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Influence of Temperature of Shot Peening on Fatigue Life

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ABSTRACT

This paper addresses the influence of shot peening temperature on micro structure evolution and mechanical properties of spring steel 60SiCr7 in the temperature range between 200°C and 250°C. In particular, surface roughness, micro hardness and local distribution of residual stresses in the surface layer were measured before and after fatigue tests. Also fracture surfaces were examined in the scanning electron microscope. It was found that the local distribution of residual stresses in the surface is drastically changed by shot peening at different temperatures, thus prolonging the fatigue life.

KEYWORDS

shot peening, residual stress, fatigue life, surface roughness, damage layer

INTRODUCTION

It is well established that shot peening can prolong the fatigue life as well as enhance fatigue strength. Most investigations were conducted with material shot peened at room temperature, in particular with respect to the influence of hardness, surface roughness and residual stress on the fatigue life (1,2). In contrast, few investigations have treated the influence of temperature on shot peening. Fatigue testing has shown that in all cases an improved fatigue strength at higher temperature was achieved (3,4). However, a full material and structural characterization of this dependence has until this time to the authors knowledge not been performed, and this work aims to present the results of a more comprehensive study of this effect.

MATERIAL AND TEST PROCEDURES

The specimens used in this investigation were made of one charge of the spring steel 60SiCr7 with the following chemical composition. (See Table 1 below.)

All specimens were annealed at 890°C, quenched in oil and tempered at 418°C for 2h. After the heat treatment the hardness of the specimens was 52 HRC. Following this all specimens were peened at different temperatures without changing the shot peening conditions. The specimens were loaded in the peening equipment at 20°C, 170°C and 250°C. The peening process changed the specimen temperature causing an estimated temperature fluctuation of about 25°C.

After shot peening, fatigue tests were carried out on a torsion machine with constant amplitude at two different stress loading levels. Residual stress profiles of the specimens in the surface layer were measured by X-ray diffraction with Cr-Kα radiation according to the $\sin\psi^2$ - method. The fracture surfaces of the broken torsion bars were imaged in a JEOL 6100 scanning electron microscope, and the surface roughness was tested on a PERTHOMETER MP4. Also Vickers hardnesses profiles of the specimens were measured.

%C	%Si	%Mn	%S	%P	%Cr	%Cu	%Al	%Mo	%Ni
0.60	1.80	0.80	0.005	0.024	0.28	0.16	0.020	0.01	0.01

Table 1: Chemical composition of the samples in wt.-%

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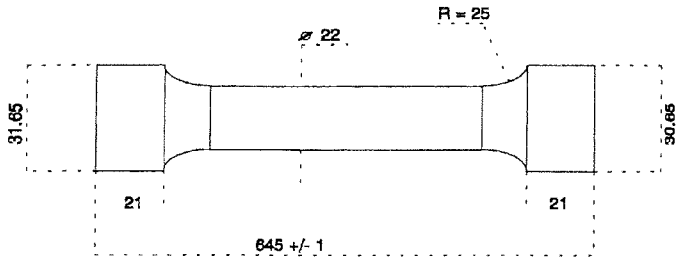

Figure 1. Specimen configuration in [mm]

equipment:	centrifugal type
shot:	wire shot, HV 640, D=0.7mm
intensity:	52mmA
peening time:	full coverage time
peening temperatures:	20°C, 170°C, 250°C

Table 2. Shot peening conditions

RESULTS AND DISCUSSION

The Vickers hardness of the specimens measured with a load of 100g was the same in the surface layer as in the bulk material. (See Figure 2 below.)

Residual stress measurements showed that the surface layer influenced by shot peening has a depth smaller than 0.3mm. Taking into account that the uncertainty of the hardness measurements is about 20 HV1 the hardness curve exhibits no change in this region compared with hardness values much below the surface of the samples.

It is obvious that the shot peening process drastically changes the topography of the surface. It was found that an increase of the temperature during shot peening produces higher surface roughness.

No relationship was found between the roughness values of the torsion bars and their fatigue limit. This fact was surprising because higher roughness suggests a higher probability of superficial micro defect and more damage in the surface layer, where the highest loading stresses in these specimens occur.

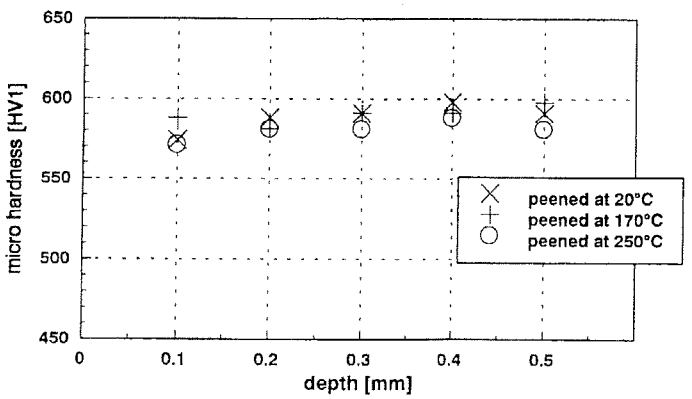

Figure 2. Vickers hardness of the surface layer

	T = 20°C	T = 170°C	T = 250°C
Ra [µm] DIN 4768	41.67	46.38	48.63
Rz [µm] DIN 4768	7.12	8.18	8.55

Table 3: Surface roughness of specimens shot peened at different temperatures

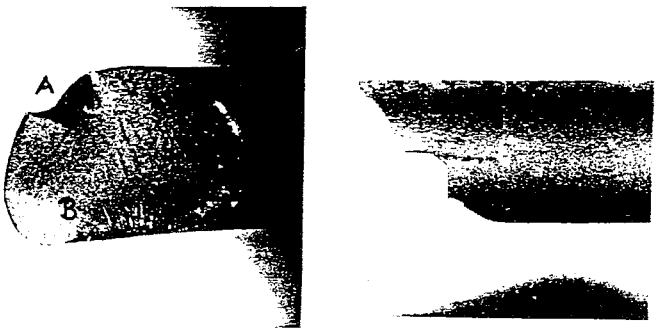

Photo 1: Configuration of the fracture surface (top view and side view)

To understand the behavior during the fatigue test all fracture surfaces were examined on a macroscopic level and in a scanning electron microscope (SEM) to find the crack initiation point and to investigate the crack propagation.

On a macroscopic level the fracture surface can be separated in two different types planes (Photo 1). One planetype (A) is smooth with areas between 1mm² and 150mm². The angle between these planes and the axis of the torsion bar is 0° and/or 90°. In such a plane the highest shear stresses occurred, which produced plastic deformation during fatigue life tests.

SEM images of these planes show that in all cases the crack started from micro defects on the sample surface like micro fissures or micro notches, or from micro defects in the volume such as inclusions, or micro fissures. In specimens tested at the lower loading stress level a higher probability of superficial crack initiation point was found than in specimens tested at the higher loading stress level. In a few cases the crack initiated in the bulk of these specimens at very big inclusions about 100µm in diameter. Plastic deformation proceeds from the crack initiation, caused by the high tensile stress concentration at this point. Marks from the plastic deformation radiate outwards from the initiation point (Photo 2). These radial line patterns can be understood by plastic deformation due to the tensile stress fields of micro defects (5).

The adjacent regions contain a parallel line pattern. These surface discontinuities have dimensions larger than the dimension of the grains (Photo 3 on next page). It is well established, that every step corresponds to a fatigue cycle during cyclic crack growth (6). Evidently during a great part of fatigue life the material is plastically deformed. It was found that the specimens with larger planes do not always correspond to specimens with low fatigue strength. SEM-micrographs show that in the surface

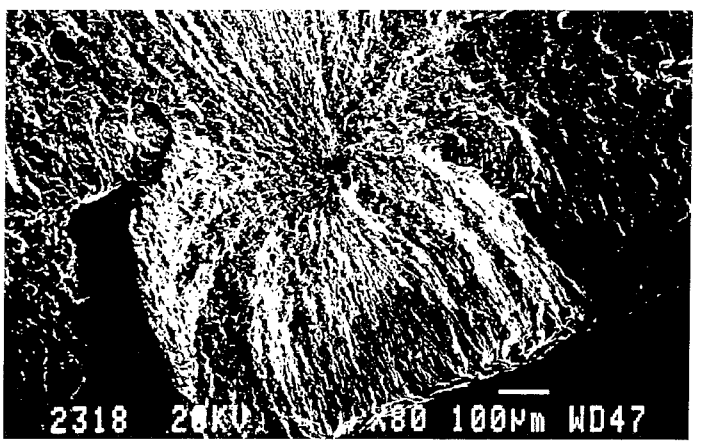

Photo 2. Crack initiation from an inclusion with a radial line pattern

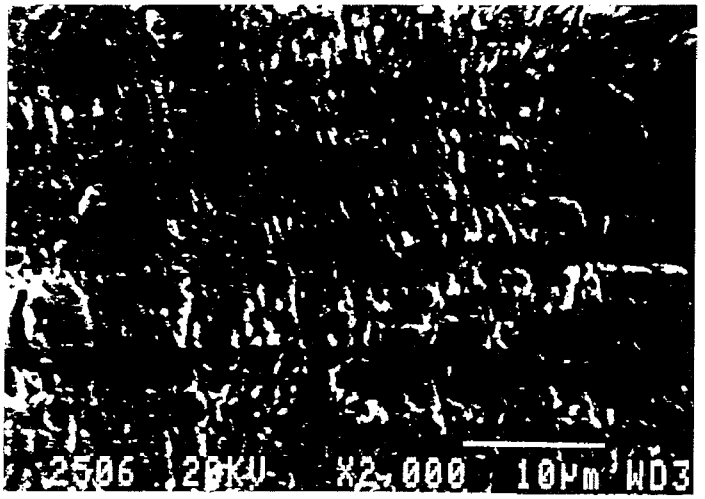

Photo 3. Ductile area of the fracture surface 1mm beneath the surface

layer, which is influenced by shot peening, less plastic deformation occurs than in the bulk material (Photo 4).

The rest of fracture surface consist of plane type (B) (Photo 1), which has a rough surface located 45° to the axis of the torsion bar. During fatigue testing in this plane the highest tensile stresses occurred. SEM-micrographs (Photo 5) reveal a mixture of intergranular and dimple fracture. This region identifies the rapid crack propagation at the time of failure.

The development of the fracture behavior explains why there is no relationship between the measured surface roughness values and fatigue strength. There is no doubt that the surface topography has an influence on fatigue life. Rough surfaces have deeper notches, where cracks can initiate due to the tensile stress concentrations in this point (7). But only the very largest notch or fissure is important, and not the average value of roughness which was measured. A sample may have a short fatigue life due to a single big notch, although its average roughness value is low.

Furthermore, the tensile stress concentration of microdefects can be compensated by the compressive residual stresses induced by shot peening. The residual stress profiles presented in Figure 4 were measured before fatigue life testing. Obviously higher temperatures during shot peening produce higher compressive residual stresses. The samples peened at 250°C have the highest compressive residual stresses and the minimum of residual stress profile is located deeper under the surface than in the other specimens.

Photo 4. Ductile area of the fracture surface 0.1mm beneath the surface

Photo 5. Fragile area of the fracture surface

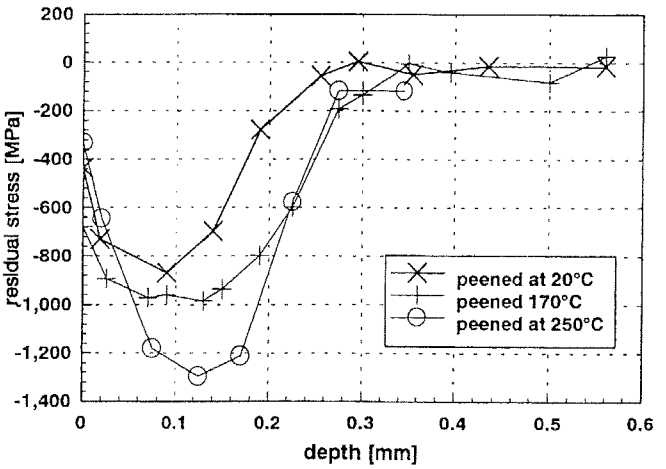

Figure 4. Residual stress curves before fatigue testing

Besides higher compressive residual stress values are found in the layer between 0mm and 0.05mm in specimens shot peened at 170°C than in other specimens. The situation of residual stresses changes drastically after fatigue limit tests. Stress measurements exhibit great reduction of the compressive residual stresses. Although stress relaxation is a microscopic effect, exhibiting great local scattering in residual stress values, all stress measurements show less stress reduction in specimens peened at 170°C than in the specimens peened at other temperatures.

To consider the influence of residual stress on fatigue strength we have to recall the development of fracture, as found in SEM-investigations. It is well known that compressive residual stresses in the surface layer delay the crack initiation. The crack started where the highest values of real stress exceeded the local fatigue limit of the material (8). The acting stress is the sum of loading stress and residual stress. Residual stresses in the specimens are produced by shot peening and caused by internal stress fields of micro defects like inclusions or micro notches. The resolution of the stress measurement equipment, which was used in this investigation, cannot detect the alteration of residual stress field of these micro defects. All specimens were found to contain the same concentration of inclusions. Therefore these defects produce only scattering in fatigue limits. But the average values of fatigue limit are mainly influenced by the compressive residual stresses in the surface layer, where the highest loading stresses occur. These stresses improve fatigue strength by

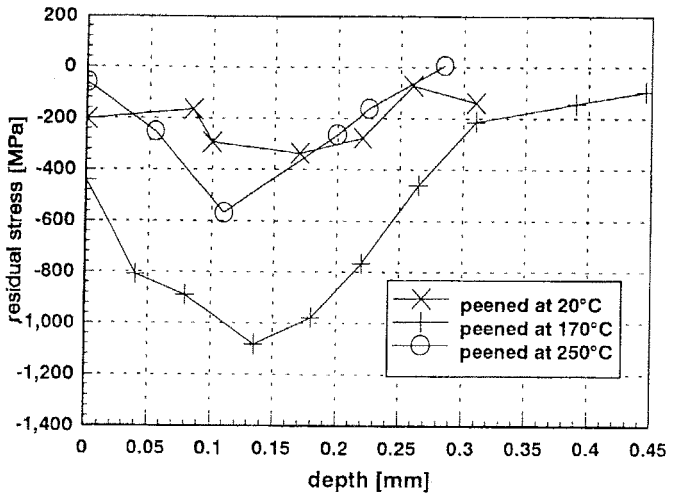

Figure 5: Residual stress profiles after fatigue testing

reducing the acting stresses under the local fatigue limit of the material (9).

SEM- investigation showed large areas damaged by plastic deformation caused by shear stresses during fatigue testing. We found no or only little plastic deformation in this damage layer 0.1mm beneath the surface. This means that high compressive residual stresses in the surface layer prevent plastic deformation in this layer and the specimens can suffer a lot of plastic deformation in the bulk material, if the surface layer keeps its stability. For example a specimen broken after more than 900,000 cycles, which represents one of the highest fatigue lives measured in this investigation, had a ductile area of about 150mm^2 .

So compressive residual stresses increase the fatigue strength of specimens by delaying the crack initiation and by preventing the damage layer from reaching the surface. The existence of two independent effects makes clear why no relationship between ductile area and fatigue strength was found.

In specimens peened at 170°C small ductile areas were found and lower surface temperatures were measured in the samples during fatigue testing. In specimens tested with a loading stress σ= 560±560 MPa the surface temperature of the samples peened at 170°C was between 40°C and 50°C, while specimens peened at other temperatures reached surface temperatures between 80°C and 90°C. Smaller ductile areas and lower surface temperatures during fatigue testing indicate reduced plastic deformation produced in the specimens. Less plastic deformation in samples peened at 170°C indicates that in these torsion bars the delayed crack initiation had played a greater role in the increase of fatigue strength than the other effect.

All experimental results show the very great importance of the compressive residual stresses induced by shot peening. Thereby the benefits of compressive residual stresses increase with higher compressive stress values, larger depth of the layer with compressive stresses and better stability of residual stresses during fatigue testing.

Surely the absolute maximum value of the compressive residual stresses is less important than the depth of the compressive stress profile or the stability of residual stresses, if the residual stresses reduce the acting stresses below the local fatigue limit of the material.

Considering these facts it is obvious that the specimens peened at 170°C have the best residual stress profile. These specimens have the same depth of the profile as the specimens peened at 250°C, but they have a higher stability of the residual stresses during the fatigue life testing . Although the specimens peened at 250°C have the highest compressive stresses before fatigue testing, they have less compressive residual stresses in the layer between 0mm and 0.05mm under the surface than the specimens peened at 20°C and 170°C. But just in this layer we have the bad influence of surface defects and the highest loading stresses. The greater damage just beneath the surface is also substantiated by the highest roughness values. The lower stability of the compressive residual stresses during fatigue testing is enhanced by the higher damage due to plastic deformation in this layer as it was found in SEM-investigation.

The favorite stress profile of the specimens peened at 170°C caused the best fatigue strength of all specimens (Table 4). The low values of compressive residual stresses and the low depth of the compressive stress profile before fatigue tests as well as the great residual stress reduction in fatigue testing in specimens peened at 20°C result in low fatigue strength, found in these specimens.

loading tension [MPa]	T = 20°C	T = 170°C	T = 250°C
560±560	176782	488029	340714
560±513	355635	816542	398401

Table 4. Average fatigue strength of the specimens

CONCLUSIONS

This investigation confirms the very important role of residual stresses induced by shot peening on fatigue strength. Higher temperatures during the shot peening process produce higher compressive residual stresses. The investigation of fracture surfaces gives useful hints to understand the development of fracture. It was found that the crack initiates from micro defects and that plastic deformation starts from this point in a plane with greatest shear stresses, which damage the material. The compressive residual stress layer delays the crack initiation and also prevents the ductile damage layer from reaching the specimen's surface. Both effects increase the fatigue strength of the specimens. The benefit of compressive residual stresses depends on the magnitude of stresses, the depth of the layer with residual stresses and its stability during fatigue testing. Although the specimens peened at 250°C exhibit higher compressive stresses than the specimens peened at 170°C, the former show the highest reduction of compressive residual stresses after fatigue testing. The reason for this behavior is that at 250°C the specimens suffer greater damage just beneath the surface during the shot peening process. Therefore shot peening at 170°C results the highest fatigue strength of the investigated samples.

REFERENCES

(1) B. Kaiser, EinfluB des Kugelstrahlens auf die Schwingfestigkeit von Federelementen aus Stahl, Draht 38/1987
(2) R. Clausen, P. Martin, Änderung der Randzone kugelgestrahlter Proben, ZwF 74 (1979) 7
(3) G. Kuhnelt, Der EinfluB des Kugelstrahlens auf die Dauerfestigkeit von Blatt- und Parabelnfedern, ICSP-1 (1981)
(4) J. Ulbricht, Vondracek, Möglichkeiten zur FedenvegvergröBerung von Drehstäben, Estel-Berichte 3\76
(5) J. R. Low, Jr., in Fracture, B. L. Averbach und Mitarbeiter. Hrsg. M.I.T., Wiley, New York (1959), S.68
(6) K.-H. Schwalbe, Bruchmechanik metallischer Werkstoffe, Kapitel 6., Hanser-Verlag (1980)
(7) L. Weber, Wechselwirkung zwischen Randschichtzustand und SchwingungsriBausbreitung in hochfesten Stähhlen, VDI-Verlag
(8) J. Broichhausen, Schadenskunde, Hanserverlag, ISBN-3-446-13409-3, 3. Kap.
(9) B. Scholtes, E. Macherauch, Auswirkungen mechanischer Randverformung auf das Festigkeitsverhalten metallischer Werkstoffe, Zeitschrift für Metallkunde 1986, H.5