Influence of Shot Peening on the Fatigue of Sintered Steels under Constant and Variable Amplitude Loading

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Introduction

The most decisive microstructural parameter of sintered steels is the porosity which determines all mechanical properties (1). The porosity can be nearly completely abolished by hot-isostatic pressing or powder forging in order to improve the material behaviour. But such techniques are often not applied in practice because of economic reasons. However mechanical surface treatments give the chance to reduce the porosity at the surface significantly and increase the fatigue properties by densifying (2).

In this paper the influence of shot peening, as surface densifying treatment, on the fatigue behaviour of the alloys Fe-1.5% Cu and Fe-2% Cu-2.5% Ni, in the densities 7.1 and 7.4 g/cm^3, as sintered and carbonitrided, having broad application in automotive industry, is investigated under constant and variable amplitude loading. In particular the role of Ni as alloying element is discussed.

Materials specimens and surface treatments

This investigation was carried out with the isostatically compacted alloys Fe-1.5% Cu with densities of 7.1 and 7.4 g/cm^3 and Fe-2% Cu-2.5% Ni with a density of 7.4 g/cm^3, see Table 1.

Material	ϱ [g/cm^3]	E and E_d* [GPa]	$S_{y0.2\%}$ [MPa]			S_{UTS} [MPa]	A_5 [%]	Z [%]	A_v [J]	Hardness HB 2.5/62.5
			monotonic		cyclic					
			Tension	Compr.	Tens./Comp.					
Fe - 1.5 % Cu	7.1	160 164	287	300	350	357	10	9	45	109
	7.4	167 184	290	312	350	371	13	16	77	121
Fe - 2% Cu - 2.5% Ni	7.4	165 171	299	325	340	399	14	14	88	123

* E = mechanical measurement E_0 = by ultrasonics
Specimen: A = 5 x 16 mm^2, l_0 = 25 mm, K_t = 1.0

Table 1: Mechanical properties in the as sintered condition

The final sintering temperature was in all cases 1 280° C. The microstructure of the Fe-Cu alloy consists of homogeneous Fe-Cu solid solution. For the Fe-Cu-Ni alloy the microstructure is similar with the exception that austenite is formed in areas of high nickel concentration.

Fatigue testing was carried out with machined and ground unnotched round specimens, having a cross section of 10 mm diameter, see Fig. 5, and with notched specimens (K_{tb} = 1.49) with a cross section of 25 mm diameter, see Figs. 6 and 7.

The shot peening parameters for obtaining three different shot peening intensities on an air blast machine are listed in Table 2.

Almen intensity A_2 [mm]	0.30	0.40	0.50
Distance of blasting nozzle a [mm]	130	130	130
Air pressure p [MPa]	0.30	0.43	0.46
Number of runs	2	2	4
Rotational speed n [min^{-1}]	23	23	23

a. Shot peening

Carbonitriding temperature	940° C
Hold time	4h
Atmosphere	0.18% CO_2 and ammonia
Quenching oil temperature	30°C

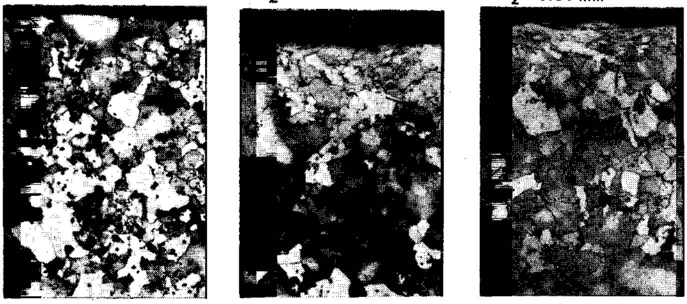
b. Heat treatment

Table 2: Surface treatments

In order to find out the optimum peening intensities, tests were first performed on unnotched round specimens fabricated from the alloy Fe-Cu with densities of 7.1 and 7.4 g/cm³. The carbonitriding parameters are also given in Table 2. The carbon content at the surface has an average of 0.8 weigth per cent. This heat treatment was applied only to unnotched and notched specimens fabricated from the alloy Fe-Cu to a density of 7.4 g/cm³ as well as to notched specimens from the alloy Fe-Cu-Ni with a density of 7.4 g/cm³. After optimizing the shot peening intensity in respect to fatigue strength and microstructure of the unnotched Fe-Cu specimens, this mechanical surface treatment was also applied to several specimens which had received a carbonitriding treatment before. Hereby the Almen intensity of A_2 = 0.40 mm was fixed. Also some shot peened specimens were carbonitrided after the mechanical surface treatment.

Influence of manufacturing parameters on the microstructure

Due to the shot peening a densification and deformation of the grains as well as a roughening of the surface occur, see Fig. 1.



a. As sintered

b. Shot peened with the Almen intensity A_2 = 0.30 mm

c. Shot peened with the Almen intensity A_2 = 0.50 mm

Material: Fe - 1.5% Cu, ϱ = 7.1 g/cm³, S_1 = 1280° C

50 µm

Fig. 1: Microstructure and influence of shot peening

The surface is more deformed for the higher peening intensity, but the deformation for the Almen intensity of A_2 = 0.50 mm becomes critical, because at this intensity some surface particles begin to break out. In the case of prior carbonitriding shot peening induces no deformation of the hard martensitic surface region (2).

For the alloys investigated, all selected shot peening intensities lead nearly to the same surface hardness governing a depth of appr. 0.2 mm, falling down to the original hardness of the materials in the as sintered state at a depth of ca. 0.3 mm, see Fig. 2.

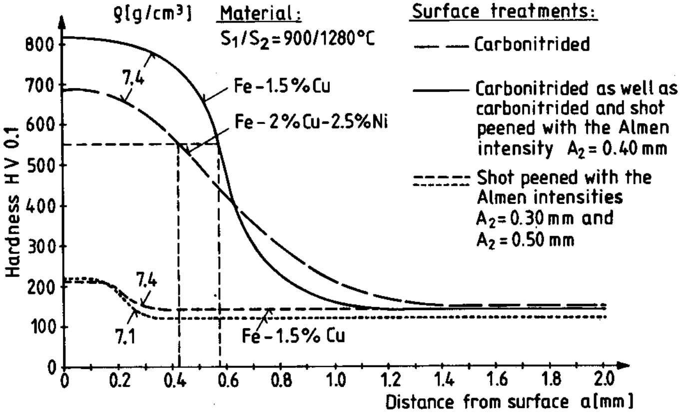


Fig. 2: Hardness distributions due to surface treatments

Carbonitriding leads to a considerably higher surface hardness, which is higher for the Fe-Cu alloy than for the Fe-Cu-Ni material. Shot peening of the carbonitrided surface (or carbonitriding of the shot peened surface) does not influence the hardness. At a depth of appr. 1 mm the hardness of the original materials is reached.

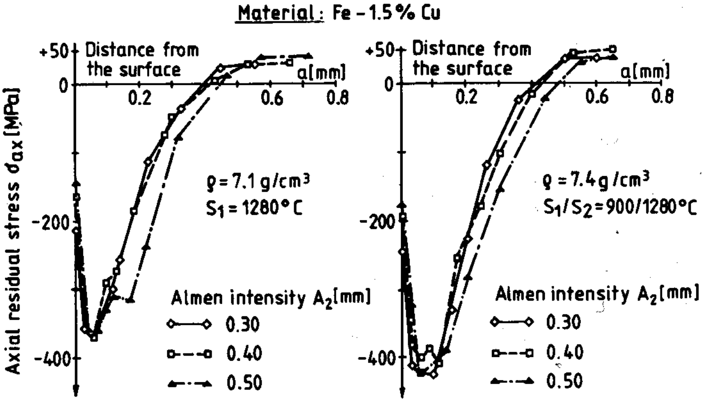


Fig. 3: Residual stress distributions on as sintered specimens due to shot peening

Figure 3 shows that for the density of 7.4 g/cm³ the residual stresses are slightly higher than for the lower density of 7.1 g/cm³ (3). For both densities, however, the magnitude of the residual stresses and their distribution are nearly equal for all shot peening intensities. This result is in accordance with the hardness measurements of Fig.2:

Once a certain degree of surface compaction is reached, neither the hardness nor the residual stresses can be increased.

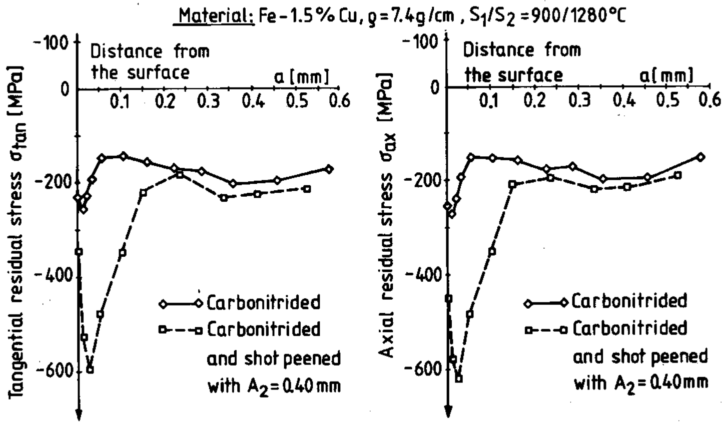


Fig. 4: Residual stress distributions on carbonitrided and after carbonitriding shot peened specimens

Figure 4 compares the residual stresses due to carbonitriding and due to carbonitriding with subsequent shot peening. The mechanical treatment increases the residual stresses significantly without influencing the hardness. However, the extension of this additionally affected zone is limited to appr. 0.15 mm, i.e. to a zone much smaller than the carbonitrided depth of appr. 1 mm.

Fatigue testing and results

Fatigue testing was performed under bending loads of constant and gaussian type variable amplitude in the fully reversed loading mode ($R = \sigma_{min}/\sigma_{max} = -1$). One sequence of the applied variable amplitude loading consisted of $5 \cdot 10^5$ cycles (4).

The S-N and fatigue-life curves were obtained by carrying out each five tests on at least two levels. By this method the mean values (probability of survival P_s = 50%) and their scatter were statistically evaluated. The curves presented give the mean values, as well as the scatter between P_s = 10 and 90%.

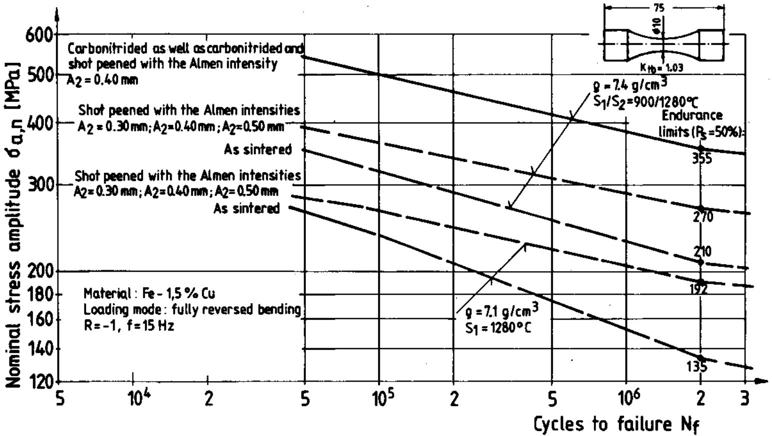


Fig. 5: Influence of density and post sintering treatments on the fatigue behaviour of the sintered steel Fe-1.5% Cu

Fig. 5 presents the results obtained on unnotched specimens. Shot peening increases the endurance limit at the lower density (7.1 g/cm^3) of the Fe-Cu alloy by appr. 40% and at the higher density (7.4 g/cm^3) by appr. 30%. These results were obtained for all three different Almen intensities (A_2 = 0.30, 0.40 and 0.50 mm) without any significant difference in the scatter of fatigue life. This result is in accordance with the hardness and residual stress measurements. But as the overpeening with the adjusted intensity of A_2 = 0.50 mm begins to destroy the surface and at the adjusted intensity of A_2 = 0.30 mm an underpeening may occur, the intensity of A_2 = 0.40 mm was chosen as the optimum.

In the region of $5 \cdot 10^4$ cycles the difference between fatigue stress of the as sintered and the shot peened material is very small. This may be explained by yielding effects. As the shot peened surface layer has a depth of about 0.2 mm and the specimens are unnotched and therefore have no sufficient constraint, they show no sufficient resistance against plastic derformation.

Carbonitriding improves the endurance limit by appr. 70% in comparison to the as sintered condition. But subsequent shot peening with the intensity of A_2 = 0.40 mm leads to no further improvement. As the magnitude of hardness and hardened depth of the carbonitrided specimens is much higher than after shot peening, yielding in the region of $5 \cdot 10^4$ cycles is not observed. Same results were obtained also with carbonitriding after shot peening.

For the component-like notched specimens Figs. 6 and 7 present the S-N and fatigue-life curves for the alloys Fe-Cu and Fe-Cu-Ni at the density of 7.4 g/cm^3. For both alloys shot peening with the optimized intensity increases the fatigue properties by appr. 25% and the fatigue life by a factor of appr. ten. Carbonitriding increases the fatigue strength for both alloys by appr. 70% in comparison with the as sintered condition.

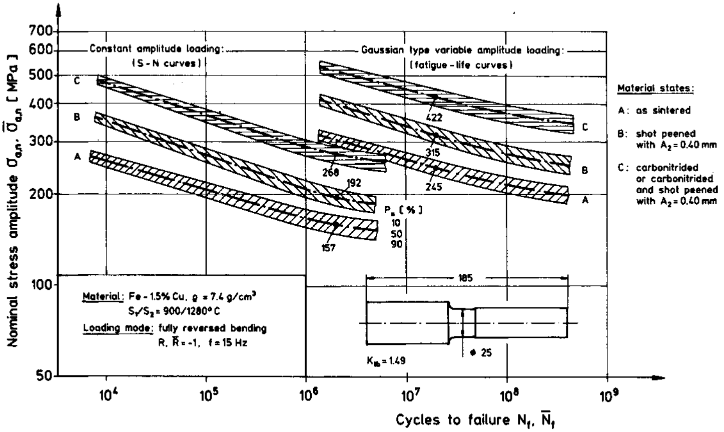


Fig. 6: Influence of different post sintering treatments on the fatigue behaviour of the sintered steel Fe-1.5% Cu under constant and variable amplitude loading

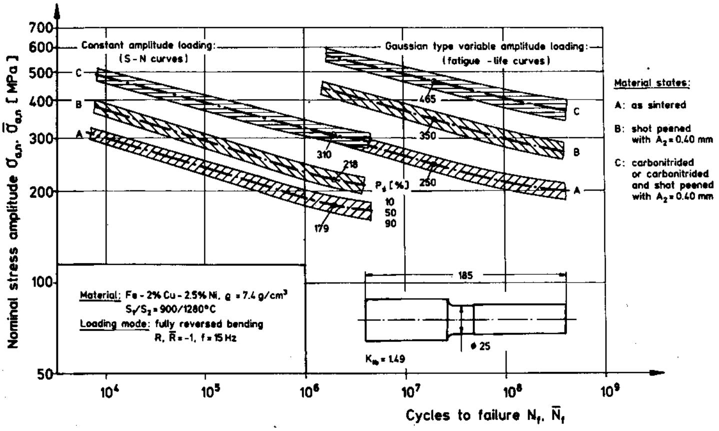


Fig. 7: Influence of different post sintering treatments on the fatigue behaviour of the sintered steel Fe-2% Cu-2.5% Ni under constant and variable amplitude loading

The subsequent shot peening of carbonitrided specimens does not lead to any further improvement as observed in the case of the unnotched specimens. Because of the geometry of the specimens and the constraint due to the notch, no difference occurs in the slope of S-N and fatigue-life curves.

Fig. 8 compares the endurance limits at 2 · 10^6 cycles and the variable amplitude fatigue strengths at 2 · 10^7 cycles. The ratios $\sigma_{a,n}/\bar{\sigma}_{a,n}$ for the appropriate material states are between 1.50 and 1.64, indicating the potential of the sintered steels also for variable amplitude loading (4). From Fig. 8 it can also be derived that the fatigue properties for the Fe-Cu-Ni alloy are in most cases only 10 to 15% higher than the values for the Fe-Cu alloy. This indicates the possibility of substitution by the Fe-Cu alloy.

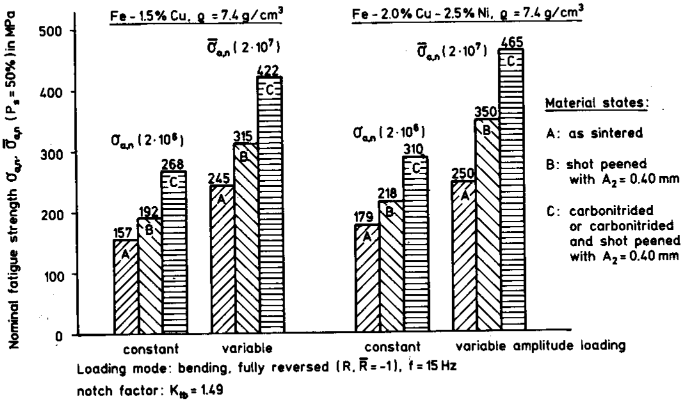


Fig. 8: Comparison of the fatigue strengths under constant and variable amplitude loading in relation to the post sintering treatments

Conclusions and summary

The improvement of fatigue life under constant and variable amplitudes by the mechanical and thermal surface treatments is a result of increased hardness, compressive residual stresses, hardened depth and the acting stress distribution due to the geometry of the specimens and of the loading mode (stress gradients). The reason that the improvement by shot peening is not as high as by carbonitriding is given by smaller hardened depth. The localisation of the crack nucleation sites is in accordance with the hardness measurements and indicates that failure originates in an area where the strength increment by the surface treatment is hardly noticeable. Therefore the fatigue features of the as sintered material govern also the fatigue behaviour of the treated material. For this reason the relative difference of the endurance limits between the alloys Fe-Cu-Ni and Fe-Cu in the as sintered state at 7.4 g/cm³ holds also for the shot peened or carbonitrided state.

The fatigue properties for the Fe-Cu-Ni alloy are in most cases only 10 to 15% higher than the values for the Fe-Cu alloy. From an economical standpoint therefore, the use of materials containing nickel in addition to copper seems questionable, because a loss of 10 to 15% of fatigue strength should always be possible to be circumvented by a modified component design.

The overriding results of the present investigation are, however, that quite generally treatments like shot peening and carbonitriding, but not their combinations, enable a significant improvement of the fatigue properties of sintered steels. Such surface treatments are much more effective than modifications of the normal processing parameters like compacting pressure and sintering temperature. Beyond this, the sintered steels show an impressive potential for variable amplitude applications, in the as sintered material state as well as in the surface treated states.

Acknowledgements

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