OPTIMIZATION OF THE FATIGUE STRENGTH OF HEAT TREATED STEELS AS A CONSEQUENCE OF AN OPTIMUM STATE OF THE SURFACE AND OF SUBSURFACE LAYERS AFTER SHOT PEENING

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ABSTRACT

New experimental results on the improvement of the fatigue strength of differently heat treated steels due to shot peening with steel shot, with ceramic beads and also with steel shot plus ceramic beads are compared. The results indicate that the beneficial effects of shot peening depend in a rather complicated way upon the ratio of surface hardness, surface roughness and the magnitude of compressive residual stresses at the surface or - if subsurface crack initiation is forced - upon the distribution of residual stresses versus depth below surface. Detailed explanations can be given considering the surface state and the distribution of residual stresses after peening. Comparisons with the fatigue strength after CBN-grinding under a tensile prestress confirm the results and explanations.

KEYWORDS

Fatigue strength, heat treated steels, steel shot, ceramic beads, grinding, surface roughness, residual stresses, crack initiation, concept of the local fatigue strength.

INTRODUCTION

A number of preceding papers [1 - 4] has shown that in order to explain improvements of the fatigue strength due to shot peening the magnitude and distribution of the compressive residual stresses induced as well as the strain hardening in surface layers and the resulting surface roughness have to be taken into account. The following paper presents new experimental results on the improvement of the fatigue strength of differently heat treated steels due to shot peening with steel shot, with ceramic beads and also with steel shot plus ceramic beads. A detailed consideration of the differences in the above mentioned characteristic features of the surface state after shot peening allows again a consistent explanation of the differences in the fatigue strength values of the differently heat treated steel specimens and offers new insights as well.

MATERIALS AND EXPERIMENTAL PROCEDURES

Table 1 indicates the chemical composition of the carbon steel and of the case hardening steel used for the investigations.

Table 1: Chemical composition of the carbon steel (Ck 45) and of the case hardening steel (16 MnCr), weight per cent

material	C	Si	Mn	Cr	Mo
Ck 45, 4 mm thick	0,45	0,20	0,73	0,18	-
16MnCr5, 6 mm thick	0,16	0,28	1,12	1,08	0,01

material	Cu	Ni	P	S	Al
Ck 45, 4 mm thick	0,01	0,03	0,016	0,003	0,03
16MnCr5, 6 mm thick	0,06	0,09	0,015	0,007	0,31

Flat specimens (thickness 2,6 mm) for fatigue testing under completely reversed bending have been produced from rolled and normalized steel sheets. The heat treatment of the carbon steel specimens was annealing at 850 °C for 15 min, quenching in a water-oil emulsion and subsequently either annealing at 160 °C (hardened specimens, 665 HV 10) or annealing at 400 °C (quenched and tempered specimens, 420 HV 10). The specimens of the case hardening steel have been normalized (900 °C, cooling in air) and then carburized at 930 °C for 50 min and hardened by quenching from 870 °C in a salt bath of 160 °C (case hardened specimens, 1030 HV 0,2).

After grinding of the heat treated specimens shot peening has been carried out with an air blast machine[1] either with steel shot or with ceramic shot or with steel shot and additionally with ceramic shot. The peening conditions were uniformly in all heat treatment states:

Steel shot: hardness 58-64HRc, average diameter 0,58 mm, Almen intensity 0,35 - 0,4 mm A, coverage 200 %

Ceramic shot: hardness 65 HRc, average diameter 0,15 mm, Almen intensity 4 N, coverage 400 %

The residual stresses have been measured by means of X-rays on a Ψ-diffractometer using chromium radiation and Ψ-angles of 0, ±18°, ± 27°, ± 33°, ± 39° and ±45°. The Θ-angles of the diffraction lines have been determined with the gravity line method and the residual stress values were calculated using the $\sin^2\Psi$-method.

In order to find out the residual stress distributions versus depth below the surface layer by layer has been removed electrolytically.

The hardness measurements have been carried out on Vickers hardness testers with two different loads, either as HV 10 or for hardness distributions versus depth below the surface as HV 02. For the measurements of the surface roughness a stylus type

[1] Metal Improvement Company, Unna, Germany

tracer was used and the maximum roughness depth as well as the roughness height have been deteminded.

For the fatigue testing under completely reversed bending 5 to 6 specimens have been cyclically loaded on each of four stress levels - two stress levels in the finite life range and two stress levels in the infinite life range. The arc sin √p-transformation has been used for the calculation of the fatigue strength and of the 5 %, 50 % and 95 % survival probabilities in the finite life range.

EXPERIMENTAL RESULTS

Quenched and tempered specimens of the carbon steel

The distributions of residual stresses versus depth below the surface in Fig. 1 indicate clearly that peening with ceramic beads results on the one hand in a magnitude of the residual stresses at the surface which is somewhat higher than the magnitude after peening with steel shot but on the other hand in a much shallower layer containing compressive residual stresses than peening with steel shot or steel shot plus ceramic shot. Nevertheless, as can be seen in Fig. 2, the specimens peened only with ceramic beads show the highest fatigue strength and in the finite life range a lifetime equal to the lifetime of specimens peened with steel shot. As a reference Fig. 2 exhibits also the S-N curve of specimens ground with a corundum wheel.

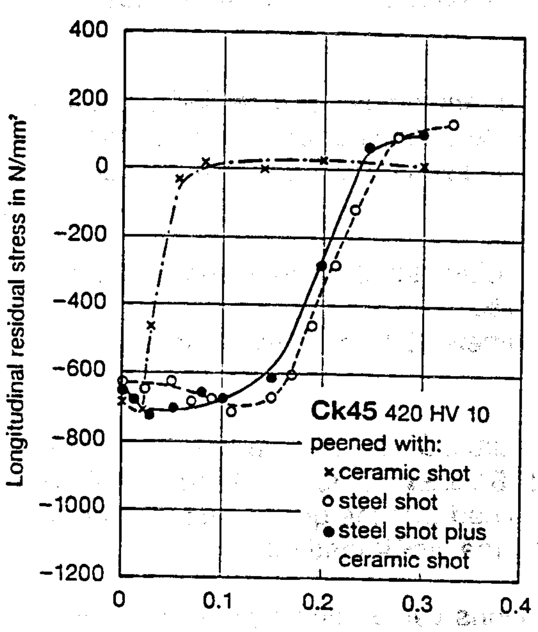

Fig. 1: Quenched and tempered carbon steel, residual stresses versus depth below surface after different peening treatments

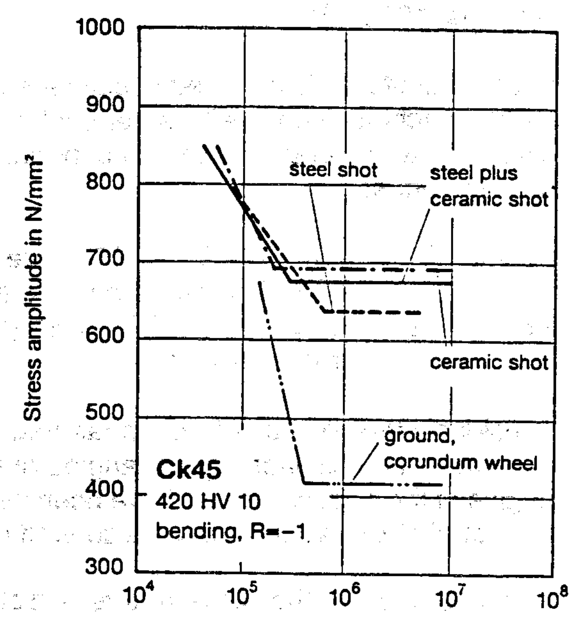

Fig. 2: Quenched and tempered carbon steel, S-N-curves after different peening treatments and corundum grinding as a reference

Table 2: Characteristic values of the Ck 45 carbon steel specimens in the quenchend and tempered state after shot peening or grinding

Type of shot or of grinding wheel	ceramic beads	steel shot	steel shot + ceramic beads	corun-dum	CBN (under tensile prestress)
residual stresses at the surface, [N/mm²]	- 690	- 630	- 647	+ 320	- 800
depth of zero stress below surface, [mm]	0,075	0,25	0,22	0,04	0,05
max. tensile stress below surface, [N/mm²]	+ 28	+ 139	+ 108	-	-
hardness: depth 0,005 mm, HV 0,2	510	500	500	-	-
core, HV 10	430	431	438	420	420
max. roughness depth [µm]	7,2	22,5	20,0	8,3	7,0

In order to explain the different results after shot peening one has to know that in all fractured specimens the fatigue cracks started at the surface. Therefore the comparison of the data in Table 2, concerning the characteristic features of the shot peened surfaces, should give the explanation of the experimental results. The magnitudes of the compressive residual stresses which can be induced by shot peening at the surface of quenched and tempered steel specimens are between 630 and 690 N/mm², that is to say not extremely high. These magnitudes are obviously not effective enough to prevent crack initiation at the surface of the specimens. Consequently surface roughness has a strong detrimental influence on the fatigue strength in the quenched and tempered state of the carbon steel. As one can see, the maximum roughness depth due to peening with the small and light ceramic beads is considerably lower than the appertaining roughness values after peening with steel shot. Therefore the specimens peened only with a ceramic shot have the best state of the surface, lowest surface roughness and highest magnitudes of compressive residual stresses, and show the best fatigue strength.

The surface roughness of both specimen series peened with steel shot is relatively high. Hence their fatigue strength values are the lower ones and even if there is no big difference between the roughness values or the surface residual stresses of the specimens peened with steel shot or with steel shot plus ceramic shot, the higher fatigue strength of the latter ones corresponds with the given explanations. Furthermore, results on ground specimens [5], also cited in Table 2 and Table 3, support these explanations, especially the fact that one can reach an extraordinary high fatigue strength of the flat and thin steel specimens using a special grinding technique (grinding under prestressing) with a wheel of cubic boron nitride which produces high magnitudes of the compressive residual stresses (800 N/mm²) in connection with a moderate maximum roughness depth (7,0 µm).

Table 3: Experimental and calculated fatigue strength values of the Ck 45 carbon steel specimens in the quenched and tempered state after shot peening or grinding

Type of shot or of grinding wheel	ceramic beads	steel shot	steel shot + ceramic beads	corun-dum	CBN (under tensile prestress)
experimental values: fatigue strength, 50 % survival probability, [N/mm²]	691	637	675	415	764
crack initiation		surface			surface
calculated values: fatigue strength, [N/mm²] according to equation (1)	763	666	680	433	817

Using formula (1) given by [1, 5, 6] quantitative estimations can be made of the fatigue strength R_D after shot peening or grinding with regard to a reference value R_W, taking into account the change of the residual stress value at the surface $\Delta\sigma^{ES}$, the hardness change Δ HV and the change of maximum roughness depht ΔR_t due to peening or grinding.

$$R_D = R_W - m\sigma^{ES} + n\Delta HV - p\Delta R_t \qquad (1)$$

$$m = \frac{\Delta R_w}{\Delta \sigma ES}, \quad n = \frac{\Delta R_w}{\Delta HV} \text{ and } p = \frac{\Delta R_w}{\Delta R_t}$$

are empirical factors [1, 5, 6] for the efficiency of residual stresses, of the surface hardness and of the surface roughness with regard to the fatigue strength. The reference value R_W for the calculations is the fatigue strength R_W = 580 N/mm² for electrolytically polished specimens. The comparison of the calculated and of the experimental values for the fatigue strength with a 50 % survival probability in Table 3 indicates a relatively good agreement of the individual values and thus of the tendency of the fatigue strength improvement as a consequence of the different surface treatments. Of course this agreement also supports the given explanations for the different efficiencies of various shot peening treatments.

Concerning the lifetime of the specimens peened with steel shot one has to assume that a surplus of the life until fracture due to a thicker layer with compressive residual stresses (see for instance [7]) is compensated by the higher surface roughness of these specimens.

Hardened specimens of the carbon steel

It is well known that shot peening of hardened steel specimens can result in extremely high magnitudes of the compressive residual stresses at the surface. This is again confirmed by the residual stress distributions versus distance from the surface in Fig. 3. As anticipated according to [8], peening with the small but very hard ceramic beads results in the highest magnitude of the surface residual stresses, however, in a very thin layer containing compressive residual stresses. Peening with steel shot produces a lower magnitude of the compressive residual stresses at the surface, but the residual stresses extend over a considerably thicker layer.

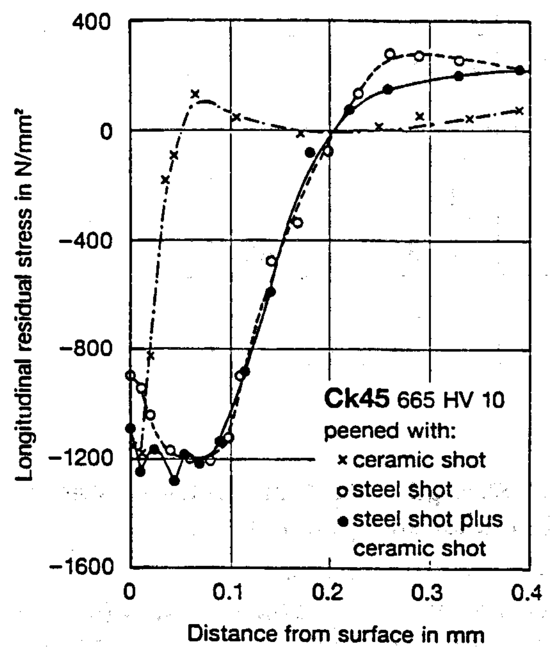

Fig. 3: Hardened carbon steel, residual stresses versus depth below surface after different peening treatments

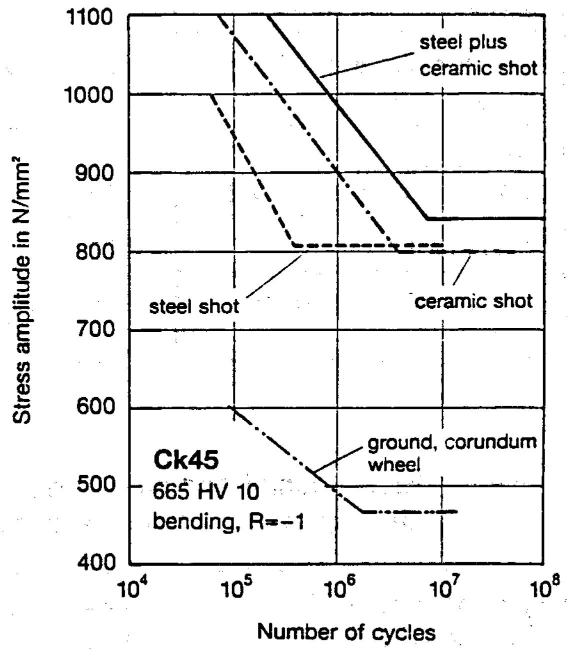

Fig. 4: Hardened carbon steel, S-N-curves after different peening treatments and corundum grinding as a reference

The results of the fatigue tests show clearly that in the hardened state with its relatively high resistance against crack initiation high magnitudes of the highly efficient compressive residual stresses at the surface can prevent the initiation of fatigue cracks at the surface if the surface roughness is low enough. At stress amplitudes in the transition range from finite to infinite life subsurface crack initiation has been observed in nearly all shot peened specimens. In the finite life range the specimens peened with steel shot, that is to say the specimens with the lower magnitudes of compressive residual stresses at the surface and the higher surface roughness (Table 4), showed fatigue crack initiation at the surface whereas in the specimens peened with ceramic beads or with steel shot plus ceramic beads the cracks started mainly below the surface.

Table 4: Characteristic values of the Ck 45 carbon steel specimens in the hardened state after shot peening or grinding

Type of shot or of grinding wheel	ceramic beads	steel shot	steel shot + ceramic beads	corun-dum	CBN (under tensile pre-stress)
residual stresses at the surface, [N/mm²]	- 1154	- 898	- 1088	+ 360	- 1160
depth of zero stress below surface, [mm]	0,055	0,21	0,2	-	0,032
max. tensile stress below surface, [N/mm²]	+ 132	+ 289	+ 221	-	+ 70
hardness: depth 0,005 mm, HV0,2	914	740	877	-	-
core, HV 10	670	667	668	665	665
max. roughness depth [μm]	6,4	8,2	8,2	10,2	6,1

Table 5: Experimental and calculated fatigue strength values of the Ck 45 carbon steel specimens in the hardened state after shot peening or grinding

Type of shot or of grinding wheel	cera-mic beads	steel shot	steel shot + ceramic beads	corun-dum	CBN (un-der tensile prestress)
experimental values: fatigue strength, 50 % survival probability, [N/mm²]	800	808	841	468	825
depth of crack initiation, [mm]	0,07	0,26	0,27	surface	0,035
calculated values: fatigue strength, [N/mm²]	767	799	853	546	782
according to equation	(2)	(2)	(2)	(1)	(2)
depth od crack initiation [mm]	0,065	0,26	0,26	-	0,04

The conclusion of these experimental findings is, that neither surface roughness, if it remains within the limits given here, nor the exact magnitudes of the compressive residual stresses at the surface, if they are higher than a certain value, can be relevant for the actual fatigue strength of the hardened and differently shot peened specimens. However, the total distribution of residual stresses versus distance from the surface in comparison with the load stress distribution is important for the fatigue behaviour of the different shot peened states considered here. In other words the concept of the local fatigue strength [9, 10] has to be applied and to give the explanation for the differences of the fatigue behaviour represented in Fig. 4.

Fig. 5 takes as an example the distribution of the local fatigue strength versus distance from the surface in comparison with the distributions of different bending load stresses for the double peened specimens.

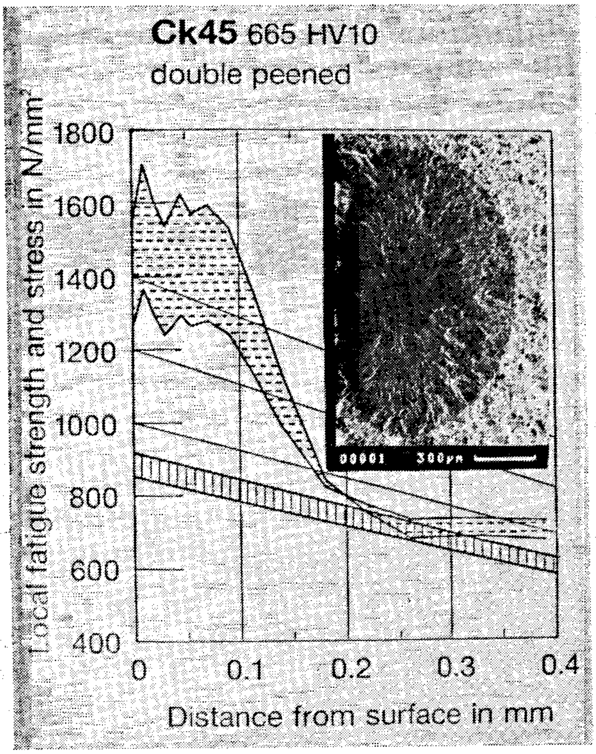

Fig. 5:
hardened carbon steel, peened with steel shot plus ceramic beads, local fatigue strength and bending load stresses versus depth below surface

The local fatigue strength values $R_{D,z}$ have been calculated with the formula

$$R_{D,z} = R_{W,z} - m\, \sigma_z^{ES} \qquad (2)$$

where z is the coordinate of the depth below surface, $R_{W,z}$ is the reference value of the fatigue strength without residual stresses, for instance in an electrolytically polished state, and σ_z^{ES} is the distribution of the residual stresses. As the factor m is given in [1, 5] within a scatterband, the calculated values for the local fatigue strength $R_{D,z}$ lie within the drawn scatterband. The load stress lines which are tangential to the local fatigue strength distribution, that is to say do not surpass it in any depth, reveal the resulting fatigue strength as load stress amplitude at the surface. Thus, in Fig. 5 one can find a minimum fatigue strength of 853 N/mm² for the double peened specimens and the comparison with the experimentally registered value of the fatigue strength for a survival probability of 50 % in Table 5 indicates a relatively good agreement. The experimental and the calculated fatigue strength values of the other shot peened specimens are also at least in a roughly good correspondence and the experimentally determided and the calculated values of the depth of crack initiation show an excellent agreement. Therefore the concept of the local fatigue strength enables an explanation for the observed tendencies: the experimentally registered fatigue strength values after peening with steel or ceramic shot are nearly equal in the hardened state of the steel as the differences of surface roughness (Table 4) have no consequences with regard to the fatigue strength and the distributions of the local fatigue strength versus depth from the surface allow this correspondence. The specimens peened with steel shot and subsequently with ceramic beads show the highest fatigue strength in the hardened state as their distribution of the local fatigue strength is the most favourable one. As a consequence of the lowest magnitude of compressive residual stresses at the surface and the high surface roughness the specimens peened with steel shot have the smallest numbers of cycles until fracture.

In Fig. 4 again also the S-N-curve of specimens ground with a corundum wheel is drawn as a reference curve and in Table 4 and Table 5 the surface characteristics and the fatigue strength values of ground specimens are registered. Tensile residual stresses at the surface of the specimens ground with a corundum wheel are the reason for crack initiation at their surface and for their low fatigue strength. In contrast with these results the specimens ground under a tensile load stress with a wheel of cubic boron nitride (CBN) show a very high magnitude of compressive residual stresses at the surface and a relatively low maximum roughness depth. Consequently subsurface crack initiation was observed in the transition range from finite to infinite life. The application of the concept of local fatigue strength and the experimental results (Table 5) clearly indicate that a similar distribution of residual stresses after grinding or after shot peening results in a nearly equal fatigue strength and this again supports the explanations given above.

Case hardened specimens

Compared with the hardened state of the carbon steel the case hardened and shot peened specimens show different results. Here again peening with ceramic beads produces the highest fatigue strength and the longest lifetime (Fig. 7). The decisive difference compared with case hardened and double peened specimens is the site of fracture initiation. In the specimens peened with ceramic beads subsurface crack initiation was observed nearly exclusively. However, in the double peened specimens crack initiation occured at the surface. As the reason for this behaviour the somewhat higher maximum roughness depth (Table 6) of the double-peened specimens has to be considered because the notch sensitivity in the extremely hard (≈ 1000 HV 0,2) case hardened state is also extremely strong. The residual stresses at the surface of both kinds of specimens are extremely high and nearly equal (Fig. 6 and Table 6) and the layer containing high magnitudes of compressive residual stresses is somewhat thicker in the double peened specimens than in the specimens peened with ceramic beads only.

These results and their explanations are again confirmed by the experimental finding that a comparable extremely high fatigue strength as after peening with ceramic beads can also be attained by CBN-grinding under a tensile prestress because this grinding technique causes subsurface crack initiation and provides also a very favourable distribution of the compressive residual versus depth below the surface.

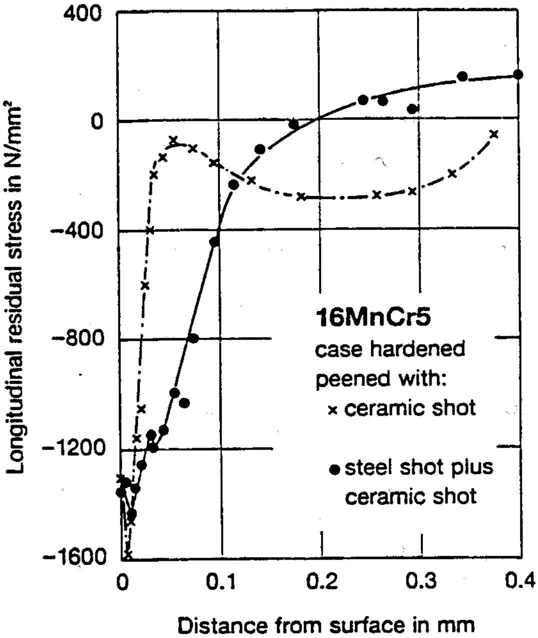

Fig. 6: Case hardened steel, residual stresses versus depth below surface after different peening treatments

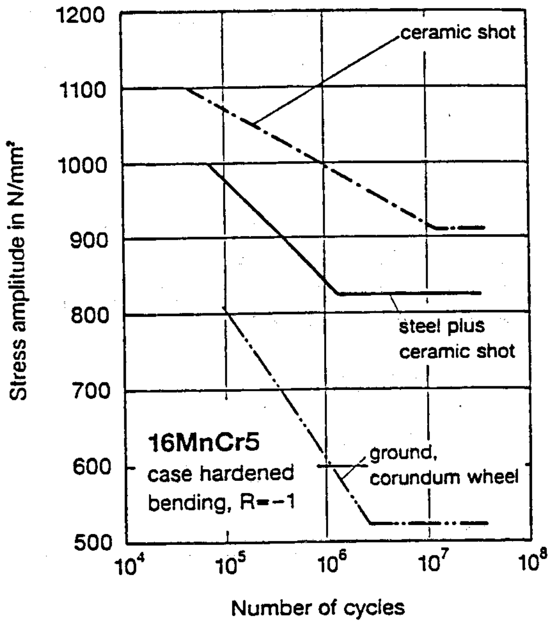

Fig. 7: Case hardened steel, S-N-curves after different peening treatments and corundum grinding as a reference

Table 6: Characteristic values of the 16 MnCr 5 case hardened steel specimens after shot peening or grinding

Type of shot or of grinding wheel	ceramic beads	steel shot + ceramic beads	corun- dum	CBN (under tensile prestress)
residual stresses at the surface, [N/mm²]	- 1312	- 1355	+ 330	- 1000
depth of zero stress below surface, [mm]	-	0,2	0,04	0,4
max. tensile stress below surface, [N/mm²]	-	+ 150	-	-
hardness: depth 0,005 mm, HV 0,2	950	1029	970	1020
max. roughness depth [µm]	4,5	7,8	15,3	7,4

Table 7: Experimental and calculated fatigue strength values of the 16 MnCr 5 case hardened steel specimens after shot peening or grinding

Type of shot or of grinding wheel	ceramic beads	steel shot + ceramic beads	corun-dum	CBN (under tensile prestress)
experimental values fatigue strength, 50 % survival probability, [N/mm²]	912	825	525	909
crack initiation	subsurface	surface	surface	subsurface
calculated values fatigue strength, [N/mm²]	879	848	-	907
according to equation	(2)	(1)	-	(2)

SUMMARY

The experimental results of the investigation indicate clearly that the fatigue strength improvement due to shot peening depends in a rather complicated way upon the ratio of surface hardness, surface roughness and the magnitude of the compressive residual stresses at the surface or - if subsurface crack initiation is forced- upon the distribution of residual stresses versus depth below the surface in comparison with the load stress distribution.

In the quenched and tempered state of steels with a medium hardness of 400 to 500 HV 10 fatigue cracks originate normally at the surface, mainly as a consequence of the relatively low resistance against crack initiation. The compressive residual stresses of a medium magnitude which can be produced by shot peening in this material state are obviously also not high enough in order to suppress crack initiation at the surface. Therefore the surface roughness is an important factor, determining the fatigue strength if the magnitudes of the surface residual stresses due to shot peening are nearly equal. Concerning the number of cycles until fracture in the finite life range, the effect of a thicker layer with compressive residual stresses can obviously also be compensated by high values of the maximum roughness depth. Consequently, in order to produce optimum fatigue strength peening conditions resulting in a low surface roughness but nevertheless high compressive residual stress, as for instance peening with ceramic beads, are favourable.

In the hardened state of steels (600 - 700 HV 10) the higher resistance against crack initiation as well as the very high magnitudes of compressive residual stresses prevent crack initiation at the surface of shot peened samples at least in the transition range from finite to infinite life. Therefore peening conditions resulting in a favourable distribution of the residual stresses versus depth below surface compared with the load stress distribution are important, whereas the exact values of the maximum roughness depth or of the compressive residual stresses at the surface are less important if they are within the usual limits. Whether the result of this investigation can be generalized that peening at first with steel shot and then with ceramic beads induces an optimum distribution of residual stresses versus depth below the surface, with a lowered maximum tensile stress below the surface (see Table 4), has to be checked in further experiments. It depends of course upon the load stress gradient, and that means upon the thickness of bending specimens, how effective a residual stress distribution can be [2, 4].

If the hardness of the material to be peened increases up to 1000 HV 10, as for instance in case hardened steels, surface roughness becomes again more important because of the increasingly strong notch sensitivity of extremely hard materials. Then crack initiation at the surface is again possible and peening conditions causing minimal surface roughness are important. Peening with ceramic beads can obviously be advantageous. Extremely high magnitudes of compressive residual stresses can be reached at the surface, but these extreme magnitudes are not the essential features for an optimum fatigue strength.

Comparisons with the fatigue strength values of specimens ground with CBN show comparable results and confirm therefore these conclusions.

The results of the investigation and the conclusions may help to find the optimum peening conditions in cases of technical importance.

ACKNOWLEDEMENT

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