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# HOW TO IMPROVE THE FATIGUE PROPERTIES OF SINTERED STEELS BY COMBINED MECHANICAL AND THERMAL SURFACE TREATMENTS

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## SUMMARY

The ever increasing demand for sintered components with improved dynamic properties was the reason for the present investigation, in which the influence of shot peening, carbonitriding and combinations thereof on the endurance limit of Fe-Cu and Fe-Cu-Ni sintered alloys was determined. Two density levels, 7.1 and 7.4g/cm$^3$, were investigated. The fatigue tests were carried out on unnotched round test specimens as well as on large notched specimens which can be considered as representative for actual engineering components. The mechanical tests were supplemented by residual stress and microstructural measurements. Compared with the as sintered condition, improvements of fatigue limits of the order of 70% could be realised. These results suggest that sintered steel must be considered as a candidate for designing highly stressed engineering components like passenger car connecting rods or gear box parts.

## 1. INTRODUCTION

There is an ever increasing demand for sintered components with improved dynamic properties, and high sintering temperatures are normally specified for sintered steels for such applications. Our previous study (1), in which the influence of density in the range 7.1 to 7.4g/cm$^3$ and of sintering temperature between 1120 and 1280 °C on the dynamic properties of Fe-Cu and Fe-Cu-Ni materials was investigated, showed, however, that the improvements are at best only of the order of 30%. (These results are summarized in Table 1 and Figure 1). Therefore, it was the goal of the present

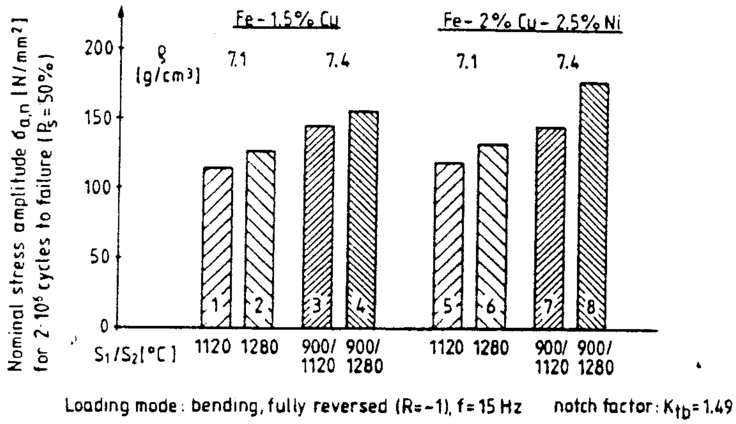



Fig.1: Improvement of the endurance limit by increase of density and sintering temperature

investigation to find out whether surface treatments like shot peening or case hardening can push the dynamic properties of sintered steels beyond these limits. For this purpose the same alloys as used in the previous work (1) were selected for the present investigation, surface treated by shot peening with graded intensities, surface heat treated by carbonitriding, and finally tested to determine their fatigue performance. The fatigue data were obtained not only with the unnotched round small test specimens, but also on large notched specimens which can be considered as representative for actual sintered components in automotive or other engineering applications. A ranking of the different surface treatments and their combinations in respect to fatigue limit is presented and interpreted with the help of microstructural observations as well as hardness and residual stress measurements.

## 2. INVESTIGATED MATERIALS AND FABRICATION PARAMETERS

### 2.1 Materials and Specimens

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

Table 1: Mechanical properties in the as sintered condition

| Material | | $\rho$ $[g/cm^3]$ | $E$ and $E_o$ *) $[kN/mm^2]$ | $S_{y0.2\%}$ $[N/mm^2]$ monotonic Tension | monotonic Compr. | cyclic Tens / Comp. | $S_{UTS}$ $[N/mm^2]$ | $A_5$ [%] ($l_o$ = 25mm) | $Z$ [%] ($A_o$ = 80mm$^2$) | $A_v$ [J] | Hardness HB 2,5/62.5 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Fe - 1.5% Cu | 1 | 7.1 | 138<br>- | 183 | 218 | 235 | 287 | 12 | 13 | 39 | 96 |
| | 2 | 7.1 | 160<br>164 | 287 | 300 | 350 | 357 | 10 | 9 | 45 | 109 |
| | 3 | 7.4 | 144<br>183 | 203 | 235 | 250 | 332 | 17 | 21 | 101 | 106 |
| | 4 | 7.4 | 167<br>184 | 290 | 312 | 350 | 371 | 13 | 16 | 77 | 121 |
| Fe-2%Cu-2.5%Ni | 5 | 7.1 | 140<br>- | 196 | 249 | 258 | 328 | 9 | 9 | 34 | 100 |
| | 6 | 7.1 | 149<br>157 | 270 | 312 | 317 | 358 | 10 | 11 | 54 | 115 |
| | 7 | 7.4 | 155<br>154 | 247 | 293 | 325 | 401 | 12 | 14 | 77 | 115 |
| | 8 | 7.4 | 165<br>171. | 299 | 325 | 340 | 399 | 10 | 14 | 88 | 123 |

* $E$ = mechanical measurement
$E_o$ = by ultrasonics

materials No. 2, 4 and 8). The final sintering temperature was in all cases 1280 °C. These alloys were isostatically compacted using water atomized iron powder. All samples originate from the same batch produced for the work reported in (1) and summarized in Fig. 1. 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, Figs. 2 and 8, and with notched specimens ($K_{tb}$=1.49) with a cross section of 25 mm diameter, Figs. 9 and 10.

## 2.2 Surface Treatment Parameters

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

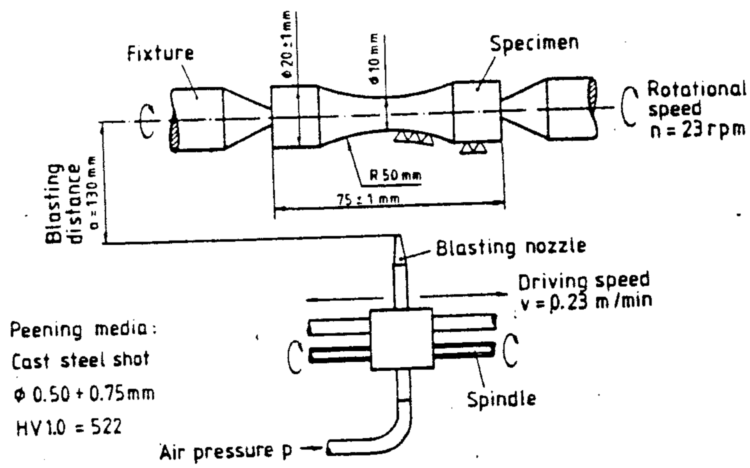



Fig.2: Schematic view of the shot peening machine

The intensity of shot peening is indicated by the deformation of a standardized metal strip and is called Almen intensity (2). The deformation is adjusted and measured on steel strips before performing the mechanical surface treatment of the specimens. 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 7.4g/cm3.

The carbonitriding parameters are also given 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 [bar] | 3.0 | 4.3 | 4.6 |
| Number of cycles | 2 | 2 | 4 |
| Rotational speed n [$min^{-1}$] | 23 | 23 | 23 |

a. Shot peening

| | |
|---|---|
| Carbonitriding temperature | 940° C |
| Hold time | 3 h |
| Atmosphere | 0.18% $CO_2$ and ammonia |
| Quenching oil temperature | 30°C |

b. Heat treatment

Table 2: Surface treatment parameters

This heat treatment was applied only to unnotched and notched specimens fabricated from the alloy Fe-Cu to a density of 7.4g/cm$^3$ as well as to notched specimens from the alloy Fe-Cu-Ni with a density of 7.4g/cm$^3$. 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.

## 3. INFLUENCE OF FABRICATION PARAMETERS ON THE MICROSTRUCTURE

### 3.1 Microstructure and Hardness Distribution

Figure 3 compares the deformation state of the surface as a function of the mechanical treatment for the unnotched specimens from the alloy Fe-Cu with a density of 7.1g/cm$^3$. These results are also applicable to notched specimens. Due to the shot peening a densification and deformation of the grains as well as a roughening of the surface occur. 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. For the alloy Fe-Cu with a density of 7.4g/cm$^3$, Fig. 4 shows not only the surface deformation due to the mechanical treatment of unnotched specimens, but also the microstructure after carbonitriding and subsequent shot peening.

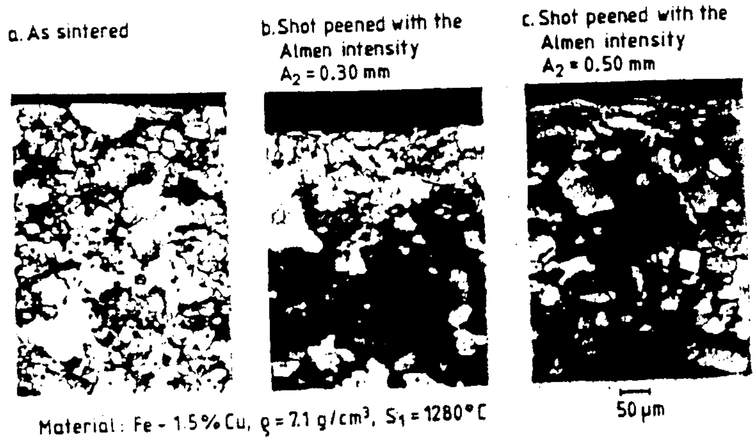



Fig. 3: Influence of shot peening on the microstructure

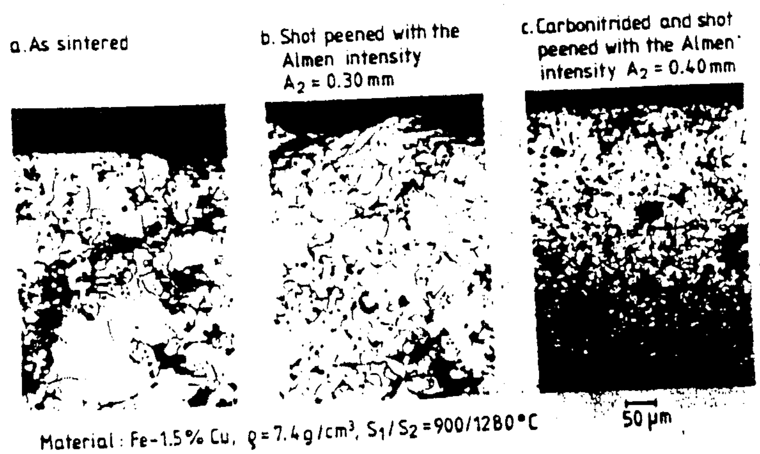



Fig. 4: Influence of different surface treatments on the microstructure

The shot peening induces no deformation of the martensitic surface region.
Because no significant densification effect beyond the surface region can be recognized, hardness measurements were necessary for a better characterization of the state of the specimens. The hardness distributions resulting from the different surface treatments are shown in Figure 5. For the

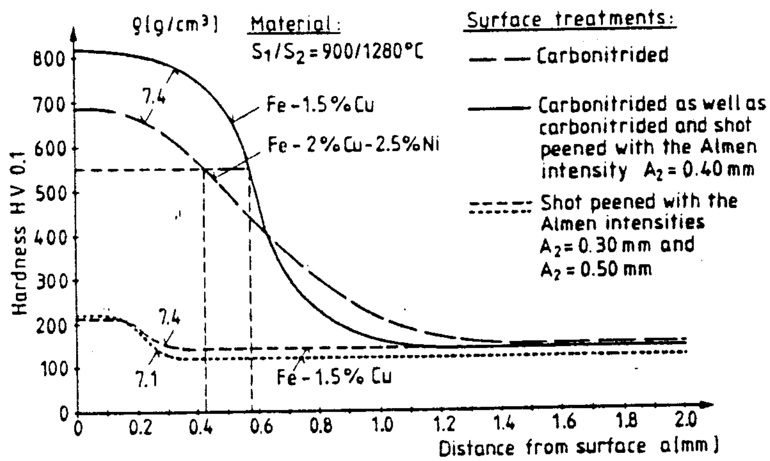



Fig.5: Distribution of hardness due to the applied surface treatments

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. As is well known, 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 does not influence the hardness. At a depth of appr. 1 mm the hardness of the original materials is reached.
These differences in the hardness level and depth of the affected zone make it likely that in the case of shot peening the fatigue failure will start just underneath the surface of a specimen. In the case of carbonitriding fatigue failure is expected to start in a distance of appr. 1 mm underneath the surface.

### 3.2 Residual Stress Distributions

The treatments applied are known to be beneficial for the fatigue life not only due to the increase of hardness, but also due to compressive residual stresses. Therefore the residual stresses in the specimens were also determined. In Figs. 6 and 7 the residual stress distributions of the unnotched specimens as determined by X-ray methods (3) are shown. In Fig. 6 only the axial residual stresses are plotted; they have the same magnitude as the tangential residual stresses (3). But this relation changes when

Material: Fe - 1.5 % Cu

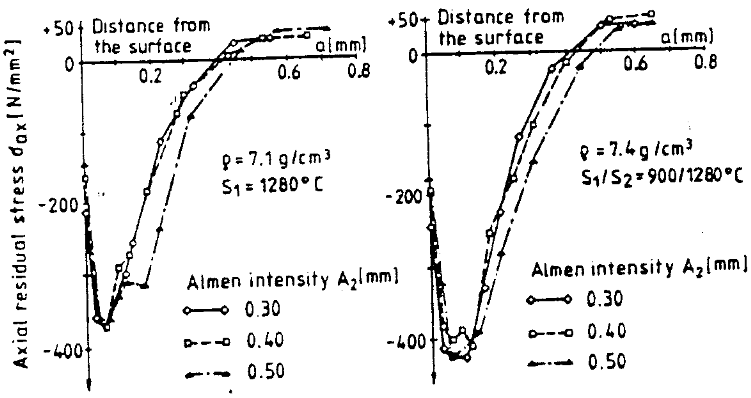



Fig. 6: Distribution of residual stresses after shot peening with different intensities

Material: Fe-1.5 % Cu, ρ = 7.4 g/cm, $S_1/S_2$ = 900/1280 °C

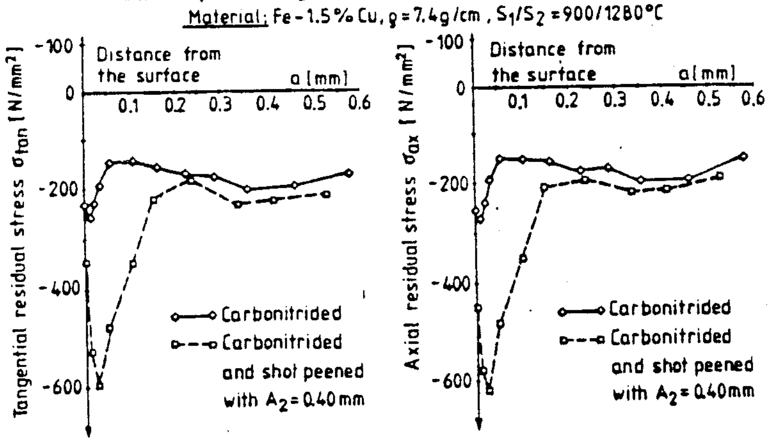



Fig. 7: Distribution of residual stresses on carbonitrided and after carbonitriding shot peened specimens

geometrical discontinuities, e.g. notches, are present. Figure 6 shows that for the density of $7.4 g/cm^3$ the stresses are slightly higher than for the lower density of $7.1 g/cm^3$. 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. 5. Once a certain degree of surface compaction is reached, neither the hardness nor the residual stresses can be increased. Figure 7 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, Fig. 5). 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.

## 4. FATIGUE TESTING AND RESULTS

Fatigue testing was performed under bending loads of constant amplitude in the fully reversed ($R = \sigma_{min}/\sigma_{max} = -1$) loading mode. For the S-N-curves, the fatigue life at the stress level in the vicinity of the presumed endurance limit (at $2 \times 10^6$ cycles to failure) was measured with at least five specimens, and for the higher stress level corresponding to appr. $1 \times 10^5$ cycles to failure, measurements were made with at least three specimens. By this method the mean values (probability of survival $P_s = 50\%$) and their scatter were statistically evaluated (4). The S-N-curves presented give the mean values.

### 4.1 Test Results

#### 4.1.1 Unnotched Specimens

Figure 8 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 42% and at the higher density ($7.4 g/cm^3$) by 29%. 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 $5 \times 10^4$ cycles the difference between fatigue stress of the as sintered and the shot peened material is very small. This

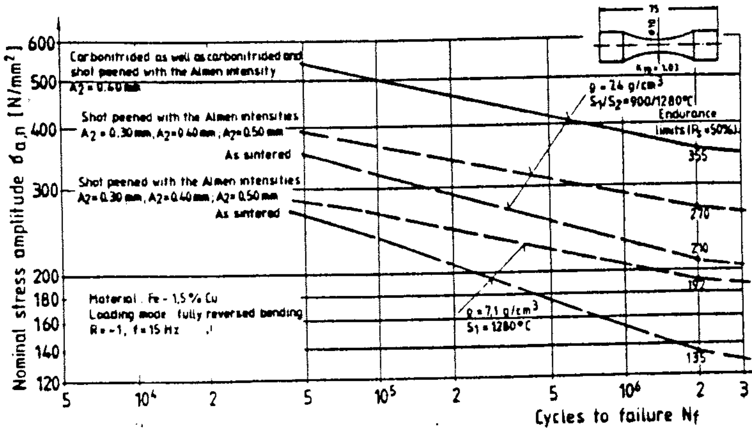



Fig. 8: Influence of density and post sintering treatments on the fatigue behaviour of the sintered steel Fe-Cu, unnotched specimens

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 deformation.

Carbonitriding improves the endurance limit by 69% 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 $5x10^4$ cycles is not observed.

#### 4.1.2 Notched specimens

Figures 9 and 10 present the S-N-curves for the alloys Fe-Cu und Fe-Cu-Ni at the density of 7.4g/cm³. For both alloys shot peening with the optimized intensity increases the endurance limit by 22% and the fatigue life by a factor of ten. Carbonitriding increases the endurance limit for both alloys by appr. 72% in comparison with the as sintered condition.

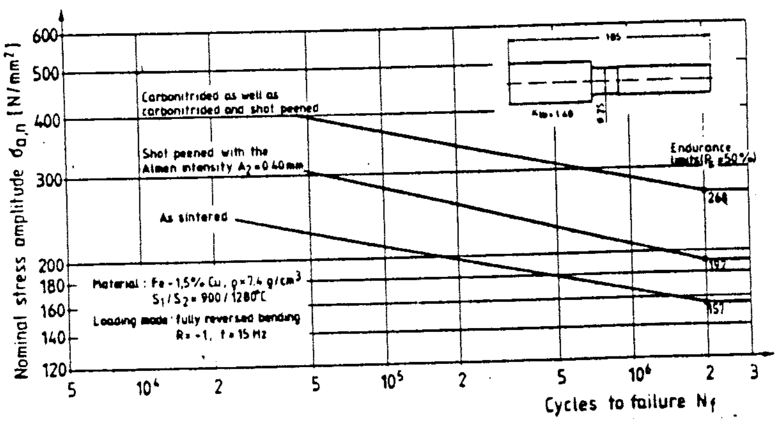



Fig. 9: Influence of different post sintering treatments on the fatigue behaviour of the sintered steel Fe-Cu, notched specimens

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 the S-N-curves.

### 4.2 Interpretation of Results

The improvement of fatigue life and endurance limit 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

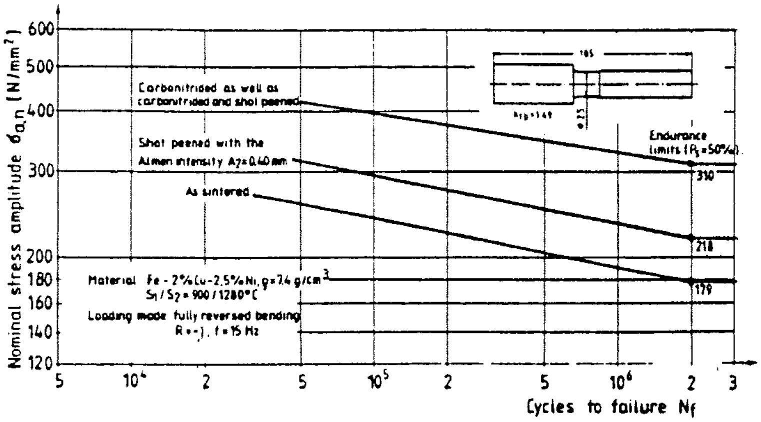
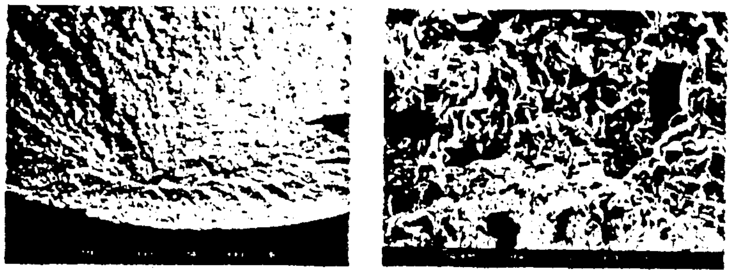



Fig. 10: Influence of different post sintering treatments on the fatigue behaviour of the sintered steel Fe-Cu-Ni, notched specimens

high as by carbonitriding is given by the smaller hardened depth. The hardened zone with its residual stresses acts as resistance against crack initiation and propagation. But this resistance is not as high as the resistance resulting from the harder and deeper martensitic layer formed by carbonitriding. In the case of shot peening the fatigue cracks originating from the material beneath the surface layer have to travel only 0.2 to 0.3 mm to reach the maximum loading stress on the surface.
Fractographical observations of carbonitrided as well as carbonitrided and shot peened specimens show that in these cases all fatigue cracks originated in a depth between 1 and 2 mm beneath the surface (Figure 11). 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 (appr. 15 %) holds also for the shot peened or carbonitrided state.

a. Macroscopic overview of crack initiation site 1.5mm beneath the specimen surface

b. Fatigue fracture surface around the crack initiation site



Material: Fe-2%Cu-2.5%Ni, $\rho$=7.4g/cm$^3$, $S_1/S_2$=900/1280°C, carbonitrided and shot peened with the Almen intensity $A_2$=0.40mm

Loading: $\sigma_{a,n}$=300N/mm$^2$, R=-1, $N_f$=1.85·10$^6$, $K_t$=1.49

Fig. 11: Fatigue crack initiation sites beneath the surface

As the improvement of fatigue strength and life depends on the time the cracks require to travel from their site of origination to the specimen surface, a further improvement of properties may be possible by a shot peening treatment prior to carbonitriding. In this case the removal of the surface porosity may put a further resistance to fatigue crack propagation towards the surface.

### 4.3 Comparison of the Results and Potential for Practical Application

Figure 12 compares the endurance limit of all investigated materials and treatments. This figure includes also a distinction between nominal and local endurable stresses. The nominal stress is defined as the stress resulting from the bending moment and inertia moment for the critical cross section where rupture takes place. In the case of unnotched specimens, nominal and local stresses are identical, but in the case of notched specimens the local stresses in the notch root are higher than the nominal stresses due to the stress raising effect of the geometrical discontinuity (described by the stress concentration factor or notch factor). For the notched specimens the local stress is obtained by multiplication of the nominal stress with the notch factor. For a proper component design the knowledge of local stresses resulting from service loading and the stress gradients are necessary (5).

On the left side of Fig. 12 the results for the unnotched specimens of the alloy Fe-Cu with densities of 7.1 and 7.4g/cm$^3$ are compared. On the right side the endurance limit for the notched specimens manufactured from the alloys Fe-Cu and Fe-Cu-Ni with a density of 7.4g/cm$^3$ are compared in terms of nominal and local stresses. The comparison of the local stresses of the alloy Fe-Cu with a density of 7.4g/cm$^3$ for notched and unnotched specimens shows that in the otched state they are 6 to 12% higher due to the con traint. At a higher stress concentration the local stresses are higher due to the steeper stress gradients. The endurance limits for the Fe-Cu-Ni alloy are only 15% higher than the values for the Fe-Cu alloy. From an

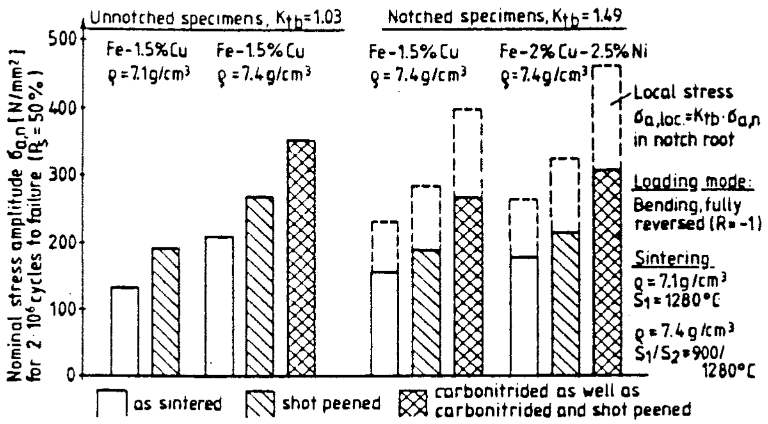



Fig. 12: Improvement of the endurance limit by different post sintering treatments

economical standpoint therefore, the use of materials containing nickel in addition to copper seems questionable, because a loss of 15% of endurable stress should always be possible to be circumvented by a modified component design. Concerning carbonitriding of small specimens, for example on rectangular bars with a cross section of 5 mm x 5 mm or 5 mm x 9 mm, higher endurance limits are obtained (5) in comparison to the present results on large specimens. This is a clear hint that for fatigue design of components size effects and effects of stress gradients have to be considered properly (5). The overriding results of the present investigation are, however, that quite generally treatments like shot peening and carbonitriding and possibly combinations thereof 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.

Also it is worth noting that the endurance limits achieved in this investigation with simple Fe-Cu and Fe-Cu-Ni sintered materials lie in the same range as the endurance limits of high quality nodular cast iron or even heat treated wrought steels, e.g. SAE 1046 (5). Therefore the results suggest that e.g. highly stressed automotive components like connecting rods or gear box parts should be considered as candidates for conversion into sintered steel.

## 5. ACKNOWLEDGEMENTS

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