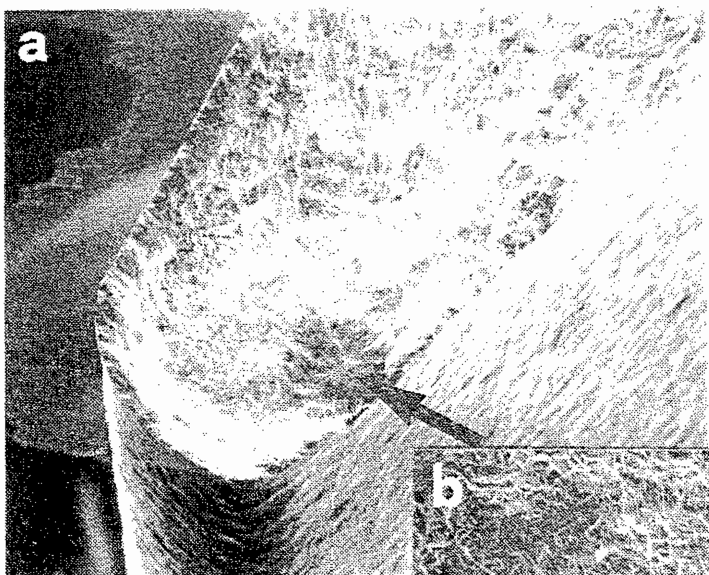


Fig. 64: Crack initiation point in a shot peened blade, tested under fatigue loading.



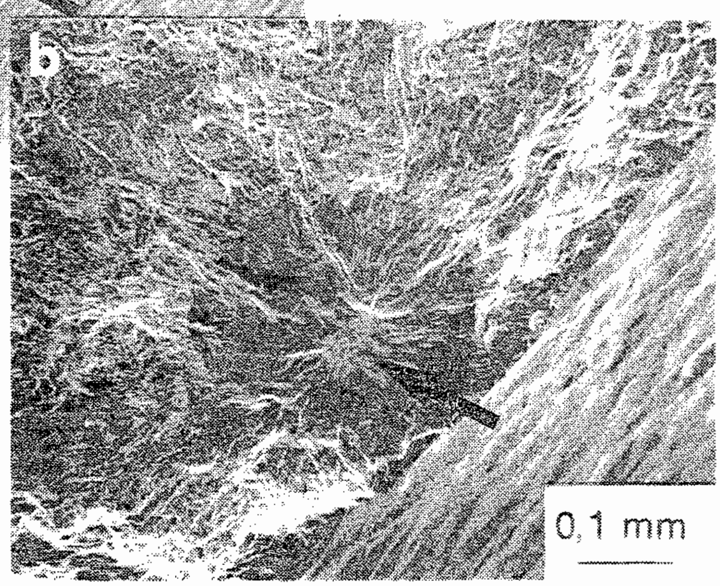


Fig. 65 a: Crack initiation point below the surface of a shot peened blade

65 b: Detail from Fig. 65 a.

more than 95% can occur in the outer substrate surface. Even after very short peening times, the formation of extremely strong cold-worked surface zones with exfoliating thin platelets was observed: platelets that become detached from the surface because their deformation behaviour is exhausted by a fatigue process. Shot peening can also act like a solid particle erosion process. This is clearly confirmed when the material loss is plotted as a function of the impact angle and a typical erosion curve is found.

The increase in fatigue strength in austenitic steels results from a work hardening of the surface zone (retardation of crack initiation due to homogenisation of slip) as well as from residual stresses (retardation of microcrack propagation due to surface compressive residual stresses). In contrast to the untreated substrate material (coarse slip distribution, sharp fatigue slip steps with early crack initiation) in shot peened surfaces a retardation of crack initiation is found because the dislocations in the fatigue slip bands have to now react with the cold worked zone. Especially under corrosive conditions the protecting passive layers are not destroyed so that the fatigue strength can be improved by 30 to 70%. For austenitic steel the shot peening treatment seems to be the optimum procedure to increase the fatigue strength, because the method for improving the crack initiation (high disslocation density and homogeneous slip distribution) beneficially influences the crack propagation at the same time (compressive residual stresses). In contrast to low-strength and austenitic steels, in titanium alloys and high-strength steel it is more the propagation of surface microcracks that is retarded.

Shot peening continues to play an important part in the production of gas turbine compressor blades and low pressure steam turbine blades. The process and peening parameters for the shot peening of the component "blade" are specified in such a way that they lead to an optimum fatigue strength. Only nummerically controlled shot peening machines allow a reproducible shot peening with the established optimum parameters. The methods of quality assessment developed at ABB, which by far surpass the usually applied methods, lead to a good reproducibility of shot peening treatments. The quality of the end product "blade" is greatly improved by shot peening because the improvements in fatigue strength obtained are used only as a technique to increase the component service safety but not to increase the allowed service loads.

11. Acknowledgements

At this point we would like to thank Mr. P. Hofmann, Mr. M. Leeser and Mr. H. Gries for their support through many years during the transfer of research results to the production size, controlled shot peening of turbine blades. In addition the help of Mrs. G. Keser, Mrs. Z. Posedel and Mrs. M. Kongsted as well as Mr. R. Baumann, who conducted metallographic investigations, is greatly acknowledged. We also would like to thank Dr. C. Wüthrich, ABB, Dr. M. Roth, EMPA and Dr. L. Wagner, TU Hamburg-Harburg for their contributions and helpful discussions. The help of Prof. H. Louis, University of Hannover and Dr. J.E. Field, University of Cambridge with water jet peening is appreciated. Water jet peening trials were carried out by WOMA Apparatebau, Duisburg and Kehrli AG, Thun. Mr. E.A. Faude from IEPCO AG provided the possibility of performing special shot peening treatments in PEENMATIC machines.

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