Fatigue Progress in Shot-peened Surface Layers

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Introduction

Unnotched flat specimens of the high strength spring steel 50 CrV 4 are quenched and tempered to UTS-levels of 1200 to 1850 MPa. The mechanical surface treatment is done by prestraining, shot-peening and shot-peening under prestress and compared to the untreated conditon.
All specimens are loaded under four-point-bending at temperatures of 20°C and -70°C with restriction to the fatigue life.
The aim of the present work is to examine the fatigue behaviour of the above mentioned surface conditions and consider the material state before, during and after the fatigue loading.

Material and Material State

The investigation was carried out on the hot worked spring steel 50CrV4 with a cross section of 100 by 15 mm and the chemical composition given in Table 1.

Table 1 : Chemical composition

Material	C	Mn	Si	S	P	Cr	V
50 CrV 4	0.55	1.04	0.37	0.012	0.012	1.10	0.13

The heat and surface treatment were done under shop conditions. Specimens with a length of 400 mm were hardened at 860°C and tempered at 390, 500 and 615°C to gain ultimate tensile stresses (UTS) of 1200, 1500 and 1850 MPa. After this, the surface treatments according to Table 2, were applied without intermediate machining.

Experimentals

The specimens were loaded under four-point-bending with a constant minimum bending stress of 200 MPa and a variable maximum bending stress.The constant stress field covered an area of 100 by 100mm².
The residual stresses (before and after fatigue loading) were evaluated by X-ray measurements. The lattice distortion was calculated according to the $\sin^2$-ψ-method /1/. To measure the residual stress profile, the surface was removed successively by electrolytic polishing.
During the fatigue loading as well the surface strain as the crack initiation and growth until fracture were measured. For the strain measurements, within the region of maximum bending stress at the specimen`s tension side, a strain gauge was applicated. These measurements were restricted to the crack-free period, because of a possible damage of the strain gauge in case of failure.
Crack initiation and growth was measured by ultrasonic surface waves. This method is described more detailed in /2/.

Table 2 : Surface and material condition

Surface condition	Symbol	Parameter	UTS
untreated	U	as heat treated, unmachined	1500 MPa
prestrained	P	like U + loaded 3 x 1.2·yield strength	1500 MPa
shot-peened	S	like U + shot-peened A2 = 0.59	1500 MPa
shot-peened after prestraining	PS	like P + shot-peened A2 = 0.59	1200 MPa 1500 MPa 1850 MPa
shot-peened under prestress after prestraining	PSP	like P + shot-peened under a prestress of 0.75 · yield strength A2 = 0.61	1500 MPa

Results

The characteristics of the surface state before fatigue is given in Table 3.

Table 3 : Surface condition before fatigue (R_{max}: surface roughness, σ_{RS}: residual stress at the surface, σ_{Rmax}: maximum residual stress and depth below surface t_d)

Surface condition	UTS [MPa]	R_{max} [μm]	σ_{RS} [MPa]	σ_{Rmax} [MPa]	t_d [mm]
U	1500	31	0	0	0
S	1500	63	-480	-690	0.19
PS PS	1200 1850	66 37	-410 -640	-640 -690	0.19 0.20
PSP	1500	·/.	-710	-960	0.29

In unpeened specimens with a UTS of 1500 MPa the surface roughness is found to be about 31 μm while the shot-peening induce a higher roughness of about 63 μm. The lower UTS of 1200 MPa shows a similar value. A significant decrease to 37 μm is to be observed after shot-peening the high strenght level of 1850 MPa.

The residual stress at the surface increases with increasing UTS. The maximum value and its depth below surface are, however, similar. Shot-peening under prestress (PSP) induces the highest residual stress at the surface.Also the maximum value is not only increased but even its depth below surface is shifted to a greater value.

The change of the surface strain during fatigue is shown in Figure 1. Prestraining before peening reduces the plastic strain rate (S→PS). Comparing the peened (PS) and peened under prestress (PSP) condition, it is obvious, that both reach the same strain level but the PS-condition earlier. Lowering the testing temperature means a decrease in plastic strain.

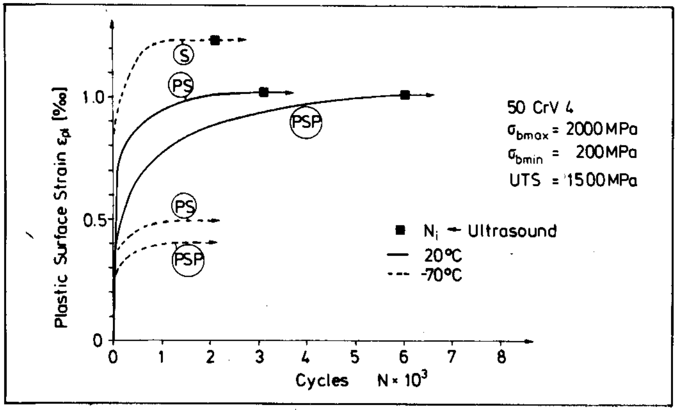


Figure 1 : Influence of surface condition and testing temperature on the plastic surface strain

Figure 2 shows some examples of cracks at and just below a shot-peened surface. With the crack start, glide traces are to be observed and the starting point is normally encountered in the vicinity of non-metallic inclusion, which locally cause a higher stress concentration.

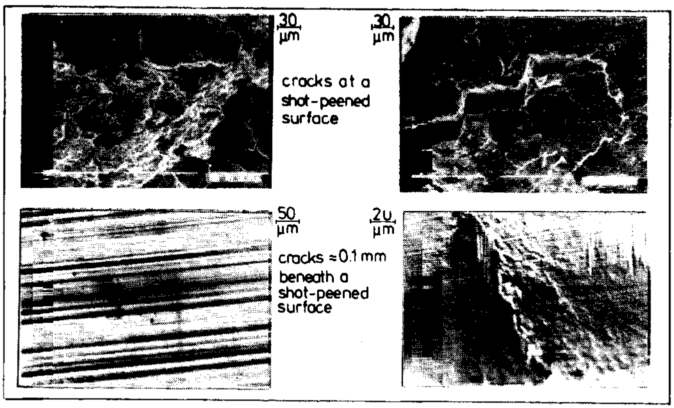
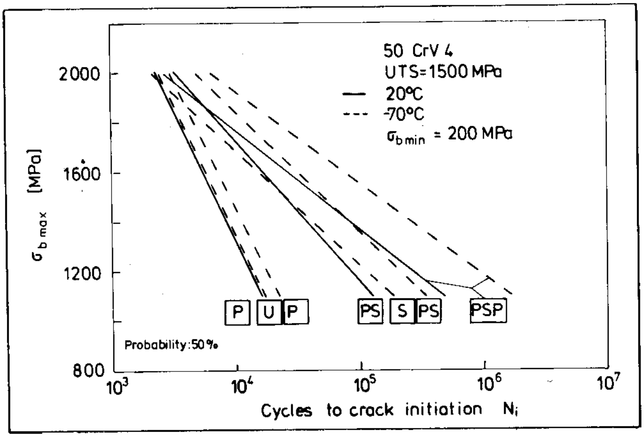


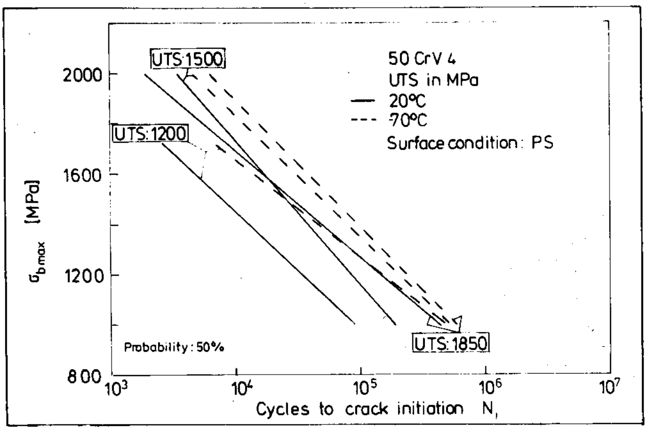
Figure 2 : Cracks in a shot-peened surace layer

The influence of the surface treatment on the period to crack initiaton is shown in Figure 3. While the unpeened prestrained (P) surface shows early crack initiation, crack start is retarded by shot-peening (PS) and further more by shot-peening under prestress (PSP). A decreased testing temperature of -70°C also enlarges the crack-free stadium.



<u>Figure 3 :</u> Influence of surface condition and testing temperature on the cycles to crack initiation N_i

On the other hand, the time to crack initiation depends on the UTS (<u>Figure 4</u>). An increasing UTS causes an increasing time to crack initiation. This correlation is valid for low temperatures, too.



<u>Figure 4 :</u> Influence of UTS and testing temperature on the cycles to crack initiation N_i

But after initiation, cracks do not grow steadily. Due to the increasing compressive residual stresses below the surface, crack growth may be delayed until N_g, the point when stable crack growth until fracture sets in. How much the different surface treatments may delay a crack is shown comparetively in <u>Table 4</u>. With growing compressive residual stresses the crack delay (N_g-N_i) increases and also the cycles to failure N_f

The fatigue life due to the surface treatment is shown in <u>Figure 5</u>

and the influence of the UTS on the fatigue life in Figure 6.

Surface condition	20°C N_i	N_g	N_f	-70°C N_i	N_g	N_f
	in relation to P			in relation to U		
U	-	-	-	1	1	1
P	1	1	1	1.3	1.1	1.1
S	-	-	-	3.1	3.3	3.4
PS	3.3	4.5	3.4	6.1	4.6	4.5
PSP	6.0	8.6	7.9	15.8	11.5	10.6

Table 4 : Influence of the surface condition on crack initiation N_i, on the crack growth at N_g and on the time to failure N_f for σ_{bmax}=1580 MPa; UTS = 1500 MPa

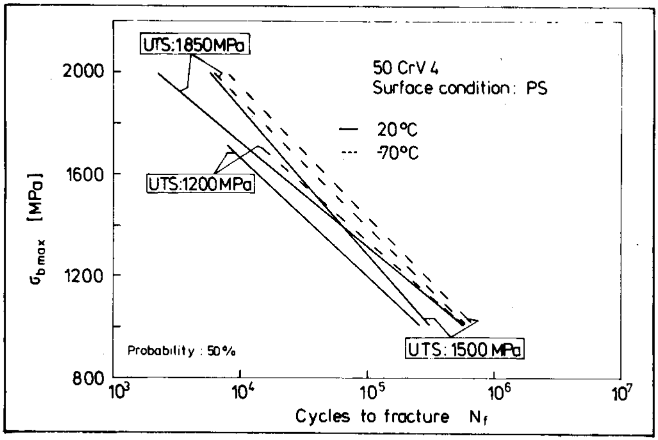


Figure 5 : Influence of surface condition and testing temperature on the fatigue life

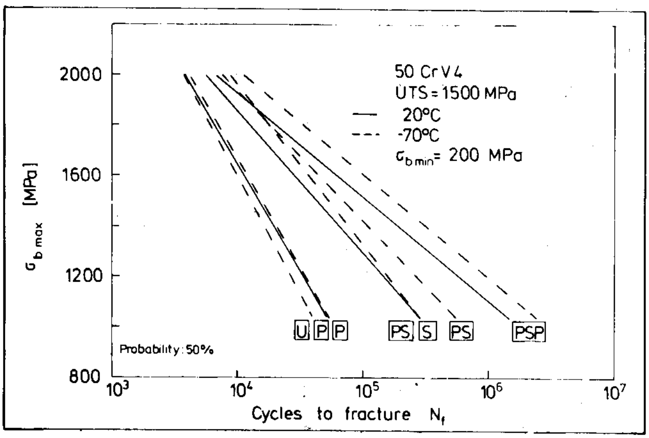


Figure 6 : Influence of UTS and temperature on the fatigue life

The fatigue life is limited by the critical crack length a_c, which depends on the UTS and temperature (Figure 7). The critical crack length is diminished by lowering the temperature and by raising the UTS and naturally depends on the loading level.

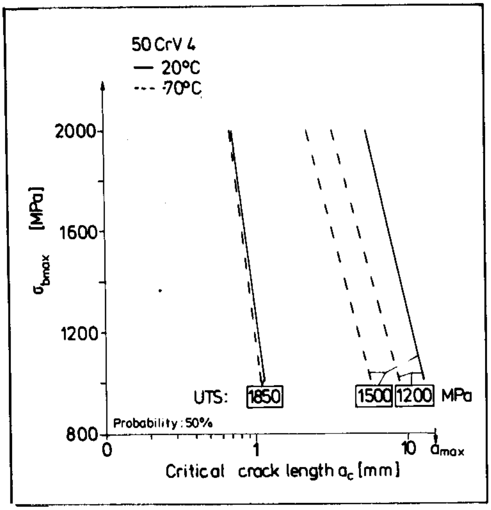


Figure 7 :
Influence of UTS and temperature on the critical crack length a_c
(a_{max} = 15 mm = specimen`s thickness)

After fatigue the change of the residual stress due to the fatigue loading is shown in Table 6 with regard to the UTS, the temperature and the surface treatment .

Table 6 : Residual stresses after fatigue loading (index see table 2, n.m.: no maximum)

Surface condition	UTS [MPa]	σ_{bmax} [MPa]	T [°C]	σ_{RS} [MPa]	σ_{Rmax} [MPa]	t_d [mm]
PS	1200	1280	20	-580	-670	0.27
PS	1200	1280	-70	-590	-740	0.13
PS	1500	1140	20	-400	n.m.	-
PS	1500	1140	-70	-540	-780	0.14
PSP	1500	1300	20	-650	-960	0.25
PSP	1500	1300	-70	-530	-910	0.27
PS	1850	1340	20	-710	n.m.	-

Discussion

Shot-peening induces a plastic deformation of the surface. The effect concerning the depth depends on the energy of the peen particles, the material`s stress condition and the material strengtht /3/. With growing UTS the surface roughness decreases, which is an indication for a lower penetration depth. The residual stress profile also depends on the UTS, as the compressive residual stress increase with the UTS at the surface but show a smaller penetration depth. Prestraining while peening produce the highest compressive residual stresses. Due to the elastic prestrain of the specimen`s surface, more kinetic energy is changed into plastic deformation, as less stress is necessary to overcome the yield strength.

The fatigue life is generally determined by the time to crack initiation, the crack growth period and the time to fracture /4/.

The crack initiation is affected by the residual stresses at the surface, the surface roughness, the material`s strength and the ambient temperature.
Crack start is found at the surface within the field of high stress concentration such as non-metallic inclusions or surface faults. These material defects are decisive under bending loading. This was found in polished specimens, too /5/. With smoothing the surface, which is to be observed with raising UTS, locally elevated surface stresses are diminished which inhibits early crack formation.
Prestraining leads to an increase of the elastic yield strength and therefore to later crack initiation.
Compressive residual stresses at the surface act like a mean stress and consequentely reduce the effective stress. The effect is the same as dropping the loading level. An indicator for such processes is the surface strain (Figure 1), which diminishes with growing compressive residual stresses at the surface.
An increasing UTS enlarges the elastic region and therefore diminishes the stressing of the surface. Low temperatures act in the same way, as they increase the material`s strength.

The crack growth depends on the residual stress profile, the material`s strenght and the testing temperature.
The maximum of the compressive residual stress after shot-peening is to be found below the surface. That means a load diminishing with growing depth below surface. When a growing crack runs into this zone, a crack stop occurs just at that point where the sum of loading stress and compressive residual stress leads to a stress intensity at the crack tip, which is less than the threshold value for stable crack growth. With an increasing compressive residual stress profile and simultaneously increasing depth of the maximum stress the crack delay is prolonged.
But nevertheless the residual stresses cannot be assumed to be always constant (Table 3 and Table 6). Depending on the loading level, the temperature and the UTS, the residual stress profile is reduced by the fatigue loading. This process affects the stress intensity at the crack tip in overcoming the threshold value and a stopped crack is able to grow further on.
The crack growth rate is determined by the UTS and the testing temperature /2,5/. Increasing the UTS or decreasing the temperature means an accelerated crack growth, which diminishes the crack growth period.

Fracture sets in when the critical crack length for a given material state is reached. The critical point may be expressed by the fracture toughness which depends on the UTS and the testing temperature /2,5/. While in specimens with a UTS of 1200 and 1500 MPa unstable crack growth sets in after a long period of crack propagation with a crack length of about 10 mm, the critical crack length in the material with a UTS of 1850 MPa is found to be 1 mm or less (Figure 7). As mentioned, a low temperature acts like a raised UTS. Therefore the critical crack length is diminished also by deep temperatures.

Summary

The effect of shot-peening on the fatigue life is discussed. The investigations are carried out on prestrained, shot-peened and shot-peened under prestrain specimens and are compared to the untreated condition. At the same time the influence of UTS and low temperatures is observed.
By inducing compressive residual stresses the time to crack initiation is delayed. Due to the residual stress profile (growing compressive residual stresses with growing depth below surface) cracks run into a zone of decreasing stresses and therefore may be delayed or stopped. This effect depends on the heigth of the compressive stresses and their extension below surface. As the residual stresses are not stable but diminish with the fatigue loading, the stress at the crack tip increase with the time which leads to increasing stress intensities at the crack tip. Therefore a stopped crack may grow further on.
The time to failure simultaneously depends on the UTS and the temperature. A growing UTS and a decreasing temperature means retarding the time to crack initiation but an increasing crack growth rate and a decreasing critical crack length.

References

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