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Fatigue Performance of the Mechanically Surface Treated Steels 42CrMo4 and 54SiCr6: Shot Peening vs. Roller-Burnishing

Dariusz Wierzchowski[1)] Alfred Ostertag[2)] Lothar Wagner[1)]
[1)] Chair of Physical Metallurgy and Materials Technology, Technical University of Brandenburg at Cottbus, Cottbus, Germany
[2)] Ecoroll AG, Celle, Germany

1 Introduction

Mechanical surface treatments such as shot peening (**SP**) and roller burnishing (**RB**) are commonly used in industrial applications to improve fatigue life and fatigue strength of cyclically loaded engineering components. These treatments lead to surface layer properties of the workpiece different from those in the bulk. For example, the yield stress in near-surface regions increases due to cold work and resulting high dislocation densities. Owing to the local plastic deformation, residual stresses are generated. In addition, the surface topography is changed. Depending on the surface treated material, other property changes can result from stress-induced martensitic transformations and/or modifications in near-surface crystallographic textures [1].

Work has shown that the fatigue performance of mechanically surface treated high-strength steels is mainly affected by near-surface residual compressive stresses which can largely suppress crack growth from the surface into the bulk of a component [2]. Increasing the strength level of the steels may increase the cyclic stability of process-induced residual compressive stresses and thus, their contribution to the improvement of the fatigue performance [3]. However, the stronger the steels the smaller is the strength differential between shot material and workpiece. As notch sensitivity of steels typically increases with an increase in tensile strength, greater contributions of surface roughness to fatigue crack nucleation resistance may result [4].

The goal of the present investigation was to determine possible strength effects on the improvement of the high cycle fatigue (HCF) performance of high-strength steels by shot peening. For comparison, the effect of roller-burnishing which leads to low roughness was also investigated.

2 Experimental

The investigation was performed on the structural steel 42CrMo4 and the spring steel 54SiCr6. The steels were delivered as Ø10 mm bar materials. Chemical compositions are given in table 1.

While the spring steel was delivered in quenched and tempered condition, the structural steel was given an austenitizing treatment at 850 °C for 30 min followed by oil quenching. The material was tempered at 450 °C for 2 hours followed by air cooling.

Table 1: Chemical composition (wt. %) of the tested steels

	C	Si	Mn	P	S	Cr	Mo	Fe
42CrMo4	0.41	0.34	0.79	0.022	0.002	1.18	0.16	balance
54SiCr6	0.55	1.44	0.70	0.007	0.006	0.70	–	balance

Tensile tests were performed on threaded cylindrical specimens having gage lengths and diameters of 20 and 4 mm, respectively. The initial strain rate was 8.3×10^{-4} s^{-1}. Tensile properties are listed in table 2.

Table 2: Tensile properties of the tested steels

	$\sigma_{0.2}$ [MPa]	UTS [MPa]	$\sigma_{0.2}$/UTS –	*El* [%]	RA [%]	HV10 –
42CrMo4	1375	1440	0.96	10.0	56	455
54SiCr6	1865	2055	0.91	9.9	58	600

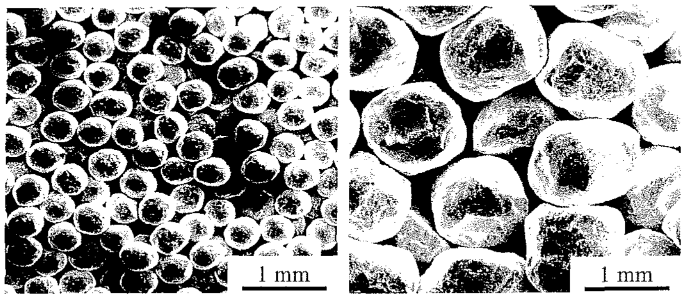
For HCF testing, hour-glass shaped specimens with a minimum diameter of 3.8 mm were machined. Turning (**T**) was done using cubic boron nitride (CBN) tool bits (0.8 mm nose radius) under cutting fluid cooling in a CNC lathe operating at a rotational speed of 2500 rpm, a feed rate of 0.1 mm/rev and a depth of cut of 0.1 mm/pass.

After machining, part of the specimens was electrolytically polished (**EP**) to serve as reference. About 120 ìm were removed from the surface to ensure that any machining effect that could mask the results was absent. Shot peening (**SP**) as well as roller-burnishing (**RB**) were performed on as-turned specimens. Shot peening to low Almen intensities (**LSP**) was carried out using spherically conditioned cut wire (**SCCW**) in an injector type system while for realizing high Almen intensities (**HSP**), rounded cut wire (**RCW**) was used in a pressure blast system. All peening treatments were done to full coverage. Shot properties are listed in table 3. As seen in the SEM pictures (fig. 1), the **SCCW** shot is almost perfectly spherical while the **RCW** shot is just rounded with some edges still present.

Table 3: Properties of the shot material

	Shape	Ø mm	HV1
SCCW	Spherical	0.34	610
RCW	Rounded	1.00	640

Shot peening of both steels was done either at low intensity of 0.20 mmA (**LSP**) or at high intensity of 0.55 mmA (**HSP**). Some tests were done with specimens being first heavily peened followed by light peening (**HLSP**) [5]. Part of the **HLSP** specimens was mechanically polished (**HLSP+MP**) using fine grained SiC paper to decrease the shot peening-induced surface roughness. Roughly 20 and 25 ìm were removed from the as-peened surfaces of 42CrMo4 and 54SiCr6, respectively.



a) SCCW b) RCW

Figure 1: Geometry of the shot material

Roller burnishing was performed in a conventional lathe using a one-roll hydrostatic system [6]. The diameter of the hardmetal ball was 6 mm. The rolling parameters were as follows: 0.2 mm/rev feed rate, 1 pass, 36 rpm rotational speed. For optimum roller-burnishing regarding fatigue life response, rolling forces of 220 N and 680 N were chosen for 42CrMo4 and 54SiCr6, respectively.

Surface roughness was measured by a profilometer. Residual stresses were determined by the incremental hole drilling method as described elsewhere [7]. Fatigue tests were performed in rotating beam loading ($R = -1$) at 100 Hz.

3 Results and Discussion

Roughness profiles and values for the various conditions of both steels are given in figure 2.

Lowest roughness values were measured for the conditions **EP**, **HLSP+MP** and **RB** (fig. 2). Much higher roughnesses were determined for the various shot peened conditions with comparatively low, intermediate and high values for **LSP**, **HLSP** and **HSP**, respectively. Comparing now roughness values between 42CrMo4 and 54SiCr6 for the same treatments, it is seen that roughness values are identical for **EP**, while most mechanical surface treatments lead to roughnesses being higher in 42CrMo4 than in 54SiCr6. Presumably, this is caused by the difference in yield stress of the steels resulting in more marked local plastic deformation in the lower strength 42CrMo4 ($\sigma_{0.2}$ = 1375 MPa) compared to the higher strength 54SiCr6 ($\sigma_{0.2}$ = 1865 MPa).

Residual stresses as measured by the hole drilling method for the various surface treatments on 42CrMo4 are illustrated in figure 3.

Only very small residual compressive stresses were found after turning (**T**) while much higher stresses were observed after the various shot peening treatments and after roller-burnishing (**RB**). Compared to light peening (**LSP**), heavy peening (**HSP**) led to somewhat lower residual compressive stresses in regions very close to the surface, whereas in deeper depths much higher stresses were observed [9]. As expected, heavy peening followed by light peening (**HLSP**) does not significantly change the residual stresses profile of the **HSP** condition. Residual stresses after roller-burnishing (**RB**) were similar to these shot peened conditions. However, stresses close to the surface were higher (fig. 3). While the magnitude of the induced residual stresses was so-

	Surface treatment	R_a [µm]	R_z [µm]	R_y [µm]	Roughness profiles
42CrMo4	EP	0.3	1.0	2.0	
54SiCr6		0.3	1.2	2.0	
42CrMo4	T	1.3	7.6	11.0	
54SiCr6		0.8	3.8	5.8	
42CrMo4	LSP	1.8	10.2	13.4	
54SiCr6		1.2	7.4	8.2	
42CrMo4	HSP	7.1	34.4	45.2	
54SiCr6		2.3	12.6	17.8	
42CrMo4	HLSP	3.3	16.2	19.4	
54SiCr6		1.5	8.6	10.8	
42CrMo4	HLSP + MP	0.3	1.6	3.1	
54SiCr6		0.3	1.3	2.3	
42CrMo4	RB	0.6	2.6	4.0	
54SiCr6		0.5	2.2	3.2	

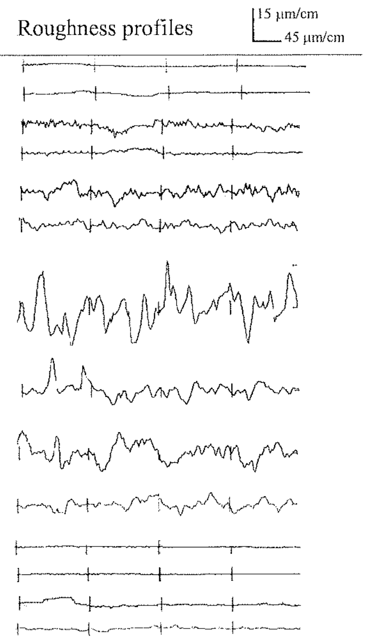


Figure 2: Surface roughness values and typical profiles for the various conditions

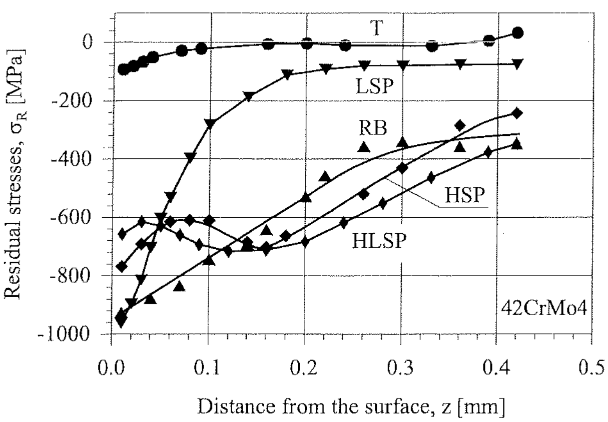
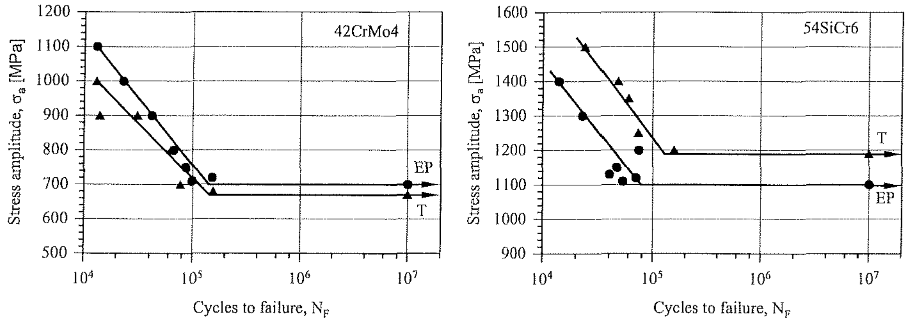


Figure 3: Residual stresses for the various surface treatments in 42CrMo4

mewhat higher in 54SiCr6, the ranking among the various surface treatments was very similar to the results on 42CrMo4.

The HCF results in terms of S-N curves for the various surface treatments are illustrated in figures 4–6 comparing results on 42CrMo4 (a) with those on 54SiCr6 (b).

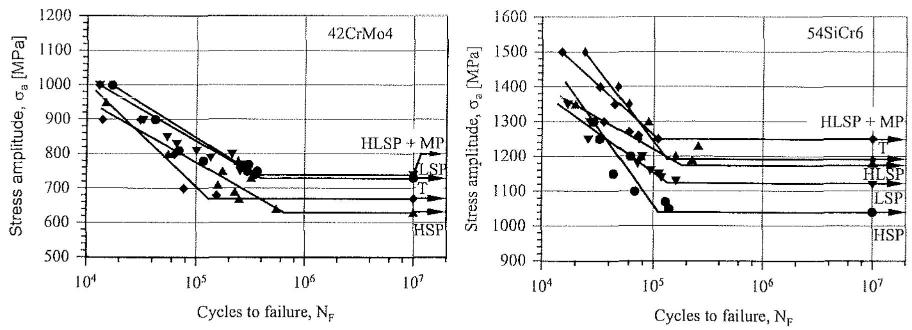


a) 42CrMo4 b)54SiCr6

Figure 4: S-N curves in rotational beam loading, effect of turning (T) as opposed to electropolishing (EP)

As seen in figure 4, turning can decrease (fig. 4a) or increase (fig. 4b) the HCF strength of the electrolytically polished reference. Thus, often found statements in the literature about potential improvements of the HCF strength caused by shot peening or roller-burnishing (e.g., 20 %) are questionable if the reference (often denoted as "not peened") is not well defined.

The effects of the various shot peening treatments on the HCF strengths are shown in figure 5. Since shot peening was performed on as-turned specimens, this condition (**T**) is also shown for comparison.

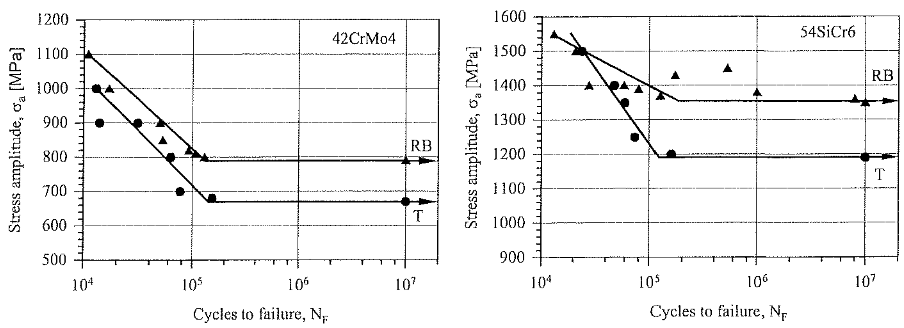


a) 42CrMo4 b) 54SiCr6

Figure 5: S-N curves in rotating beam loading, effect of various shot peening treatments

Heavy peening (**HSP**) decreases the HCF strengths of both 42CrMo4 (fig. 5a) as well as 54SiCr6 (fig.5b) while slight peening (**LSP**) gave improved results. Best fatigue performance was observed for the condition **HLSP + MP** particularly for 54SiCr6 (fig. 5b). Since the residual stress profiles of **HSP** and **HLSP + MP** hardly differ (fig. 3), the marked difference in HCF performance between these two conditions is mainly due to roughness effects. Fatigue cracks were nucleated at the surface for all shot peened specimens indicating that surface roughness was directly involved in the crack nucleation process [8].

The effect of roller-burnishing on HCF strengths is illustrated in figure 6. For both 42CrMo4 and 54SiCr6, roller-burnishing (**RB**) led to marked improvements of the fatigue performance of the as-turned (**T**) conditions.



a) 42CrMo4 b) 54SiCr6

Figure 6: S-N curves in rotating beam loading, effect of roller-burnishing

Comparing the results after roller-burnishing (fig. 6) with those after conventional shot peening (fig. 5), it is obvious that roller-burnishing is by far superior. Only if the shot peening-induced high surface roughness is reduced as is the case in **HLSP + MP**, similar increases of the HCF strengths as observed after roller-burnishing can be expected (compare fig. 6 with fig. 5).

4 References

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