Practical Aspects of the Application of Shot Peening to Improve the Fatigue Behaviour of Metals and Structural Components

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Introduction

The aims of this paper are to describe the favourable effects of shot peening which can be useful for the improvement of the fatigue behaviour in practical applications and to direct attention to the special peening conditions, which have to be obeyed as well as to indicate limitations in improving the fatigue behaviour by shot peening. In order to fulfil these purposes it is necessary to classify structural components in different categories. Of primary importance for the classification is the kind of the material and the state of the material of the structural components. Therefore this aspect shall serve as clue in the following. Other aspects concerning the effectiveness of shot peening for structural components of different shape and dimensions or under different kinds of loading have to be taken into consideration separately for different materials and material states. Especially results on the effectiveness of shot peening in notches respectively of notched parts can not simply be transferred from one state of a material to the other. Also not simply transferable from one material to the other are results about the influence of shot peening on the fatigue behaviour under different loading modes as loading with constant or with variable amplitudes, loading with or without mean stresses or tension-compression-, bending- or torsional loading. Such results have also to be discussed separately in the different sections.Therefore in the following - after a short summary of principally important facts concerning the effects of shot peening - the experimental results about shot peen induced improvements of the fatigue behaviour are reported in different sections for different materials. For steels the different strength or hardness levels of the material can be represented by different structural components. Welded joints of steels are typical components in a relatively soft, normalized state or in a quenched and tempered state of the material. Other typical structural components in a quenched and tempered state are forgings. Gears and springs are typical representatives for structural components in a relatively hard materials' state - at least in surface layers - which are often or mostly shot peened. Concerning Al and Ti alloys it shall be discussed how significant important results from tests with specimens are for structural components. Finally some remarks shall be made about the effect of shot peening of sintered materials

Principal results about the effects of shot peening

Shot peening changes the state of the surface and of layers close to the surface by inducing a distinct hardness distribution in surface layers, a distinct distribution of compressive residual stresses in surface layers and a distinct surface roughness and possibly also by changing the retained austenite content in surface layers of hardened steels or for instance by closing of surface pores in sintered materials.

The thickness of the layer, which is strain hardened and which contains compressive residual stresses after shot peening, increases with an increasing peening intensity and especially with an increasing shot diameter The magnitudes of compressive residual stresses at the surface and at the maximum below the surface increase with increasing hardness of the peened material - supposed that the shot hardness meets at least nearly the hardness of the peened material. Details about the dependence of the residual stress distributions on the peening conditions are reported in(10,11). Surface roughness increases for instance with increasing shot velocity (12), but depends on other peening parameters in a complicated way (13). Surface roughness decreases with increasing hardness of the peened material if constant peening conditions are considered.

Each of the shot peening induced changes of the surface state has its own definite influence on the fatigue behaviour and it depends on the shot peening conditions, on the ultimate strength respectively hardness of the shot peened material, on the dimensions of the structural component and on the notch geometry how strong the contribution of each individual influence to the total change of the fatigue strength is.

Surface hardening as well as compressive residual stresses contribute to the fatigue strength improvement after shot peening - surface hardening by retardation or prevention of crack initiation and compressive residual stresses by retardation or prevention of crack propagation. In material states with a low ultimate strength, in the following called "soft material states", the fatigue strength improving effect of surface hardening is strong and dominating, whereas the influence of compressive residual stresses on the fatigue strength is relatively weak. With increasing ultimate strength respectively hardness of the material the influence of compressive residual stresses becomes stronger and dominating, whereas the effect of surface hardening decreases and can become negligible in a very hard state of a material (1). Experimental results indicate that in materials of medium hardness - with crack initiation at the surface - the magnitudes of compressive residual stresses at the surface and in layers very close to the surface are relevant to the fatigue strength improvement, whereas the thickness of the layer with compressive residual stresses is relevant to the increase of lifetime in the finite life range (1). In hard shot peened materials crack initiation can occur below the surface. Then the total distribution of compressive residual stresses is connected with the fatigue strength improvement.

An increase of surface roughness - possibly resulting from shot peening - has a detrimental effect on the fatigue strength which has to be taken into account as a negative contribution to the total fatigue strength improvement. The effect of surface roughness is relatively weak in the soft state of a material but becomes much stronger with increasing hardness of the material. As on the other side the possible increase of surface roughness is large in the soft state of a material and becomes smaller with increasing hardness, the negative contribution of surface roughening due to shot peening can remain nearly constant on the whole (1), if unfavourable peening conditions are avoided. In any case sharp indentations, for instance due to broken shot, have to be avoided especially in notch sensitive materials. If in very hard materials crack initiation occurs below the surface, a roughening of the surface due to shot peening should have no or minor influence on the fatigue strength.

In total one can conclude that peening conditions for optimum fatigue strength should result in a surface hardening as strong as possible and in compressive residual stresses with magnitudes as big as possible and a penetration as deep as possible in connection with a surface roughness as low as possible. But as a shot peening treatment with these results would be not economical in many cases compromises have to be made for practical applications.

Steel in the normalized or quenched and tempered state of medium hardness

Welded joints

As a consequence of inherent notches the fatigue strength of welded joints of structural steels is lower than the fatigue strength of the base material. Due to the increasing notch sensitivity the fatigue strength of welded joints can be improved only very little or can even not be improved by application of high strength structural steels in the normalized or in the quenched and tempered state - unless special postweld treatments are used. Shot peening has been proved to be a potential postweld treatment which can improve the fatigue strength of welded joints considerably and which allows to make use of the advantages of high strength structural steels in welded constructions. Therefore a number of papers reported quite recently on shot peening of welded joints (2).

Investigations of (3) indicate that it is possible to enhance the fatigue strength of butt welded joints over the fatigue strength of the black plate even for a material with an extremely high ultimate strength as StE 890. The fatigue strength improvement due to shot peening increases with the ultimate strength of the base material if an appropriate welding technique and a sufficiently high Almen intensity is used (6, 7, 15). The higher the ultimate strength of the structural steel the higher is the Almen intensity which is necessary to get optimum results (3, Fig.1).

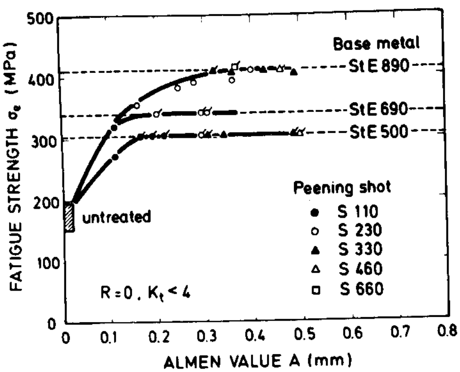

Fig. 1 Relation between Almen intensity and fatigue strength under bending loading of butt welds of different structural steels (3)

Shot peening can be as efficient in improving the fatigue strength of welded joints as other kinds of postweld treatments like TIG dressing (4, 5, 6) - or can be even more efficient if optimum peening conditions are used (3, 6, 8).But in any case (steels St 52-3, StE 500 V, StE 690 V and StE 885 V) a smaller slope of the S-N-curves in the finite life range was observed after shot peening of welded joints than after TIG-dressing (4, 5, 6). This result is a typical consequence of the relief of shot peen induced compressive residual stresses during cyclic loading with relatively high stress amplitudes. Results from (8, 9) show that a residual stress state with a relatively thick layer of compressive residual stresses, which is favourable for the fatigue life of welded joints, can be reached mainly with a sufficiently big shot diameter, whereas the peening time and especially the peening pressure have minor influence on the depth of the affected layer. But on the other side a sufficiently small shot diameter is recommended in order to assure the treatment and opening of sharp notchlike defects as undercuts or weld bead defects. Therefore either a compromise of the shot size has to be found or double peening should be applied.

Results of (6, 7, 14) indicate that it can be advantageous to produce a flat weld seam profile with a notch factor as small as possible before shot peening. Their fatigue tests refer to butt welded joints of 10 mm thick plates whose surfaces were ground before welding. The fatigue strength of manual arc welded joints of the steels St 52-3 and StE 690 was improved due to shot peening by 50 % respectively 74 % but nevertheless remained below the fatigue strength of the corresponding base material with a ground surface (Fig. 2). Contrasting and much better results have been found if extremely flat weld seam profiles without any undercuts were produced by TIG-welding, for instance TIG-welding of cover passes. The fatigue strength of such weldments is already higher than that of

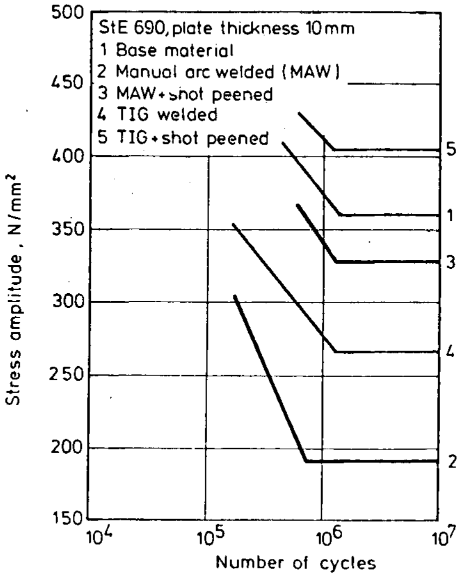

Fig. 2 S-N curves for a fracture probability of 50 % of the base material StE 690 and differently butt welded and shot peened joints under completely reversed bending (7).

manual arc welded joints and consequently additional shot peening enhances the fatigue strength above the fatigue strength of the machined, but unpeened base material (Fig. 2). It is worth to note that these findings indicate that even the relatively high fatigue strength of the ground base material of the steel StE 690 can be reached or surpassed - at least under laboratory conditions - if an advanced welding technique and subsequent shot peening are combined. This combination is not only effective in completely reversed bending but also in tension-compression loading. The discussion of the results of (6, 14) includes a separation of the influences of compressive residual stresses and of surface hardening due to shot peening (7). This separation explains that the contribution of surface hardening to the total fatigue strength improvements of the welded joints is in any case appreciable - in accordance with older results (1) on steels with an ultimate strength of the same order of magnitude. In the manual arc welded state of the steel StE 690 for instance the contribution of surface hardening to the fatigue strength improvement equals the contribution of compressive residual stresses. In the TIG-welded state with the extremely flat weld seam profile surface hardening contributes much more to the total fatigue strength improvement than in the manual arc welded state - and also much more than compressive residual stresses. Obviously surface hardening due to shot peening can be more effective in welded joints with a smooth, flat profile of the seam than in welded joints with a marked notch effect of the weld seam - an observation which is in agreement with the usual fatigue strength - hardness relation for specimens with a different notch factor and which is discussed in detail in (14). Consequently it is advantageous to make use of the high efficiency of surface hardening by the production of flat weld seam profiles before shot peening. Surface hardening is also more effective under completely reversed bending than under tension-compression loading - but nevertheless in combination with the effect of the compressive residual stresses shot peening can appreciably improve the fatigue strength of welded joints under tension-compression loading (6, 7).

Results of (8,9) indicate that the number of cycles until crack initiation increases clearly with increasing peening intensity and confirm thus the important influence of surface hardening on the fatigue life respectively the fatigue strength.

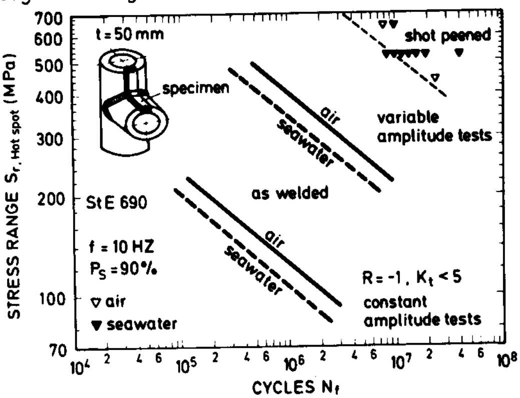

Fig.3 Fatigue strength of V-shaped welds under constant amplitude and variable amplitude loading in air and in sea water

Investigations of (3,16) show another aspect of the influence of shot peening on the fatigue behaviour of welded joints. As illustrated in Fig. 3 variable amplitude tests in air of V-shaped submerged arc welded joints resulted in an approximately 26 times longer fatigue life after shot peening than without shot peening and the corresponding factor for variable amplitude tests in sea water was 33.

Results of (8,9) complete the knowledge about the possible effects of shot peening under variable amplitude loading. These authors demonstrate that a 50 times repeated tensile preloading with a stress amplitude of 450 N/mm^2 has no adverse influence on the residual stress field due to shot peening and hence no influence on the lifetime in a following constant amplitude test. Compressive preload stresses partially relieve the residual stresses due to shot peening, but even after a compressive preload stress of -400 N/mm^2 a compressive residual stress of -190 N/mm^2 remains present at the surface and hence the lifetime in subsequent constant amplitude loading is longer after shot peening than without it (Fig. in (12)).

Forgings

The following different applications of shot peening to forgings illustrate also different possible aims of shot peening treatments in general. Some applications of shot peening to forged structural components are directed towards the possibility of using simpler heat treatments like controlled cooling after forging (17). Normally shot peening is used to compensate for the fatigue strength reduction due to scaling on the surface or due to surface decarburazation of the forged material. Fig. 4 indicates that shot peening of forged specimens with scaling and a decarburized surface layer enhances the fatigue strength nearly to the value of polished specimens without any surface damage

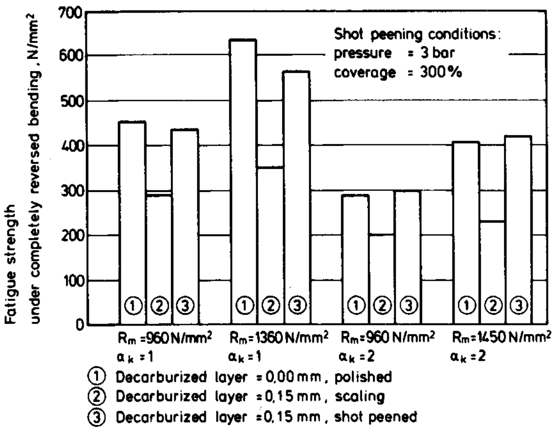

Fig.4: Influence of shot peening on the fatigue strength of unnotched and of notched forged specimens with decarburazation and without decarburazation (18,19).

for α_K = 1 and above the value of the polished specimens for α_K = 2 - nearly independently of the ultimate strength of the material (18,19). The most promising application of shot peening however is the possibility to take advantage of the potential of materials with an enhanced ultimate strength. Similar to the situation in weldments an increase of the ultimate strength of a material cannot be transferred to an equivalent increase of the fatigue strength, unless additional treatments remove or compensate the detrimental effects of scaling on the surface and of decarburized surface layers of forgings. Fig. 4 indicates clearly that the difference between the fatigue strength of forged specimens with a different ultimate strength is small in the decarburized state with scaling and without shot peening. Polishing - which removes scaling and decarburazation - as well as shot peening enhance the fatigue strength of the forgings considerably - particularly in the state with the higher ultimate strength. (Rm = 1360 N/mm^2 respectively 1450 N/mm^2) Consequently - for unnotched (α_K = 1) and also for the notched (α_K = 2) specimens - an appreciable fatigue strength improvement due to a higher ultimate strength can be realized in the shot peened state. The reasons for this high efficiency of shot peening are the nearly complete removal of the hardness loss due to surface decarburazation (20) and the embedding of the stress raising surface defects due to scaling in a compressive residual stress field which lowers the peak stresses of the defects and delays or even prevents the initiation - or possibly already propagation - of short cracks from the defects.

Results with the same tendency as illustrated in Fig. 4 have been found in fatigue tests on forged connecting rods of unalloyed or low alloyed carbon steels with an ultimate strength of nearly 800 N/mm^2 (0.45 % C) respectively nearly 1150 N/mm^2 (0.42 % C, 1 % Cr, Mo). Only after machining, nitriding or shot peening the forged connecting rods with the higher ultimate strength showed a markedly higher fatigue strength (21).

Results on forged truck axles (steel with 0.35 % C, Mn, controlled cooling after forging, ultimate strength about 900 to 1000 N/mm^2) indicate clearly that shot peening can also improve the bending fatigue strength (R = 0,1) of larger structural components by about 90 % (22). The same investigation offers the information that blast cleaning with cut wire after grinding of critical areas may as well improve the fatigue strength considerably. (19) refers also to the effects of blast cleaning, which is at least able to compensate for the loss of hardness in a dacarburized layer. Investigations of (23) refer to forgings of the alloy TiAl6V4 and show that shot peening can be beneficial for specimens with scaling.

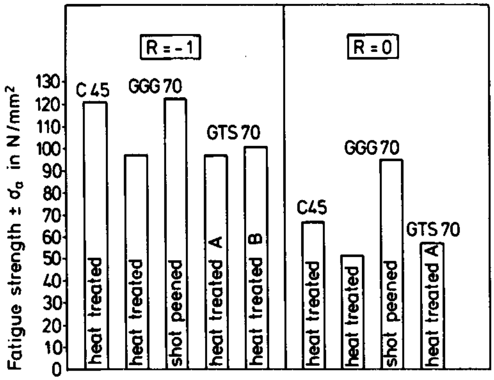

Fig. 5 Fatigue strength of forged and of cast crankshafts in the heat treated and in the heat treated and shot peened state (26).

From an economic point of view it can be advantageous to replace forged structural components by components of nodular or of malleable cast iron. Shot peening is a useful method to improve the fatigue strength of cast structural components so much as to reach or surpass the fatigue strength of forged components (26). Fig. 5 shows that after shot peening the fatigue strength of crankshafts of nodular cast iron (GGG 70) equals the fatigue strength of forged crankshafts in the heat treated state (C 45) for R = -1 and surpasses it for R = 0 (24,25).

Steel in the quenched and tempered state of high hardness or in the quenched or case hardened state

Leaf springs and coil springs

Steel springs are typical structural components which are used in the quenched and tempered state with a relatively high hardness (400 to 550 HV) respectively ultimate strength (1400 to 1900 N/mm^2) and which are mostly shot peened. Therefore many publications on the fatigue strength improvement due to shot peening of leaf springs or coil springs exist. As a consequence of the high hardness of the material compressive residual stresses contribute to a large extent to the increase of fatigue strength and surface hardening with its beneficial effect and surface roughening with its detrimental effect has also to be taken into consideration. It is important for steels with a hardness over 500 HV to use a shot with a sufficiently high hardness, for instance 580 to 640 HV.

As a consequence of the production from a rolled raw material leaf springs normally exhibit a roller skin, small rolling defects and a decarburized surface layer whereas coil springs due to their specific production process show a typical surface roughness, sometimes with longitudinal groves, and possibly a decarburized surface layer. Nonmetallic inclusions may also be effective as stress raisers in surface layers. Therefore in practical applications an important advantage of shot peening is again to reduce or even to remove the detrimental influence of these defects by embedding them in a field of compressive residual stresses or by levelling off the loss of surface hardness.

Appreciable attention has been addressed to the influence of shot peening on the fatigue strength of spring steels with decarburized surface layers in connection with oxidation in these layers. Shot peening is able to compensate the detrimental effect of a decarburized layer nearly completely, if the decarburazation is not very pronounced and not very deep. Investigations of (27,28,30,31) show for instance that shot peening of a material with a decarburized layer in which excessive ferrite and oxides along grain boundaries have been observed to a depth of nearly 10 µm results in the same fatigue strength as shot peening of the same material without decarburazation. If the decarburazation is very strong and deep shot peening can not totally restore the fatigue strength of the shot peened material without decarburazation - even if the fatigue strength improvement of a decarburized material can be as high as 65 % and of a material with a pronounced oxidation in surface layers as high as 100 % (28,29). Fig. 6 illustrates the effects of shot peening on the torsional fatigue strength of specimens of a steel with 0.55 % C and 0.75 % Cr in different states with decarburazation and without decarburazation. The influence of decarburazation and of subsequent shot peening is obvious (27,28,29).

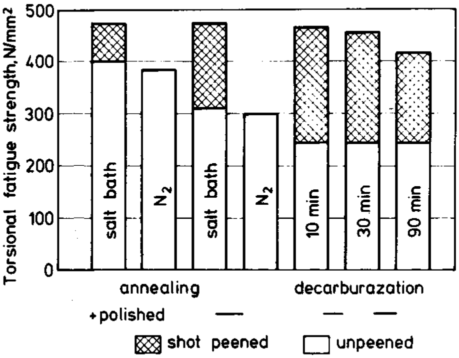

Fig. 6 Influence of shot peening on the torsional fatigue strength of a spring steel in differently quenched and tempered states without and with decarburazation (27, 28,29).

As reasons for a limitation of the efficiency of shot peening have to be considered: the limited depth of surface hardening due to shot peening, the relatively small magnitudes of compressive residual stresses (32), the relatively large surface roughness and possibly the formation of cracks in a pronounced decarburized and consequently soft layer (27).

(59) recommends double peening as an appropriate and optimized technique for shot peening of leaf springs with a decarburized layer (Si-Mn steel, decarburized depth 0.11 - 0.13 mm). Variations of shot diameter and of Almen intensity in the usual peening process with one shot size resulted only in relatively small variations of the increased fatigue life. However subsequent peening with a smaller shot size (0.4 mm) or with glass beads after peening with a shot of a relatively large diameter (0.7 mm) prolongs the fatigue life considerably more than the usual peening, obviously as a consequence of a reduced surface roughness.

The detrimental effects of nonmetallic inclusions in layers close to the surface or of crack like longitudinal scratches in spring steels can be removed by shot peening if these defects are not too large or too deep, for instance smaller than 20 µm in diameter (29,30). Then they can be totally embedded in the field of high magnitudes of compressive residual stresses. Inspection rules for spring steel wire therefore recommend for instance to eliminate all parts with longitudinal crack like groves deeper than 30 µm or with nonmetallic inclusions larger than 15 µm (21). Nonmetallic inclusions in deeper layers of hardened and shot peened materials, where only low compressive or tensile residual stresses are present, can be the initiation sites of subsurface cracks (30).The conditions of subsurface crack initiation are of practical importance and shall be discussed separately.

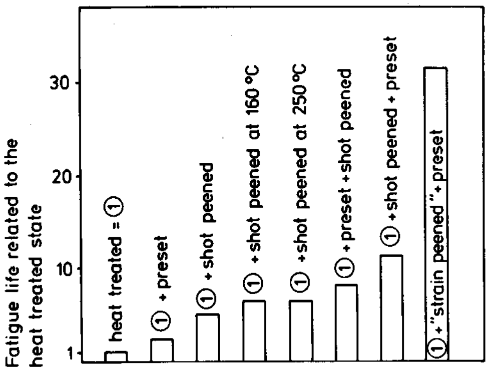

Fig. 7 Fatigue life improvement of specimens of the quenched and tempered spring steel 50 Cr V 4 due to different presetting and shot peening treatments (25,34).

Peening under a tensile load produces particularly high magnitudes of compressive residual stresses - the higher the load prestress the higher the magnitude of the induced compressive resisual stresses (33). Therefore this peening method, called "strain peening", results in especially big improvements of the fatigue strength and is recommendable for structural components as leaf springs. Fig. 7 shows that in comparison with the fatigue life improvement due to strain peening all other variations of peening and presetting can be considered as minor important (25,34) and the paper of (34) indicates additionally that peening under a higher prestress would result in an even bigger fatigue life prolongation. According to the results of (35) strain peening is also particularly effective if spring steels show decarburazation in surface layers (steel with 0.55 % C, ultimate strength ≈1430 N/mm^2, decarburized layer of 0,13 to 0,16 mm thickness).

Overpeening is possible in the quenched and tempered state of spring steels. That is to say the fatigue strength improvement can decrease as a consequence either of excessive surface roughness or of surface cracks in connection with very high peening intensities, for instance very high shot velocities. Nevertheless even with surface cracks due to overpeening the fatigue strength can be higher than in the unpeened state (1,32,36,37). The peening induced compressive residual stresses prevent obviously the propagation of these cracks. (28) reports on a specific overpeening effect in alloyed steels with a low heat conductivity, for instance a steel with 0.5 % C and 1 % Cr. Extremely hard martensitic layers can be formed in such steels due to overpeening and cracks in these layers can initiate the fracture of the spring.

Case hardened gears

Case hardened gears are structural components with very hard surface layers. In such states of the material with hardness values over 600 HV and up to 900 HV it is very important that a shot of nearly the same hardness as the peened material is used. Then the compressive residual stresses can achieve very high magnitudes and these are strongly effective and can be taken as the only or at least main beneficial influence on the fatigue strength. The reason for that is their stability during cyclic loading of such material states (32). The resulting surface roughness has to be taken into consideration as long as crack initiation occurs at the surface.

(40,41) for instance have found fatigue strength improvements of 36 %, 41 % and 33 % if case hardened gears (steel 16 MnCr 5)with moduli of 3, 5 and 8 and with hardness mean values of 565 HV3, 620 HV3 and 501 HV3 have been peened with a shot of a hardness between 54 and 58 HRc and a diameter of 0.58 mm. Peening of gears with a modulus of 5 with a shot of a hardness between 48 and 52 HRc and 0.73 mm diameter resulted in a fatigue strength improvement of only 22 %. This comparatively low fatigue strength improvement could definitely be attributed to the considerably lower magnitudes of compressive residual stresses after peening with the shot of an insufficient hardness. Fig. 8 shows the S-N curves before and after shot peening of gears (steel 16 MnCr 5, hardness approximately 600 HV3) with a modulus of 5 and different notch root radii (40). Obviously the fatigue strength after shot peening and also the fatigue strength improvement (28 %) due to shot peening was markedly bigger for the gears with the larger radius. That is to say, in structural components of hardened steels with

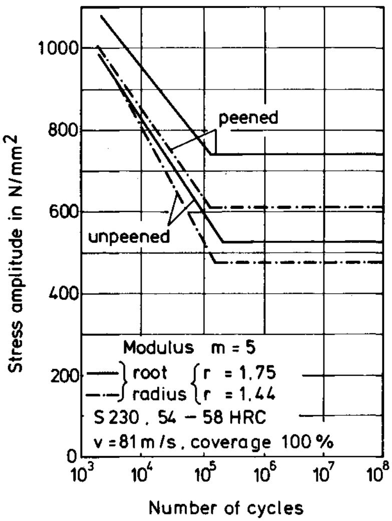

Fig. 8 S-N curves of gears with a modulus of 5 and different root radii before and after shot peening. Steel 16 MnCr 5. Shot diameter 0.58 mm (S230). v = shot velocity, (40

a hardness of approximately 600 HV shot peening cannot compensate completely the fatigue strength reduction due to a notch and therefore it is worth to produce notch radii as large as possible before shot peening.

Shot peening and notch effects

The magnitudes of shot peening induced compressive residual stresses can become especially big in notches, as some results indicate for instance α_n times higher than in flat specimens under the same peening conditions (α_n=notch factor, (1,11,38). But as the following model considerations indicate, the influence of the especially high residual stress magnitudes in notches remains limited - unless the state of the material is extremly hard.

As a basis for the discussion of shot peening effects in notched test pieces, Fig. 9 compares the possible influence of residual stresses on the fatigue strength of notched and unnotched test pieces in material states of a different hardness. The underlying assumption of the schematical diagram is that in each material state only that portion of the residual stresses can become effective which is equal to the difference between the yield strength and the stress

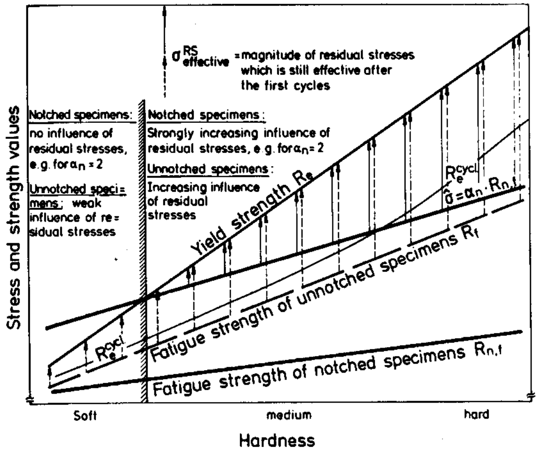

Fig. 9 Schematical representation of the residual stress magnitudes $\sigma^{RS}_{effective}$ which can be still effective after the residual stress reduction during the first cycles of loading. Comparison of $\sigma^{RS}_{effective}$ for notched and unnotched specimens of a different hardness. Re^{cycl} = cyclic yield strength (for comparison), $\hat{\sigma}$ = peak stress amplitude of notched specimens, α_n = notch factor.

amplitude - respectively the peak stress amplitude for notched specimens. Residual stress magnitudes which surpass this difference are relieved during the first cycles of cyclic loading. In (42) the load induced relief of residual stresses and its dependence on the hardness of a material is explained in detail on the basis of experimental results for flat specimens. The difference between the yield strength and the stress amplitude for infinite life respectively the fatigue strength is very small in the soft state of a material and increases with increasing hardness of the material. Therefore that portion of the residual stresses ($\sigma^{RS}_{effective}$) of flat specimens which can have an influence on the fatigue strength is very small in the soft state and increases with increasing hardness. For notched specimens the increase of the fatigue strength with increasing hardness is less steep than for flat specimens. The peak stress amplitude in the notch ($\hat{\sigma}$) is however higher than the nominal stress amplitude of the fatigue strength and may be even higher than the yield strength of a soft material. Consequently no influence of shot peen induced residual stresses can be anticipated in notched specimens of soft materials and notched specimens should show also a markedly smaller influence of residual stresses on the fatigue strength than flat specimens in the state of a material with medium hardness. But as Fig 9 demonstrates, the effective magnitude of residual stresses ($\sigma^{RS}_{effective}$) increases more rapidly with increasing hardness for notched specimens than for flat specimens and hence in an extremely hard state of a material the influence of residual stresses on the fatigue strength can become nearly equal for notched and for flat specimens. For comparison the diagram indicates also schematically the cyclic yield strength, which governs the continuous fading of residual stresses after the first cycles (42). Effects of the multiaxiality of the residual stress state in a notch are neglected in this simple model.

These model considerations are at least a first approach to explain the discrepancies between the results (6,40) and (1,39) concerning the compensation of a fatigue strength reduction due to notch effects. As already quoted, (6) has found for welded joints (hardness ≈ 260 HV) and (40) for gears (hardness ≈ 600 HV) that shot peening cannot completely remove the fatigue strength reduction due to the appertaining notches. Experimental results of (1,39) reveal on the contrary nearly the same fatigue strength under completely reversed bending of case hardened and subsequently shot peened specimens (≈900 HV) with a notch (α_K = 1.6) and without a notch. In accordance with the above-mentioned model the extremely high magnitudes of compressive residual stresses (1500 N/mm^2) in a notch of an extremely hard material can obviously be so effective as to completely remove the fatigue strength reduction due to the notch. It has to be emphasized however that this result is restricted not only to an extremely hard material but presumably also to a limited notch factor and that even under these conditions the registered fatigue life of the notched specimens was markedly shorter than that of the unnotched specimens (1, 39).

Subsurface crack initiation

Subsurface crack initiation as a typical phenomenon in cyclically loaded hardened and shot peened materials is a direct consequence of the very high magnitudes of compressive residual stresses which are induced in a relatively shallow surface layer by shot peening. It has to be assumed that this surface layer has got a higher fatigue strength than deeper layers with small compressive or even tensile residual stresses. That is to say in this surface layer higher tensile load stresses are necessary for crack propagation than in deeper layers.

These assumptions and the conditions for subsurface crack initiation can be explained in detail and quantitatively with the concept of local fatigue strength improvement (1,42,43,44,45). The concept is based on the afore mentioned idea that due to the effect of different magnitudes of compressive residual stresses the surface and each layer below the surface have locally different fatigue strength values. If the fatigue strength of the material without residual stresses and the distribution of residual stresses versus depth below the surface are known, the local fatigue strength improvement due to the local magnitude of the compressive residual stress can be calculated. An appropriate equation for this calculation is $\Delta R_f = m \cdot \sigma^{rs}_{local}$, where m is an empirical value which is close to 0.4 for hardened materials (1,42,46).

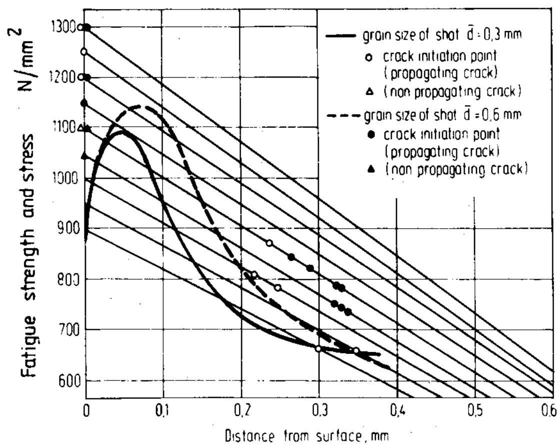

Fig.10 Schematical illustration of subsurface crack initiation on the basis of the local fatigue strength concept. Thick drawn lines = local fatigue strength distributions. Thin drawn lines = bending load stress lines. Circles and triangles = experimentally determined crack initiation sites,(43).

Fig. 10 exhibits curves of the local fatigue strength versus depth below the surface as thick drawn respectively thick drawn dashed lines. These curves are based on measured residual stress distributions after shot peening with a shot diameter of 0.3 mm respectively 0.6 mm and are calculated point by point in the above-mentioned way. It seems logical to compare the load stress lines, for instance for bending (thin drawn lines in Fig. 10), with the local fatigue strength curve and to assume that fatigue cracks can only initiate in those depth zones where the load stress is higher than the local fatigue strength. According to this consideration at high stress amplitudes the surface should be the crack initiation site, but for lower stress amplitudes fatigue cracks can only initiate in distinct depths below the surface. The surface value of that load stress line which just does not cross the local fatigue strength curve defines the fatigue strength of the shot peened material with compressive residual stresses. As can be seen in Fig. 10, the depths of the crack initiation sites which have been observed in scanning electron micrographs of fracture surfaces, agree well with the possible depth values predicted by the described concept (open and full circles in Fig. 10). For medium stress amplitudes small cracks could be detected at the surface, but obviously the propagation of these cracks was stopped in small distances below the surface by the high magnitudes of compressive residual stresses respectively the high local fatigue strength values (open and full triangles in Fig. 10).

Subsurface crack initiation has the practically important consequence that the distribution of compressive residual stresses in deeper layers below the surface becomes important for the attainable fatigue strength improvement. Fig.11 offers a schematical illustration to this fact (42). The thick drawn lines and the dotted line represent different distributions of the local fatigue strength R_f (z) as they result from different distributions of compressive residual stresses versus depth below the surface. The thin drawn load stress lines demonstrate that each of the different local fatigue strength distributions allows a different maximum load stress at the surface without crack initiation. This maximum surface load stress which is indicated by that load stress line which remains just completely below the local fatigue strength line, represents the fatigue strength of the corresponding specimen. As one can see, the attainable fatigue strength is higher the deeper the schematically exaggerated "knee" of the local fatigue strength distribution is. That means practically, the thicker the layer with compressive residual stresses the bigger can the fatigue strength improvement be and therefore peening conditions are preferable which produce relatively thick layers of compressive stresses.

Another consequence of the described subsurface crack initiation is the fact that the fatigue strength respectively the fatigue strength improvement due to shot peening can become lower the bigger the bending height respectively the thickness of the test piece is. Experimental results from (42,44,45) confirm a bending height dependence of the fatigue strength after shot peening of very hard, unnotched specimens of an unalloyed carbon steel (0,45 % C, 840 HV 0.1) in the thickness range between 2 mm and 6 mm. In the thickness range between 10 mm and 14 mm nearly constant fatigue strength values were observed, which were equal to the fatigue strength of hardened and electrochemically polished specimens with zereo residual surface stresses but appreciably higher than the fatigue strength of hardened specimens with the original tensile surface stresses due to hardening. In the quenched and tempered and subsequently shot peened state (610 HV 0.1) of the specimens no subsurface crack initiation and nearly no bending height dependence of the fatigue

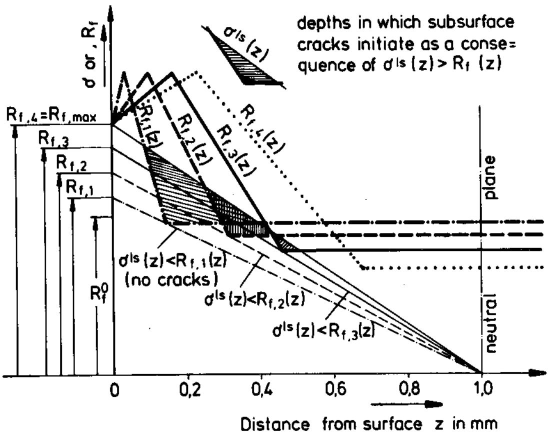

Fig. 11 Schematical illustration of different fatigue strength values $R_{f,i}$; which are attainable in connection with different distributions of the local fatigue strength $R_{f,i}(z)$ respectively in connection with different distributions of compressive residual stresses. R_f^0 = fatigue strength in the residual stress free state. σ^{ls} (z) = load stress distribution (42)

strength could be determined. The practical consequences of these experimental findings have still to be pursued carefully.

Titanium alloys

Investigations concerning the influence of shot peening on the fatigue behaviour of specimens of titanium alloys revealed the following main results. The range of peening conditions which result in an improvement of the fatigue strength compared with the milled state is very limited. (1) reports for instance that peening of unnotched specimens of the aged alloy Ti-6Al-4V with steel shot of 0.45 mm diameter (A = 0.25 mm) and subsequently with glass beads led to an improvement of the bending fatigue strength (R = -1) of ≈30 %. However after peening with steel shot only the fatigue strength has fallen the more below the fatigue strength of the milled specimens the higher the Almen intensity was. The differences of the fatigue strength could be related to differences in surface roughness, which was big after peening with steel shot - especially with a high Almen intensity - and was smoothened by additional peening with glass beads. The surface roughness of the notch sensitive titatnium alloys has obviously a strong influence on the fatigue strength.

According to (47,48) surface hardening contributes markedly to the improvement of the fatigue strength under rotating bending after shot peening of the alloy Ti-6Al-4V.

It has to be noted that shot peening can produce extremely high magnitudes of compressive residual stresses in titanium alloys (49, 50,51) and that residual stresses have a strong and often dominating influence on the fatigue strength of titanium alloys. Quantitative results of (52) indicate that the influence of residual stresses on the fatigue strength of the alloy Ti-6Al-4V is as strong as in hardened steels (sensitivity for residual stresses $\Delta R_f/\sigma_{rs}$ = 0.4).

It is in agreement with this strong influence of residual stresses that subsurface crack initiation occurs in cyclic loading of shot peened titatnium alloys (47). Detailed investigations of (47,51,53) reveal that subsurface crack initiation is a reason for a number of rather complicated results concerning the fatigue behaviour of the shot peened alloy Ti-6Al-4V. (47) attributed subsurface crack initiation to a subsurface maximum of the tensile residual stresses which balance the compressive residual stresses in layers close to the surface.

In rotating bending fatigue tests of unnotched and of notched specimens of the alloy Ti-6Al-4V shot peening with steel shot (0.3 mm diameter) caused mainly an increase of fatigue life and fatigue strength in comparison with the electrochemically polished state (48). The amount of the fatigue strength improvement depended upon the type of the microstructure of the specimens and on the peening conditions. With increasing peening pressure as well as with increasing peening time the fatigue strength of age hardened specimens attained a maximum (51). Higher peening pressures respectively peening times than those corresponding to the maximum resulted again in a decrease of the fatigue strength which could be more or less pronounced. The overpeening effect due to an excessive peening pressure is thought to be a consequence of an increase of the subsurface tensile stress maximum which promoted early subsurface crack initiation. The overpeening effect due to a prolongation of the peening time after reaching saturation (100 % coverage) had to be attributed to cyclic softening during prolonged peening. A softening of surface layers after an extended peening time could be revealed with micro hardness measurements, whereas the surface roughness reached a saturation value already at relatively short peening times. In a softened surface layer the compressive residual stress magnitudes decrease more rapidly and more pronounced during fatigue loading and thus a reduction of the fatigue life compared with that one after optimum peening exposure time is understandable. Whether this overpeening effect is weak or strong - and may result in a fatigue strength which is lower than that one of the electrochemically polished specimens - depends upon the sensitivity of the alloy and its microstructure to cyclic softening. Alloys which were not age hardened showed no overpeening effects (51).

In tension - compression fatigue tests mainly a lower fatigue strength after shot peening (steel shot, peening pressure 4 bars, peening time 4 min) was observed than after electrochemically polishing (53). As an example Fig. 12 exhibits the S-N-curves for electropolished specimens and for shot peened specimens with a coarse lamellar microstructure. The decrease of the fatigue strength - even in connection with otherwise optimum peening conditions - is attributed to the subsurface tensile residual stress maximum which can be especially detrimental as in tension - compression loading the full load stress

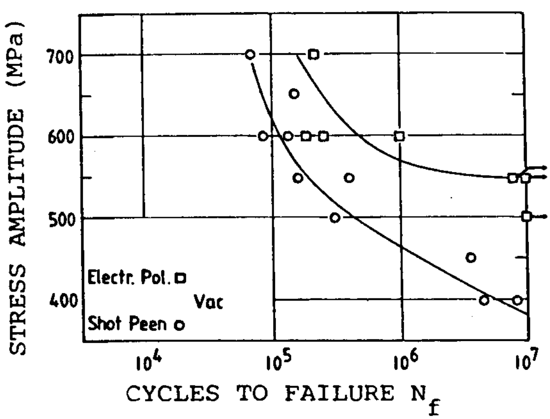

Fig. 12 S-N curves of electrochemically polished and of shot peened specimens of the alloy Ti-6Al-4V. Tension-compression loading in vacuum. Coarse lamellar structure, (53)

is effective in any depth below the surface. Therefore, according to the model considerations for steels (Fig. 11), a decrease of the fatigue strength compared with the more or less residual stress free state of the electropolished specimens has to be anticipated. Interesting enough shot peening resulted in an improvement of the tension-compression fatigue strength exactly for a microstructure and a loading direction (fine equiaxed structure loaded in the rolling direction) in which cyclic softening is particularly pronounced. It is thought that an early and pronounced decay of the subsurface maximum of tensile residual stresses led to crack initiation at the surface and made the fatigue strength improvement possible (53). It should be checked whether the reported detrimental effect of subsurface crack initiation in tension-compression loading can also occur in bigger structural components, as one can suppose that such parts would not contain very pronounced maxima of tensile residual stresses below the surface after peening.

(54) reports on variable amplitude tests ("Falstaff" stress sequence) on notched specimens (K_t = 1.6) of the alloy Ti-6Al-4V. Shot peening was able to improve the fatigue life by a factor of two, the same factor as was found for constant amplitude loading of notched specimens. It is interesting to note that peening was partly performed successfully with an especially hard shot (HRc62).

Investigations of (55) indicate that shot peening is also a method to improve the fatigue life of Ti-6Al-4V powder compacts - particularly in the high cycle fatigue range. Despite partial closure of surface porosity the fatigue crack initiation in peened material still occured at surface and near-surface porosity.

Aluminium alloys

Aluminium alloys can be peened with steel shot, with beads of aluminium oxide or with glass beads - respectively with steel shot and subsequently with glass beads (56). (57) were able to show that peening with a cast iron shot (0.43 mm diameter, hardness 46-50 HRc) or with glass beads (0.125 - 0.250 mm diameter) resulted in nearly the same distributions of compressive residual stresses and also of the half width of X-ray diffraction lines and of the hardness versus distance from the surface, if the Almen intensity was nearly the same for both peening media. Consequently the S-N-curves of fatigue tests under completely reversed bending of flat specimens of the alloy Al-5Cu-2Mg were also nearly identical after peening with cast iron shot respectively with glass beads with a nearly equal intensity. The investigations of (57,58) revealed furthermore an increase of the bending fatigue strength (R = -1) with increasing Almen intensity (A = 10 mm to 30 mm), whereas the differences in the fatigue life after peening with different intensities decreased with increasing stress amplitudes, presumably as a consequence of the decay of compressive residual stresses during the first few cycles which became more pronounced the higher the stress amplitude was. The shot peening induced fatigue strength improvement as against the electropolished state was different for the differently heat treated states of the material "as received" (rolled), "underaged" and "peak aged". The differences between the fatigue strength and fatigue life values of these different material states could be explained as consequences of different magnitudes of shot peening induced compressive residual stresses, different amounts of work hardening and a different micro notch sensitivity of the materials. Accordingly it is sure that also in aluminium alloys the surface roughness, the work hardening and the compressive residual stresses in surface layers determine together the fatigue strength respectively the fatigue strength improvement by shot peening. (56) reports on fatigue life improvements in cyclic bending tests of aluminium I-beams. A sufficiently high peening intensity and peening time with steel shot was necessary to get an appreciable fatigue life improvement. Peening only with glass beads resulted in the lowest fatigue life prolongation whereas peening with steel shot and subsequently with glass beads led to the longest fatigue life, presumably due to a smoothening of the surface roughness by the final glass bead treatment.

Summary

From the quoted experimental results the following conclusions can be drawn:

Optimization of peening conditions

From experiments with specimens it is well established that with respect to an optimized fatigue behaviour the shot peening induced surface roughness should be as low as possible whereas the shot peening induced work hardening in surface layers as well as the magnitudes of the compressive residual stresses should be as high as possible and the layer with compressive residual stresses should be as thick as possible. There is no doubt that these rules should be obeyed in principle also in practical applications - even if in practice compromise have to be made. To attain these conditions, at least as good as possible, the following indications have to be observed:

- Sharp indentations in the peened surface have to be avoided under any circumstances, especially in notch sensitive materials as for instance Ti-alloys. That means that broken shot has to be separated carefully.
- A coverage below 98 % respectively 100 % would include the risk of islands with tensile residual stresses at the surface and has therefore to be avoided (49)
- If shot peening is restricted to zones which are crack sensitive in fatigue loading the width of the shot peened zones has to be sufficiently wide and is has to be taken into consideration that very high stress amplitudes, for instance due to overloading, may induce then fatigue cracks in the unpeened zones.
- It is very important to choose a type of peening medium which is adequate to the kind of the peened material. Steel shots, glass beads and ceramic beads are availabe. For the effectiveness of ceramic beads it is referred to (64,65) in the Conference Proceedings.
- It is highly important that the shot hardness is adequate to the hardness of the peened material. Peening of hardened or case hardened steels has to be performed with an especially hard shot (1, 40, 41).
- The higher the yield strength of a peened steel the higher is the peening intensity which is necessary for optimum fatigue strength (3). If the peening intensity is not sufficiently high, the fatigue strength of shot peened welded joints of notch sensitive high strength structural steels, for instance, can become even lower than that one of shot peened welded joints of steels with a lower yield strength (3). If aluminium testpieces are peened only with glass beads the Almen intensity is normally not big enough as to get optimum fatigue strength. It can be necessary to use a relatively big shot diameter to get a sufficiently high Almen intensity.
- The fatigue strength of steels reaches a saturation value or a flat maximum with increasing peening intensity (3,32,37). The fatigue strength of titanium alloys can reach a rather pronounced maximum with increasing peening intensity (51).
- Overpeening is possible in connection with high peening intensities: the

fatigue strength improvement can decrease again, for instance at very high shot velocities as a consequence of excessive surface roughness or of surface cracks (32,37) or at excessive peening times of titanium alloys as a consequence of cyclic softening (51). Even if the danger of overpeening should not be overestimated for steels, as it occurs only at extremely high peening intensities, it must be avoided by carefully controlling the peening conditions and the peened surface.

- Continuous controlling of all peening parameters is a nowadays possible and useful method to ensure optimum results with respect to the fatigue strength (60,61).
- Double peening is recommendable under distinct conditions. It can be important, for instance in weldments, to treat sharp notch like defects with a small steel shot at first and afterwards to reach a sufficiently high peening intensity with a bigger shot (8,9). On the other side it is obviously possible to smoothen the surface roughness after peening with steel shot by subsequent peening with a smaller steel shot or with glass beads, if the surface of the material is sufficiently ductile as it may be in welded joints (6,7) or in structural components with decarburized layers (59) or in aluminium components (56).
- Strain peening can be recommended as particularly favourable peening method for all components which can be prestressed with a tensile load during peening without the danger of cracking.

Optimization of other manufacturing processes in connection with shot peening

The result of a shot peening treatment depends also on the other manufacturing processes before and after peening. The following rules can be layed down.The effect of shot peening can be especially pronounced and beneficial, that is to say the fatigue strength improvement due to shot peening can be especially big if components with distinct kinds of damage in surface layers or with other kinds of incompleteleness are peened.

- Shot peening is for instance able to compensate detrimental effects of scaling, decarburazation and/or oxidation as well as of inclusions in surface layers (18,19,21,27,28,29,35,59). But the fatigue strength of the shot peened state without any surface damage can only be reached - or at least nearly reached - if the mentioned kinds of surface damage are not too pronounced (27,28,29).
- Shot peening is also able to lower the fatigue strength reduction due to geometrical notches considerably. But a complete compensation of the detrimental notch effects, that is to say an enhancement of the fatigue strength of a notched testpiece up to the value of the unnotched testpiece, is only possible in a very limited number of cases, for instance if unnotched components with a roller skin are the basis for comparison or - as some experiments indicate (1) - in extremely hard states of steels.
- Mostly shot peening can bring the fatigue strength to a higher absolute value the lower the stress concentration factor is, as has been shown for instance by (40,41) for gears or by (6,7) for welded joints. Therefore if one wants not only to compensate for distinct detrimental effects in fatigue loading, but wants to make the best use of shot peening, it is worth to bring the material and the component into the best condition before shot peening. The combination of adequate manufacturing methods with shot peening offers a great potential for the achievement of high fatigue strength values of structural components. Examples are the combination of shot peening with an advanced welding technique which produces extremely flat weld seam profiles by (6,7) or the combination of grinding of the weld toes and subsequent shot peening by (62).

The present state of knowledge does not allow a comment whether mechanical treatments following shot peening, for instance to smoothen the surface roughness, can be recommended in general - although experimental results indicate that electrochemical polishing of quenched and tempered and shot peened steel specimens can improve the fatigue strength considerably (1,32). But it is not known in detail how mechanical post treatments like lapping would change the shot peening induced distribution of compressive residuals stresses. In any case, it has to be emphasized that normal grinding with a hand grinding tool introduces relatively high magnitudes of tensile residual stresses in a thin surface layer and should therefore be avoided after shot peening (22,63)

Effectiveness of shot peening treatments

- It is experimentally verified that shot peening improves the fatigue behaviour of steels in the normalized or quenched and tempered state under bending loading (1-9, 14-22, 24-37, 59) under tension-compression loading (6,7,14) and under torsional loading (27,28,30,31).
- In hard states of steels it has to be taken into account that as a consequence of subsurface crack initiation the fatigue strength after shot peening becomes in principle dependent on the bending height. In any case a fatigue strength improvement was observed in comparison with the hardened state with tensile residual stresses at the surface (42,43,44,45). No detailed information is available about the tension-compression fatigue behaviour of shot peened steels in a hard state.
- For the titanium alloy Ti-6Al-4V shot peening induced fatigue life and fatigue strength improvements are reported for completely reversed bending (1) and for rotating bending (47,48,51), whereas under tension-compression loading of age hardened microstructures a decrease of the fatigue life and of the fatigue strength was also observed after shot peening and attributed to subsurface crack initiation as a consequence of a subsurface tensile stress maximum (51,53).
- Experimental results for aluminium alloys show for instance an improvement of the fatigue behaviour under bending loading (56,57).
- In general shot peening is more effective in the high cycle range of S-N-curves than in the low cycle fatigue range: the fatigue life prolongation decreases mostly with increasing stress amplitudes in the finite life range. These findings are a consequence of the decreasing effectiveness of the shot peening induced compressive residual stresses which decrease during the first few cycles more pronounced and more rapidly if the stress amplitude is enhanced (42).
- A number of experimental results proves that shot peening can produce a fatigue life improvement under variable amplitude loading of steels (3,8, 9, 16) as well as of the titatnium alloy Ti-6Al-4V (54).
- Experimental results of (8,9) about the effect of tensile or compressive preload cycles on the shot peening induced compressive residual stresses and on the lifetime in a following constant amplitude test support the findings about the effectiveness of shot peening in variable amplitude tests and offer also some information about the possible effectiveness of shot peening in fatigue tests with mean stresses (R = -1). According to the results of (8,9) shot peening should be very effective in fatigue tests with tensile mean stresses and could be less or even not effective in tests with compressive mean stresses.
- Fig. 13 indicates schematically (e.g. with the arrows) that shot peening - if properly performed - is more effective the higher the ultimate strength of a material is. As a consequence of subsurface crack initiation the effectiveness of shot peening is limited for thick test pieces in a

hard state of a material.

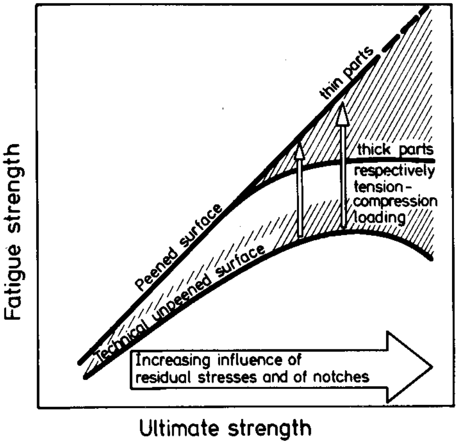

Fig. 13 Schematical representation of the effectiveness of shot peening in material states of a different hardness

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