THE EFFECTS OF SHOT PEENING AND DEEP ROLLING ON THE SURFACE LAYER AND THE MECHANICAL PROPERTIES OF SINTERED IRON

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ABSTRACT

The surface states and the mechanical behaviour of sintered iron (ASC 100.29) with different initial densities were studied after shot peening and deep rolling. This included the investigation of topography, depth profiles of microhardness, density and residual stresses and the determination of the behaviour at tensile, impact and alternating bending fatigue loading. The influence of the parameters used during the mechanical surface treatments on these properties will be discussed.

SUBJECT INDEX

Sintered Iron, Densification, Alternating Bending Fatigue

INTRODUCTION

The increase of the fatigue properties of powder-metallurgical components is limited in the case of conventional sintering treatments. Therefore several enhanced but very expensive sintering strategies were developed, as it is well accepted that the fatigue strength of sintered materials mainly depends on alloying and on density [1,2]. In [3] and [4] it is shown that the size and the number of pores strongly lower the material's fatigue strength, since the true load bearing cross-sectional area is reduced. However the local stress concentrations induced by the notch effects of pores close to the surface are more important for fatigue behaviour as they promote the detrimental initiation of cracks [5]. Thus, for materials states with relatively low density, mechanical surface treatments may be an economically fine alternative due to densification effects in the surface layer, which usually will be the highestly loaded area of a component. Therefore not only the work hardening and residual stress state after mechanical surface treatments like shot peening or deep rolling but also local densification effects are of major interest. The separation of the effects of these changes in the surface state imposed by those densification treatments on the behaviour at fatigue loading has not yet been investigated systematically.

In this paper results are shown for the peened and deep rolled flat samples made from unalloyed sintered iron (ASC 100.29) which have two different initial densities. The characteristics of near surface regions as well as the fatigue strength will be compared and evaluated for both mechanically surface treated variants.

MATERIAL AND SPECIMEN GEOMETRY AND EXPERIMENTAL PROCEDURE

The investigations were performed using unalloyed sintered iron specimens (Höganäs ASC 100.29) and compact Armco-iron for comparison. Two sets of flat hour-glass specimens (90x11x5 mm) were pressed to nominal densities of 6.9 g/cm^3 and 7.2 g/cm^3, resp.. They were sintered for 30 minutes at 1150 °C in an atmosphere of H_2(10%)-NH_3(10%). The compact Armco iron (7.87 g/cm^3) was subjected to a grain coarsening annealing at 600° C in N_2 atmosphere in a fluidized Al_2O_3 air bed for two hours and cooled down in air in order to adjust the grain size to that of the porous material of 35 to 40 µm. The chemical composition in weight-% of the sintered and the Armco-iron is presented in Tab. 1.

[g/cm^3]	C	N	P	Cu	Si	Al	Mn	Cr	Ni	Fe
6.9	0.015	0.015	0.005	0.010	<0.001	0.003	0.093	0.018	0.023	Bal.
7.2	0.049	0.015	0.007	0.014	<0.001	0.003	0.099	0.026	0.030	Bal.
7.87	0.010	-	0.006	0.008	0.023	0.004	0.054	0.018	0.024	Bal.

Tab. 1: Chemical composition (wt.-%) of the materials states investigated

The shot peening (SP) treatments were performed using an air blast machine at room temperature. Cast iron shot S170 56 HRC was used at peening pressures of 1.6, 4 and 8 bar with a media flow rate of 1.6 kg/min and a resultant plain coverage of the sample surface. The Almen intensities were measured to be 0.33, 0.50 and 0.66 mmA, resp.. The deep rolling (DR) treatments were carried out using a so-called ball-point tool with a hydrostatic spherical carbide element (Ø 6.35 mm), which allows deep rolling of free formed surfaces of non-rotational symmetric specimens at a constant pressure. Plain coverage was attained by meandering the surface with a 0.04 mm spacing between each track in such a manner that maximum compressive residual stresses are generated perpendicular to the specimen's axis. Hence the pressures were varied between 55 and 380 bar and feed rates were adjusted to 1000 mm/min so that the hydrostatic ball conveyed loads ranging from 137 to 950 N. The porosity of shot peened specimens was measured using computer aided image analysis of optical micrographs. The S-N-curves were determined by performing amplitude controlled alternating bending tests at a frequency of 25 Hz using 25 to 30 specimens. The results were analysed applying the arcsin$\sqrt{P}$ - method [6]. Residual stresses were measured using CrKα-radiation at the {211}-interference lines of the ferritic phase at 13 angles between –60° and +60° according to the $\sin^2\psi$-method [7], using a Young's modulus of 210000 N/mm^2 and a Poisson's ratio of $\nu = 0.28$. Subsequent X-ray measurements after electrolytic removal of thin surface layers enabled the determination of the depth distribution of the residual stresses. The mechanical elastic properties of porous materials are governed by the shape and concentration of the pores [8]. Therefore the residual stress values were corrected by a method described by [8], applying the results of the pore depth profiles. To compensate the effects imposed by the material removal, the results finally were corrected according to the method of [9].

RESULTS

Shot peening and deep rolling of the sintered iron for both nominal densities 6.9 and 7.2 g/cm^3, resulted in significant differences in the surface roughness, Rz. Shot peening of sintered iron results in a linear increase of the roughness Rz with increasing pressure varying from 1.6 to 8 bar. The Rz values in this pressure range, measured by a confocal white light microscope, are more than doubled from 19 and 14 µm in the inital state to 47 and 42 µm, resp.. On the other hand deep rolling at pressures of 55 and 100 bar yields roughness values of 0.60 and 0.55 µm, resp., which are smaller by more than one order of magnitude compared to the untreated state. At a pressure of 180 bar the onset of slight pitting at the specimens surface can be observed, which increases Rz to 1.70 µm. At a maximum pressure of 380 bar the measured roughness of 13.70 µm almost equals that observed at the initial state. It can be inferred that shot peening increases the Rz value while deep rolling decreases it markedly.

In order to characterise the influence of shot peening on the pores resident in the surface layers of the sintered iron, the change of porosity as a function of the distance z from the sample surface was determined by conducting computer aided measurements. The initial porosity P_0 in the untreated condition for both nominal densities 6.9 and 7.2 g/cm^3 amounts to 13.28 % and 8.50 %, resp.. The depth profiles of the change of porosity for shot peened samples are depicted in Fig. 1. In the less dense material (Fig.1a) maximum changes of porosity of about 12 %, 11 % and 10.60 % can be observed in the surface layer of the samples, which were shot peened at 1.6, 4 and 8 bar. At the lowest pressure value, porosity increases instantaneously beginning below the surface and then attains the initial porosity P_0 at z = 0.30 mm (standard deviation considered). At 4 and 8 bar the penetration depth of the densification effects increased to greater depths of 0.35 and 0.45 mm, resp.. The curve progressions of the denser material (Fig.1b; 7.2 g/cm^3) are comparable to that observed in Fig. 1a. The maximum changes of porosity in the surface for 1.6, 4 and 8 bar peening pressures are 8, 5.80 and 8.5 %. The 4 bar-curve shows significant residual porosity, the reproducibility of this effect is yet to be validated. The initial porosity value is reached below the surface in 0.25, 0.40 and 0.60 mm depth. For both nominal densities the penetration depth of the densification effects is enhanced with increased pressures, where greater depth penetration can be achieved for the higher initial density. The latter requires further investigations. Penetration depths of deep rolled conditions have been generated in preliminary measurements using light microscopy images. Deep rolling at pressures of 55, 150 and 180 bar revealed densification effects in surface layers up to 0.25, 0.45 and 0.60 mm. However first computer aided measurements of conditions treated with the maximum pressure indicate a densification of the complete cross section of the samples as the change of porosity in the core region for both nominal densities amounts to 12.78 and 6.60 %.

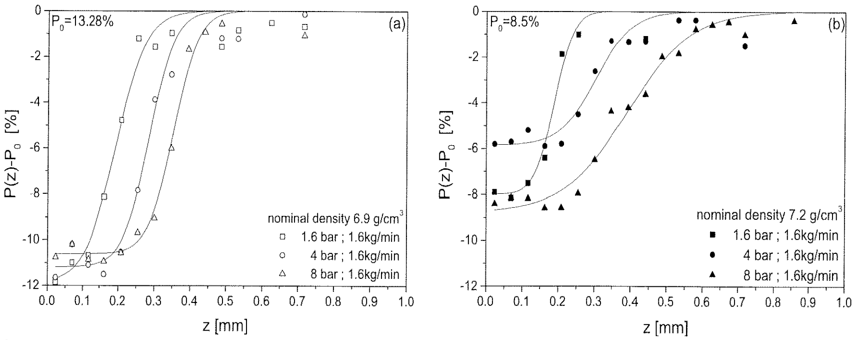

Fig. 1: Depth profile of the change of porosity of sintered iron after shot peening

The microhardness continuously increases from the core to the surface for both surface treatments. The changes of the near surface microhardness as well as the penetration depth of microhardness is summarized in Fig. 2. Due to the work hardening process, induced by shot peening and deep rolling the microhardness of initially 80 HV 0.1 is increased by about 90 HV 0.1 for both nominal densities close to the surface. In contrast to the shot peening at 1.6 bar, the increase only resulted in 70 HV 0.1 and 80 HV 0.1 for the nominal densities 6.9 and 7.2, resp.. The penetration depth of the microhardness-increase rises for both surface treatments with increasing pressure, where deep rolling enables maximum penetration depths.

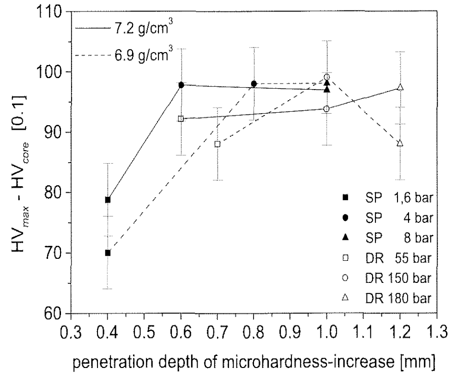

Fig. 2: Change of near surface microhardness in dependency of the penetration depth of microhardness-increase after shot peening and deep rolling

Fig. 3 shows the corrected residual stress distributions of samples of both nominal densities after shot peening at 1.6, 4 and 8 bar. Independent of the peening pressure characteristic depth distributions with a subsurface maximum of resultant residual compressive stresses. With increasing pressure these maxima were found in increasingly higher depths and at smaller residual stress values. At larger depths the residual stresses gradually decrease to zero. The depth at which the residual stresses change their sign seems to be shifted to larger values with increasing pressure. Already planned further measurements will confirm the certainty of these effects.

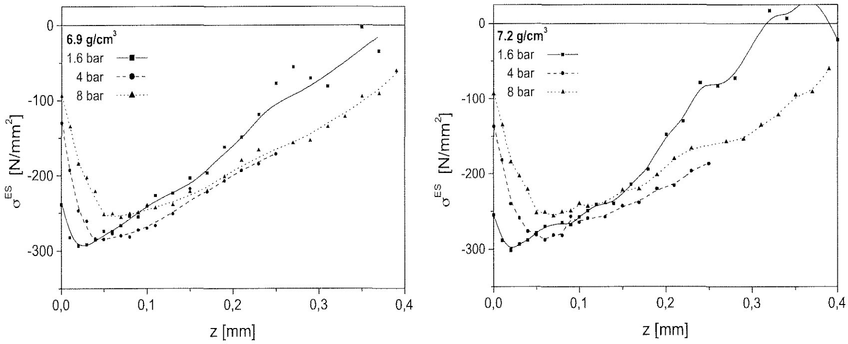

Fig. 3: Residual stress distributions as a function of depth for shot peened specimens

Besides the investigations of the effects on the surface layer, additional experiments have been conducted to obtain mechanical properties (Young's modulus E; 0.2 %-proof-stress $R_{p0.2}$, ultimate tensile stress R_m and elongation to fracture A). The results which have been derived from tensile tests are listed in Tab. 2. Each value indicates the average of five measurements. In contrast to the compact material the mechanical properties of the initial state of the two sintered irons are smaller. However deep rolling enables a significant rise of $R_{p0.2}$ and R_m. Furthermore, the treated material responds with embrittlement, which reduces the elongation to fracture to one half.

Nominal Density [g/cm^3]	E [N/mm^2]	$R_{p0.2}$ [N/mm^2]	R_m [N/mm^2]	A [%]
6.9	158000	127	236	23
7.2	160000	148	234	29
7.87	208000	234	346	61
7.2 (DR; 150 bar)	156000	254	323	17

Tab. 2: Mechanical properties

Impact bending tests revealed the work hardening capacity of both the shot peened and deep rolled sintered iron. Compared to the initial state all treated material conditions exhibited a reduction of maximum impact strength with increasing shot peening intensities and rolling pressures.

The alternating bending strengths of untreated, shot peened and deep rolled specimens are summarized in Tab. 3. After shot peening at 1.6 bar the fatigue strength is increased by 20 % from 120 to 144 N/mm^2. Higher shot peening pressures of 4 and 8 bar once more yield a rise of 23 and 33 % to 149 and 159 N/mm^2, resp.. As for the shot peened specimens, the fatigue strength of the deep rolled specimens for both nominal densities increases with rising pressure. It is apparent that the smaller density shows smaller alternating bending strengths, yet. The relative increases are bigger compared to those of the more dense material. The maximum increase amounts up to 67 %.

Shot Peening	0 bar	1,6 bar	4 bar	8 bar
7.2 g/cm^3 $R_{fs,50\%}$ [N/mm^2]	120	144	149	159
Deep Rolling	0 bar	55 bar	150 bar	180 bar
6.9 g/cm^3 $R_{fs,50\%}$ [N/mm^2]	93	145	155	-
7.2 g/cm^3 $R_{fs,50\%}$ [N/mm^2]	120	151	177	194

Tab. 3: Fatigue strengths of untreated, shot peened and deep rolled specimens

DISCUSSION

The effects of shot peening and deep rolling on the surface layer and the mechanical properties of sintered iron were investigated. It can be seen that shot peening treatments cause an increase of Rz and deep rolling treatments reduce Rz severely. In both cases the results are almost independent of the initial material's density.

The change of porosity shows that for both mechanical surface treatments, increasing penetration depth of densification effects can be generated with increased pressures. For shot peened samples an approximation of this relation reveals, for pressures above 3 bar, that for the higher density greater penetration depths can be generated. This would be valid, provided that the plastic deformation perpendicular to the surface is more pronounced than the parallel plastic elongation, which induces residual compressive stress. Deep rolling, however, enables the deepest densification effects.

A comparison between shot peening and deep rolling reveals that for medium and maximum pressures the change of near surface microhardness is limited to about 100 HV 0.1. However, the penetration depths of microhardness of deep rolled specimens are larger compared to shot peened, owing to higher interaction forces.

Shot peening at different pressures generates different residual stress conditions in sintered iron for both nominal densities. Owing to the different material strengths, the surface and maximum compressive stresses of the samples with 7.2 g/cm^3 nominal density are slightly above those which were measured for the less dense material. However, with increasing peening pressure, surface and maximum residual stresses decrease. This can be attributed effects of the deformation work during shot impacts, which allow a higher plastification perpendicular to the surface than parallel to the surface. Therefore densification is more dominant than stretching, which only would induce compressive residual stresses.

The results of the tensile tests of deep rolled specimens at 150 bar show a deformation behaviour characterised by significantly larger values of the mechanical properties and reduced strains. A numerical estimation of the quasi-statical deformation behaviour of only the region affected by deep rolling has been conducted, using the data obtained from the tensile tests and residual stress measurements and assuming a simple surface-core-model [11]. The results indicate material resistances, which are higher than those of the compact Armco-iron.

The impact strength of shot peening and deep rolling on the sintered iron for both densities shows a substantial reduction with increasing intensities and pressures. This is caused by the intense deformation of the surface layers as well as the presence of pores in the unaffected bulk material.

The increased fatigue strengths, attained by both types of mechanical surface treatments, can be attributed to the gain in densification and work hardening which prevents the initiation of cracks. As the compressive residual stresses will severely relax they won't enhance the fatigue properties. A comparison indicates that deep rolling has a higher potential to increase the fatigue strength as it affects larger depths and also significantly reduces the surface roughness.

SUMMARY

The Influence of shot peening and deep rolling on the surface characteristics and mechanical properties of sintered iron was investigated. Shot peening increases whilst deep rolling decreases the Rz values. Shot peening and deep rolling lead to densification and work hardening effects, which increase with increasing process pressure. Maximum residual stress decrease but depth increase with increasing process pressure. Mechanical properties, especially tensile and alternating bending strength severely increase with increasing pressure, especially for deep rolling.

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