Fatigue Strength of Case Hardened and Shot Peened Gears

Communication from the Institut für Werkstoffkunde I, Universität Karlsruhe
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1. Introduction

Shot peening is a production treatment for components as for example springs, shafts or gears resulting in improvements of the fatigue strength. Shot peening induced changes occur in the surface of the workpiece and in layers close to the surface. These changes enclose the surface topography, characterized by the values R_{max} and R_a of surface roughness, residual stresses and their depth profiles as well as work hardening in surface layers. Often, investigations on small laboratory specimens are used for optimizing of the shot peening parameters and for determination of basic relations about the fatigue behaviour /1-3/. Whether the hereby obtained results can be transferred to components has to be controlled in separate component tests. The present paper reports on results of shot peened gears and gearlike specimens, which not have been machined after heat treatment.

2. Experimental Details

2.1 Material, heat treatment and dimensions of gears and specimens

One batch of the case hardened steel 16MnCr5 (German specification) with the chemical composition given in Table 1 was used for the production of the gears. All test components have been heat treated togehter. Carburizing has been carried out in endogas with a CO_2-content of 0.21 % for nine hours at a temperature of 940°C. After cooling to 830°C and holding for 1 hour at this temperature the test objects have been hardened in oil of 60°C and annealed for 1.5 hours at 170°C. This heat treatment resulted in a surface carbon content of 0.80 to 0.85 Mass% and a case hardening depth (EHT HV 550) for 550 HV of > 1mm. Gears with 23 teeth and a modulus of 3, 5 or 8 mm were used. Fig. 1 illustrates the shape and dimensions of the gearlike specimens, in the following called "specimens". The dimensions of the gears, as well as of the specimens (variation of thickness D and notch radius R) are given in Table 2.

2.2 Shot peening treatments

Recent investigations (17, 18) showed higher increases of the fatigue limit under fully reversed bending of case hardened flat specimens if a shot with a high hardness (54-58 HRC) was applied compared with peening with a shot of normal hardness (48-52 HRC) and otherwise equal peening conditions. Therefore the presented investigations made predominantly use of a high hardness shot (cut wire steel shot S 230, mean diameter d = 0.58 mm, 54-58 HRC) in a wheel type peening machine. The shot velocity was 81 m/sec and the coverage 100 %. This peening condition has been the optimum one for flat case hardened bending fatigue specimens /1, 17, 18/ and led to an Almen intensity of 0.47 mm A2 /4/. Additionally a shot peening treatment with S 330 (mean diameter d = 0.73 mm), a shot hardness of 48-52 HRC, 73 m/sec shot velocity and 100 % coverage was carried out for some gears. An Almen value of 0.72 mm A2 was measured for this treatment.

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Element	C	Si	S	P	Mn	Cr
	0,13	0,2	0,025	0,009	1,23	1,09
Element	Ni	Mo	V	Cu	Al	B
	0,13	0,04	0,014	0,16	0,045	0,008

Table 1: Chemical composition of the material used

Gears (23 teeth)				"gearlike"specimens	
Modulus (mm)	Width (mm)	Pitch diameter (mm)	Tooth bottom radius (mm)	Thickness D (mm)	Notch radius R (mm)
3	20	69	1,1	5	1,0
5	30	115	1,44	8	1,0
5	30	115	1,75	8	2,5
				8	6,25
8	50	184	3,2	13	6,25

Table 2: Dimensions of the gears and the specimens

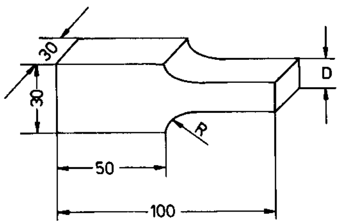

Fig. 1: Shape and dimensions of the "gearlike" specimens

Another aim of the research program was to compare the results of peening treatments with the wheel type machine with results of similar treatments in an air blasting equipment. Therefore peening was also performed in an air blasting machine whose nozzle was moveable in all directions and offered the possibility for an exact treatment of components with a difficult shape. For example the notch root at the bottom of the gear teeth could be peened under an angle up to 75° whereas at the notch root of the specimens an angle of 90° could be reached. In the wheel type machine a relatively broad scatter of the peening angle is caused by the process itself. In the air blasting machine a shot

(S 230) with a high hardness (54-58 HRC) was used with a peening pressure of 6,4 bar and 300% coverage. An additional glass bead peening (glass beads with 120 µm mean diameter, a peening pressure of 1 bar and 100 % coverage) should prove the effectiveness of this treatment.

2.3 Residual stress measurements

The residual stresses were determined by X-ray measurements with a ψ-diffractometer and by the so-called $\sin^2 \psi$ - method with chromium-K_α-radiation. The residual lattice strains of {211} planes of the martensite were measured from the shifts of the appertaining interference line profiles in the following directions against the surface normal of the notch root: gears: ψ = 0°, ± 8°, ± 16°, ± 24°, ± 32°; specimens: ψ = 0°, ± 9°, ± 18°, ± 27° and ± 36°. The 2Θ-position of the interference lines was determined by the middle of the peak width for 66 % of maximum peak heighth. Depending on the problem different diaphragms were used. All specimens were measured with a slit shape aperture of 0,3 x 7 mm². Square shaped apertures of 0,2 x 0,2 mm², 0,5 x 0,5 mm² and 1,0 x 1,0 mm² were used for the gears with modulus 3, 5 and 8 mm. A special type of aperture in front of the scintillation counter led to symmetric line profiles.

Measurements of the circumferential residual stresses couldn' t be realized without a mechanical change of the geometry of the gears. Therefore at four tooth gaps, each in a distance of 90° from the other, axial residual stresses were determined in the notch radius on both sides of the bottom of the gap (see Fig. 2).Then one of the adjacent teeth was removed by spark erosion and the axial residual stresses were measured again at the original locations. Actually measurements of the circumferential residual stresses as a function of the depth were made at that location with the smallest changes in the axial residual stresses before and after spark erosion removing of the next tooth. In most cases no changes in the axial residual stresses occured after the spark erosion treatment. In Fig. 2 the geometrical conditions are illustrated for the measurement of the circumferential residual stresses.

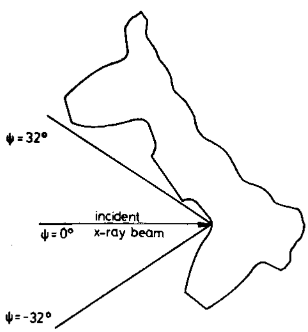

Fig. 2: X-ray path for measuring the circumferential residual stresses at the bottom of the teeth.

Residual stress distributions versus depth below the surface were determined by measurements after elctrochemically removing material layers with thicknesses of 0,04; 0,08; 0,10; 0,15 and 0,5 mm. From all interference lines the width at half maximum was calculated and is named as half width.

2.4 Measurements of the amount of retained austenite

For selected heat treatments and geometries of gears and specimens the amount of retained austenite was determined by means of the X-ray phase analysis /6/. According to /7/ the retained austenite content was calculated after measuring diffraction line intensities of the {211}-planes of the martensite and the {220}-planes of the austenite with chromium K_α-radiation. The accuracy of the measurements was proved with standards.

2.5 Fatigue tests

Cyclic loading with a sinusoidal load-time-function was conducted with individual teeth of the gears and with the specimens in resonance fatigue testing machines. All tests were performed in the bending mode with a R-ratio of 0. S-N curves were established by testing six specimens on each of four stress levels. The fatigue limit was determined with 3 x 6 samples on three different stress levels, while the low cycle region was verified with only 6 samples on one stress level. The data were interpreted with the arc sin $\sqrt{p}$ transformation method /8/. 10^7 cycles were taken as limiting number for the evaluation of the fatigue strength. The quoted fatigue limits for a R-ratio of zero refer to a fracture probability P of 50%.These values represent the resistance of the material against fatigue fracture in the notch root with the character of nominal stresses.

Fatigue tests of the gears were conducted according to DIN 3990 part 3. For each of four to six stress levels up to 4 teeth were loaded in the same way as the specimens. Teeth with a number of cycles higher than $5 \cdot 10^6$ were formally estimated to be run-outs. The fatigue limits of the gears were calculated with the arc sin $\sqrt{p}$-method as well as with the staircase-method /9/. Both methods showed only small differences in the calculated fatigue limits. In the case of a big difference the mean value of both calculations was formed. The quoted values represent fatigue limits for a limiting number of cycles of $5 \cdot 10^6$ and a fracture probality of 50 %.

3. Results

The investigations on gears and specimens included variations of the shot peening parameters, of the geometry and of the content of retained austenite. The test objects were not machined after the conventional heat treatment. Therefore all gears and specimens show damage in a surface layer of about 10 µm thickness provable by exact inspection.

3.1 Variation of shot peening parameters

3.1.1 Depth profiles of residual stresses, half width and hardness

Fig. 3 shows residual stress and half width distributions of unpeened and peened gears with a modulus of 5 mm. The residual stresses of the unpeened gears increase from the surface value of -515 N/mm^2 to -110 N/mm^2 in a depth of 0,1mm. For greater distances from the surface an decrease to a value of -360 N/mm^2 in 0,5 mm depth is observed.

The residual stress distributions of peened gears show the typical maximum of residual stresses below the surface and a continuous increase to the values caused by the heat treatment in bigger distances from the surface. Different shot peening treatments result in different thicknesses of layers with high magnitudes of compressive residual stresses and different values of the maximum of compressive residual stresses. With the shot S 330 of a normal hardness only a maximum residual stress value of -810 N/mm^2 in a depth of 0,03 mm is obtained

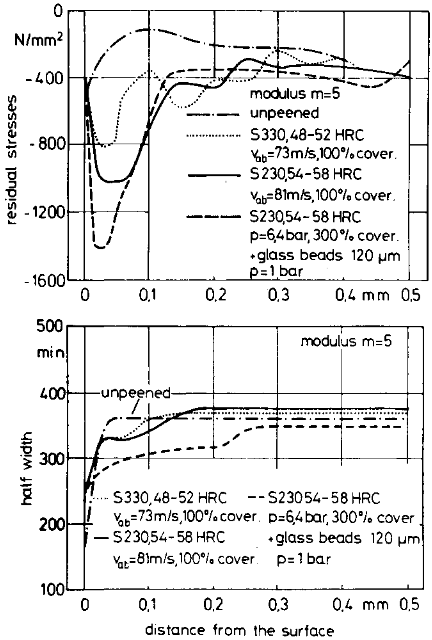

Fig. 3: Distributions of residual stresses and half widths for case hardened and shot peened gears with a modulus of 5

S 330 = cut wire shot with 0.73 mm mean diameter

S 230 = cut wire shot with 0.58 mm mean diameter

V_{ab} = shot velocity

p = air pressure

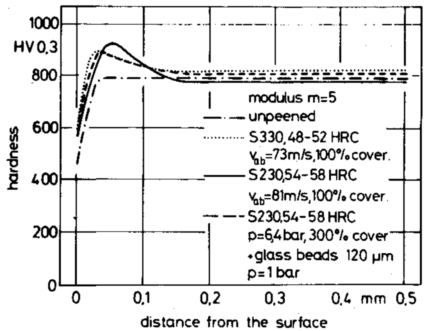

Fig.4: Hardness distribution HV0.3 for case hardened and shot peened gears with a modulus of 5

and in 0.1 mm depth the values of residual stresses induced by the heat treatment are reached. The high hardness shot however leads to a maximum residual stress value of -1020 N/mm^2 in a depth of 0.03 to 0.06 mm for peening with 100% coverage, and to a value of -1423 N/mm^2 in a depth of 0.02 mm for peening with 300 % coverage and additional glass bead peening. The half widths of the X-ray interference lines of unpeened gears have low values at the surface which are caused by the damage due to the heat treatment. These values increase up to 360 min within a depth of 0.03 mm and remain constant for bigger surface distances. After peening higher half width values at the surface of the gears occur, compared with the unpeened gears. Different penetration depths of the varied shot peening treatments could be demonstrated by the half width values too, reaching the values of the unpeened gears in different distances from the surface. In the depth of the maximum residual stresses there is a typical small decrease of the half width values known for hardened and shot peened steels.

Hardness distributions HV0.3 are indicated in Fig. 4. A higher hardness is obtained for the shot peened gears in the depth of the residual stress maximum compared to the unpeened gears (see Fig. 3). In surface distances > 0,15 mm no differences appear in the hardness versus depth profiles of the differently treated gears which would be more pronounced than the normal scatter of the hardness values due to production and measuring errors.

Fig. 5. shows residual stress and half width distributions versus depth below the surface for the specimens. The residual stresses resulting from heat treatment increase drastically in a surface layer of 0.03 mm thickness and oscillate between values of -50 N/mm^2 and -200 N/mm^2 in deeper layers. There is a satisfying correlation between the residual stress distribution of the gears (see Fig. 3) and the corresponding one for the specimens after shot peening with high hardness shot and 100 % coverage on the wheel type machine. Higher values of the maximum compressive stresses occur - analogous to the results for the gears - if compressed air peening with the same hard shot, 300 % coverage and additional glass bead peening was used. The layer with high magnitudes of compressive residual stresses - for example with magnitudes > 400 N/mm^2 - shows an increased thickness of 0.2 mm for the compressed air peening of the specimens compared with 0.12 mm after the same peening procedure of the gear. The obtained maximum values of compressive residual stresses are lower for the specimens than for the gears with a modulus of 5 after each comparable shot peening treatment.

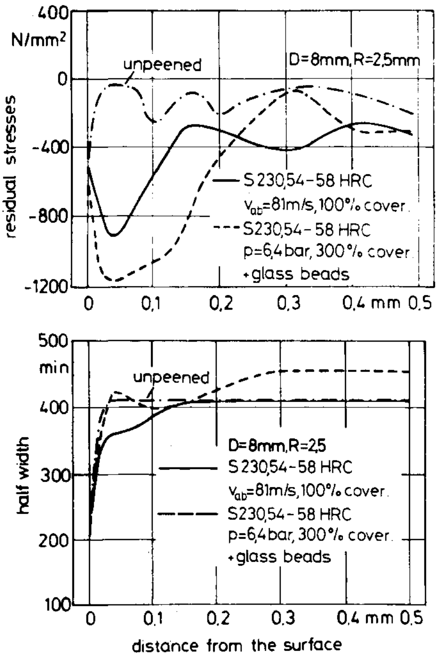

Fig.5: Distribution of residual stresses and half widths for case hardened and shot peened specimens with a notch radius of R = 2,5 mm

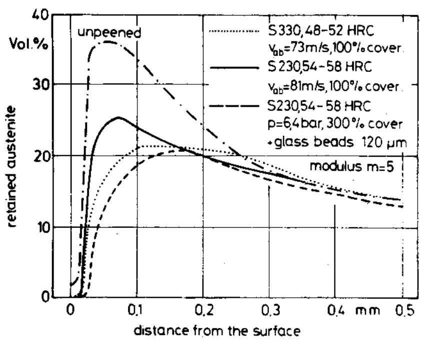

Fig. 6: Distribution of retained austenite for case hardened and shot peened gears with a modulus of 5

3.1.2 Depth profiles of retained austenite

Fig. 6 indicates the results of retained austenite measurements on the gears after peening with different peening parameters. In the unpeened state the retained austenite increases from 2 Vol. % at the surface to a value of 36 % in a depth of 0.05 to 0.07 mm and then decreases again in bigger surface distances to a value of about 13 %. Shot peening with a high hardness shot (S 230) and 100 % coverage causes a decrease of the content of retained austenite to 26 Vol. % in a depth of 0.08 mm. The gears peened with 300 % coverage show in this depth an additional decrease of the retained austenite content to 15 - 17 Vol.%. After peening with S 330 the content of retained austenite is about 20 % in a depth of 0.08 to 0.09 mm, remains constant at this level down to a depth of 0.25 mm and then decreases steadily with increasing depth as also indicated for the other two peening treatments. The retained austenite contents of the unpeened and peened gears meet each other in a depth of about 0.20 to 0.25 mm. As demonstrated in Fig. 6 the peening treatment with S 330 results in a bigger amount of strain induced retained austenite transformation than the peening with the hard shot S 230 and 100 % coverage. Similar results have been obtained for the specimens /4/.

3.1.3 S-N-curves

The effects of the different shot peening treatments on the S-N-curves of gears and specimens are shown in Fig. 7a und 7b. Shot peening with the shot S 330 (hardness 48 - 52 HRC) and an Almen intensity of 0.72 mm leads to a 22% increase of the bending fatigue limit. If the harder shot S 230 with an

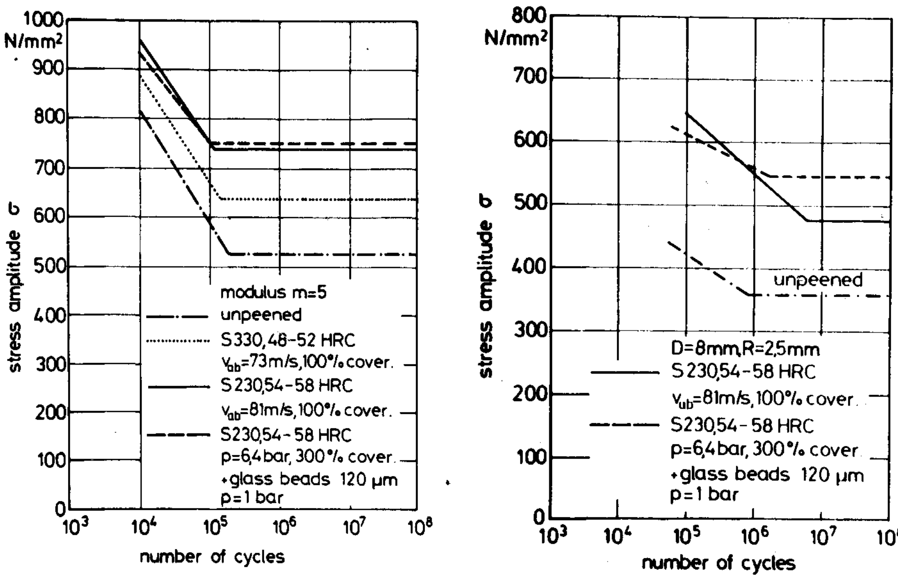

Fig.7: S-N-curves of the bending fatigue tests
a: case hardened and differently shot peened gears with a modulus of 5
b: case hardened and differently shot peened specimens with the notch root radius R = 2,5 mm

intensity of 0.47 mm A2 was used, a higher increase of the bending fatigue strength for R = 0 of 41 % is achieved. Finally the treatment with high hardness shot S 230, 300 % coverage and additional glass bead peening yields in an increase of 43 %. The effects of the different shot peening treatments on the low cycle fatigue region of the S-N-curves show the same tendency as described

Gears, modulus of 5								
Shot peening treatments	σ_{ES} (N/mm^2)	half width (min)	hardness (HV 3)	R_t (µm)	R_a (µm)	retained austenite (Vol.%)	σ_b schw. $5\cdot10^6$ 50%	increase in %
unpeened	-514	156	620	8.0	0.74	< 3	527	-
S 230,54-58HRc v_{ab} = 81 m/s, 100% coverage A2 = 0.47 mm	-360	240	735	14.2	1.2	< 2	742	41
S 230,54-58HRc 6.4 bar 300% coverage +glass beads d = 120 µm p = 1 bar	-442	218	722	11.1	1.1	< 2	754	43
S 330,48-52HRc v_{ab} = 73 m/s 100 % coverage A2 = 0.72 mm	-530	235	702	10.5	1.1	< 2	641	22
Specimens (D = 8 mm, R = 2.5 mm)								
unpeened	-436	168	585	6.7	0.7	< 2	358	-
S 230,54-58HRc v_{ab} = 81 m/s, 100 % coverage	-484	280	730	14.2	1.5	< 2	480	34
S 230,54-58HRc p = 6.4 bar, 300 % coverage + glass beads d = 120 µm p = 1 bar	-610	274	709	11	1.4	< 2	547	53

Table 3: Characteristic values of the surface state and results of fatigue tests for the gears with a modulus of 5 and for the specimens:
v_{ab} = speed of the shot in the wheel type machine, p = peening pressure in the air blast machine, A2 = Almen intensity A2, σ_{ES} = circumferential residual stresses, R_t and R_a = surface roughness values. Bending fatigue limit at $5\cdot10^6$ cycles for R = 0 and for a fracture probability of 50 % = $\sigma_{b\ schw,5\cdot10^6,\ 50\%}$

for the fatigue limits. Comparing the S-N-curves of the gears and the specimens a discrepancy has to be stated for the absolute values and also for the shot peening induced increase of the fatigue limits. In spite of that for both kinds of test pieces the same tendency for the increase of the fatigue limit due to different shot peening treatments has been found: the specimens show a 34 % increase of the fatigue limit after peening with S 230 (54-58 HRC) in the wheel type machine and a 53 % increase after treatment with S 230 (54-58 HRC), 300 % coverage and additional glass bead peening in the air blast machine. Remarkable are the high numbers of cycles at which the transitions from the low cycle to the high cycle fatigue region occur in the S-N-curves of the specimens.

Table 3 compiles characteristic values of the obtained surface state of the gears with a modulus of 5 and of the specimens together with the fatigue limit values and their increase due to shot peening in percent.

3.2 Variations of the component size

In Fig. 8 and Fig. 9 results of unpeened and of shot peened gears of modulus 3, 5 and 8 are summarized. The shot peening treatments remained constant for all geometries. For the unpeened gears of modulus 3 and 8 have been obtained the same distributions of residual stresses and half widths as already demonstrated for the m = 5 gears in Fig. 3. For reasons of clearness in Fig. 8 the distributions of residual stresses and half widths are not drawn for the unpeened gears. Unpeened gears with m = 8 show remarkably low residual stress

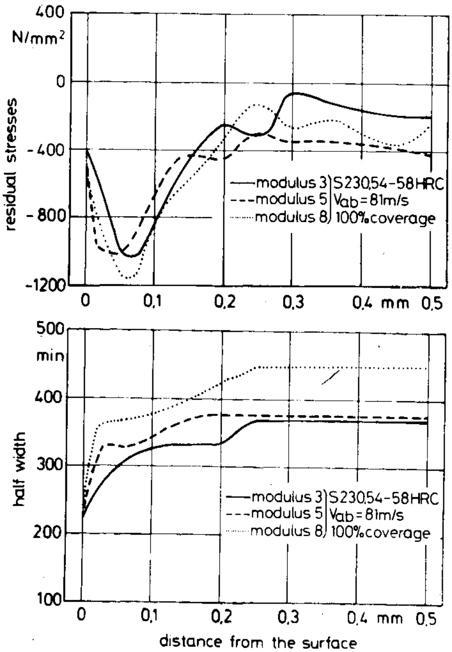

Fig.8: Distributions of residual stresses and half width for case hardened gears with modulus 3, 5 and 8 for constant peening parameters

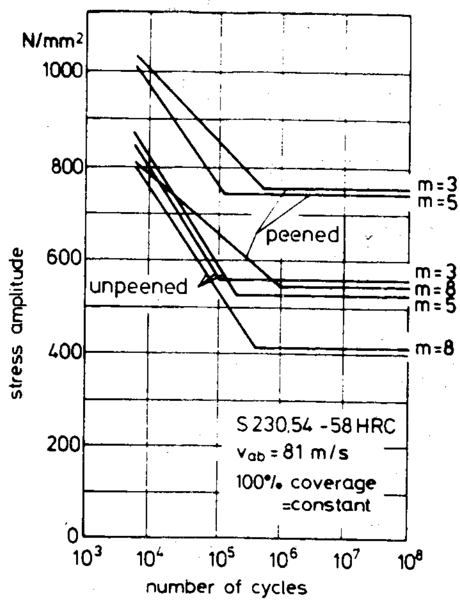

Fig. 9: S-N-curves of the bending fatigue tests on case hardened and uniformly peened gears with modulus 3, 5 and 8

Modulus (mm)	Shot peening treatment	σ_{ES} (N/mm^2)	half width (min)	hardness (HV 3)	R_t (µm)	R_a (µm)	retained austenite (Vol.%)	σ_b schw. $5 \cdot 10^6$ 50 %	increase in %
3	unpeened	-495	168	563	7.6	0.7	< 3	558	-
5	unpeened	-514	156	620	8.0	0.74	< 3	527	-
8	unpeened	-196	153	501	8.4	0.83	< 3	412	-
3	S 230,54-58 HRc v_{ab} = 81 m/s 100% coverage	-405	227	703	9.0	0.9	< 3	758	36
5	as m = 3	- 360	240	735	14.2	1.3	< 3	742	41
8	as m = 3	- 530	248	684	13.7	1.3	< 3	548	33

Abbreviations and symbols see Table 3

Table 4: Characteristic values of the surface state and results of fatigue tests for gears with different moduli

values at the surface compared to the other gears with smaller moduli (see Table 4). As can be seen in Fig. 8 nearly equal residual stress depth profiles are to be found for similar shot peening treatments of the differently sized gears. The half width distributions for gears with m = 3 and m = 8 are also in good agreement with that one already shown in Fig. 3 for the gears with m = 5. The overall higher half width values for gears with m = 8 are caused by the changed geometry of the diaphragms used for these measurements. The distributions of hardness versus distance from the surface are the same for the gears with m = 3 and m = 8 as for the gears with m = 5, which already have been indicated in Fig. 4.

Fig. 9 presents the results of the fatigue tests. The unpeened and peened gears with m = 8 show an evident decrease of the fatigue limit compared to the gears with m = 5. The reason is probably the so called "size effect" - the dependence of the fatigue limit on the dimensions of the testpieces. The investigated shot peening treatment increases the fatigue limit of the gears with the different moduli on an average of 37 %.

Table 4 compares characteristic values of the surface state of the investigated gears with m = 3, 5 and 8 and also the fatigue limits and their increase due to shot peening in percent.

4. Discussion

It is widely accepted that the fatigue resistance of hardened or case hardened steel specimens depends to a great extent on the residual stresses, that is to say in the present investigation on the magnitudes of the shot peening induced compressive residual stresses and possibly their distributions below the surface /1, 11, 12, 19/. Assuming that the fatigue cracks start at the very surface the fatigue limit of hardened steels is also strongly influenced by the surface roughness, whereas the surface work hardening affects the fatigue resistance of hardened materials without damaged surface layers only little/11/.

However, it has to be noticed, that the investigated material states include a heat treatment induced surface damage in the form of surface oxidation and surface decarburization /4/. This surface damage is clearly indicated by the lowered surface values of the half width of the X-ray interference lines and of the hardness and also by the absence of detectable contents of retained austenite at the surface compared with layers deeper below the surface (see Fig. 6 and Table 3 and 4). Shot peening strain hardens the damaged surface layer as proved by the remarkable increases of the surface hardness (about 120 HV 3 average) of the gears and specimens (160 HV 3 average) and also by the similar increase in the half width values. Therefore it is evident that strain hardening of the damaged surface layer also contributes to all the observed increases of the fatigue limit due to shot peening.Other investigations also proved that shot peening is able to improve especially the fatigue behaviour of surface damaged testpieces /1/. The shot peening induced increases of hardness and half width values are somewhat higher for the specimens than for the gears, but independent of geometrical variations of all the testpieces. The distributions of the half widths show characteristic indentations in the region of the compressive residual stress peak. Such results are well known and explained by other authors /1, 12/ as consequence of changes in the dislocation structure and possibly carbon diffusion. The increase of hardness in the depth of maximum compressive residual stresses (Fig. 4) is directly due to the influence of compressive residual stresses on hardness as shown by /12/ for hardened steels.

Tables 3 and 4 demonstrate that the heat treatment results in compressive residual stresses in the crack sensitive areas of the test pieces - in the circumferential direction of the gears as well as in the direction of the tangent on the notch root radius of the specimens. It should be noticed that those compressive residual stresses are lower for the gears with m = 8.

Shot peening produces the characteristic residual stress distributions with a pronounced maximum magnitude of compressive stresses below the surface, as has been found in a number of investigations /1, 12, 15, 20/ for hardened and case hardened steels. It should be noticed however, that shot peening causes only small increases of the magnitudes of surface residual stresses if compared with the purely case hardened states. For the gears even decreases of the surface residual stresses have been observed, but of course there must be taken into account some scatter of the residual stress values for the different gears. The magnitudes of the surface residual stresses after shot peening are comparable to those observed by /1/ for case hardened flat specimens with small oxide inclusions in the surface layer. The residual stress values of samples with surface damage of this kind are definitely lower than those of case-hardened specimens without surface layer damage /1/. Therefore it seems to be logical to consider the relatively low surface compressive residual stresses of the gears and specimens of this investigation also as a result of a lower yield strength due to oxydation and decarburization in a thin surface layer. It should be also taken into consideration that shot peening produces a widely biaxial and symmetrical residual stress state at the surface.

The distributions of compressive residual stresses as well as their peak value below the surface depend clearly on the shot peening parameters. After peening with S 330 with normal shot hardness only a relatively low maximum magnitude of compressive residual stresses and only a thin layer of compressive residual stress magnitudes higher than 400 N/mm^2 could be observed - in spite of the high Almen value. The investigations show again clearly /17, 19/, that a fit of the shot hardness and the hardness of the workpiece is necessary if one wants to obtain the highest possible magnitudes of compressive residual stresses in the deepest possible layer. Concerning the variations of shot peening parameters for the gears the highest magnitudes of peak residual stresses could be observed after peening with a hard shot, 300 % coverage and additional glass bead peening (air blasting machine). With the same peening conditions the specimens showed somewhat lower maximum magnitudes of residual stresses but a drastically improved penetration depth of high magnitudes of compressive residual stresses (see Figures 3 and 5). This result might be a consequence of the possibility to adjust the peening nozzle of an air blasting machine exactly vertical towards the notch root. As already mentioned, for the gears the angle of impingement is at a maximum of 75 degrees, as a consequence of the shading by other teeth, whereas for the specimens an angle of 90 degrees is possible. For the lower impingement angle a smaller plastic zone below the surface and hence a smaller penetration depth of compressive residual stresses is attained /10/.

There are only small differences in the residual stress distributions of the shot peened gears with different moduli. This similarity can be caused by the overall equality of the shape of the gears.

The decrease of the fatigue limit values with increasing modulus of the gears (see for example Table 4) is a remarkable observation in the unpeened and in the peened state. This decrease could be a consequence of the so called "size-effect", the well known dependence of fatigue resistance on testpiece dimensions. In the unpeened condition it has to be considered also, that the gears with m = 8 show drastically lower hardness and compressive residual stress values compared to the gears with m = 3 and m = 5. For hardened and shot peened flat specimens /14/ reports on a dependence of the fatigue limit in fully reversed bending on the bending height which is caused by fatigue crack initiation in different depths below the surface. The presence of conditions, promoting sub surface fatigue crack initiation cannot be excluded for shot peened gears with m = 8. Comparing the different shot peening conditions, peening with a shot of low hardness (S 330, 48-52 HRc) is the most unfavourable treatment to increase the fatigue limit (Fig. 7a). The relatively low increase of the fatigue limit can be explained by the residual stress distribution with relatively low magnitudes of compressive residual stresses (Fig. 3). It is obvious, that the fatigue limit can not depend exclusively on the surface values of the compressive residual stresses, because just for this treatment relatively high stress magnitudes occur at the surface.

The different peening treatments with the high hardness shot resulted in nearly the same fatigue limit for the gears with m = 5, although air peening with 300% coverage causes substantially higher peak residual stresses than wheel peening with 100 % coverage - but hardly a higher penetration depth. This indicates, that a maximum possible magnitude of the compressive residual stress peak must not be of primary importance for an optimum fatigue strength - either because relaxation of peak residual stresses occurs during fatigue loading, especially if notches are present, or because the penetration depth is important too. The specimens showed a difference of the fatigue limits of 67 N/mm^2 after peening with the above mentioned different conditions. But in this case air peening with 300 % coverage produced not only higher compressive stress magnitudes but also a deeper penetration of highly compressive residual stresses than wheel peening.

5. Conclusions

The reported investigations illustrate the effects of shot peening treatments on the fatigue behaviour of gears and "gearlike" specimens of the case hardened steel 16MnCr5. For a constant geometry of the test pieces the peening conditions have been varied and on the other side for constant shot peening parameters the size of the gears have been varied. The state of the material in surface layers is characterized by a maximum of compressive residual stresses below the surface and - in comparison to the unpeened test pieces - by an increase of half width and hardness values. Surface roughness shows also an increase, compared with the unpeened test pieces. The amounts of retained austenite decrease due to shot peening.

Shot peening treatments with different shots in different types of machines (air blasting machine and wheel type machine) cause residual stress distributions with significantly different values and penetration depths. Peening with shot of the usual hardness (48-52 HRc) improves the bending fatigue strength (R = 0) of gears only relatively little (22 %). With shot of higher hardness (54-58 HRc) a considerably bigger increase of the bending fatigue limit for an equal tooth geometry (modulus of 5, tooth bottom radius 1.75 mm) occured (41% increase with peening in a wheel machine, 100 % coverage). The fatigue strength improvement of the gears with a modulus of 3 and 8 showed somewhat lower values of 36 and 33 %. After air peening with the shot of 54-58 HRc (300 % coverage and additional glass bead peening) nearly the same fatigue limit of the gears with m = 5 was obtained (43% increase) as after peening with a wheel type machine. The peening with an air blasting machine however resulted in a 53% increase of the fatigue limit for the specimens which is remarkably higher than that one after wheel peening of the specimens (34%).

The obtained improvements of the fatigue behaviour after the different shot peening treatments correspond very well with the distributions of residual stresses with consideration of the peak magnitudes and penetration depths obtained in each case.

In addition to the information about the possible improvements of the fatigue strength due to shot peening of gears with different moduli, the comparison with the possible fatigue strength improvements of the specimens offers indications how to optimize shot peening treatments for other components in practice. The comparison of the obtained residual stress distributions is helpful in explaining the fatigue test results.

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References

(1) R. Schreiber: Untersuchungen zum Dauerschwingverhalten des kugelgestrahlten Einsatzstahls 16MnCr5 in verschiedenen Wärmebehandlungszuständen. Dissertation Univ. Karlsruhe 1976
(2) N.N. Proceedings "First International Conference on Shot Peening",Paris, 14.-17.9 1981. Pergamon Press 1982
(3) Proceedings "Second International Conference on Shot Peening", Chicago, 14.-17.5 1984. The American Shot Peening Society, Paramus, N.J. 1984
(4) T. Hirsch, E. Macherauch: Untersuchungen zur Zahnfußdauerfestigkeit kugelgestrahlter Zahnräder. Forschungsvorhaben Nr. 15/II der FVA, Frankfurt 1983
(5) E. Macherauch, P. Müller: Das $\sin^2\psi$-Verfahren der röntgenographischen Spannungsmessung. Z.f. angewandte Physik 13 (1961). S. 305-312
(6) E. Macherauch, H. Wohlfahrt: Grundprinzipien der quantitativen röntgenographischen Phasenanalyse (RPA). Härterei-Techn. Mitt. 27 (1972), S.230-232
(7) U. Ilg: Strukturelle Änderungen in unterschiedlich wärmebehandelten Wälzkörpern aus 100 Cr 6 und 20 MnCr 5 bei Wälz- sowie Wälz-Gleitbeanspruchung. Dissertation Univ. Karlsruhe 1980
(8) D. Dengel: Die arcsin $\sqrt{P}$-Transformation - ein einfaches Verfahren zur graphischen und rechnerischen Auswertung geplanter Wöhlerversuche. Z.f. Werkstofftechnik 6 (1975), Nr. 8, S.253-288
(9) H. Bühler, W. Schreiber: Lösung einiger Aufgaben der Dauerschwingfestigkeit mit dem Treppenstufenverfahren. Arch. f. Eisenhüttenwesen 28 (1957), S. 156
(10) S.A. Meguid, J.K. Duxbury: A practical Approach to Forming and Strengthening of Metallic Components Using Impact Treatment, in (2), S. 217-228
(11) B. Syren: Der Einfluß spanender Bearbeitung auf das Biegewechselverformungsverhalten von Ck 45 in verschiedenen Wärmebehandlungszuständen. Dissertation Univ. Karlsruhe, 1975
(12) P. Starker: Der Größeneinfluß auf das Biegewechselverhalten von Ck 45 in verschiedenen Bearbeitungs- und Wärmebehandlungszuständen. Dissertation Universität Karlsruhe, 1981
(13) E. Macherauch, H. Wohlfahrt, R. Schreiber, R.-P. Koesters, R. Geschier, W. Bender: Verbesserung der Bauteileigenschaften durch Strahlen. HFF-Bericht Nr. 6, Hannover, 1980, S. 11/1-11/20
(14) P. Starker, E. Macherauch: Kugelstrahlen und Schwingfestigkeit.Z.f. Werkstofftechnik 14 (1983), S.109-115
(15) J. Hoffmann: Der Einfluß fertigungsbedingter Eigenspannungen auf das Biegewechselverhalten von glatten und gekerbten Proben aus Ck 45 in verschiedenen Werkstoffzuständen, Dissertation Univ. Karlsruhe, 1984
(16) H. Wohlfahrt: Kugelstrahlen und Dauerschwingverhalten in (2). S. 675-693
(17) R. Schreiber, H. Wohlfahrt, E. Macherauch: Untersuchungen zum Dauerschwingverhalten kugelgestrahlter Einsatzstähle. Forschungsvorhaben Nr. 15 in "Forschungsreport 1977" der Forschungsvereinigung Antriebstechnik e.V., Frankfurt/Main, 1977
(18) R. Schreiber, H. Wohlfahrt, E. Macherauch: Untersuchungen zum Dauerschwingverhalten kugelgestrahlter Einsatzstähle. Forschungsvorhaben Nr. 15 in "Forschungsreport 1978" der Forschungsvereinigung Antriebstechnik e.V., Frankfurt/Main, 1978
(19) E. Macherauch, H. Wohlfahrt: Eigenspannungen und Ermüdung. In "Ermüdungsverhalten metallischer Werkstoffe".Hrsg.D.Munz. DGM-Informationsgesellschaft Verlag, Oberursel 1984, S. 237-283
(20) H. Wohlfahrt: The Influence of Peening Conditions on the Resulting Distribution of Residual Stress in (3), S. 316-331