Comparing Fatigue Notch Sensitivities of Various Alloys Before and After Mechanical Surface Treating

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Abstract

Rotating beam fatigue specimens of various metallic materials with smooth (k_t = 1) and notched geometries (2.1 ≤ k_t ≤ 2.7) were mechanically surface treated by burnishing (BB, RB). Materials investigated were AISI 304 (Fe-18Cr-10Ni-0.05C), IMI 230 (Ti-2.5Cu), Beta C (Ti-3Al-8V-6Cr-4Zr-4Mo), AZ80 (Mg-8Al-0.5Zr), α-brass (CuZn30) as well as Al2024 (Al-4Cu-1Mg). The high cycle fatigue (HCF) performance of the mechanically surface treated smooth and notched specimens was compared with that of the electropolished baseline conditions (EP).

The HCF performance of electropolished IMI 230, Beta C, AZ80 and Al2024 was found to be highly notch sensitive while AISI 304 and α-brass were much less notch sensitive. After mechanical surface treating, the fatigue notch sensitivities of all tested materials were markedly reduced.

Keywords: fatigue notch sensitivity, ball-burnishing, roller-burnishing

Introduction

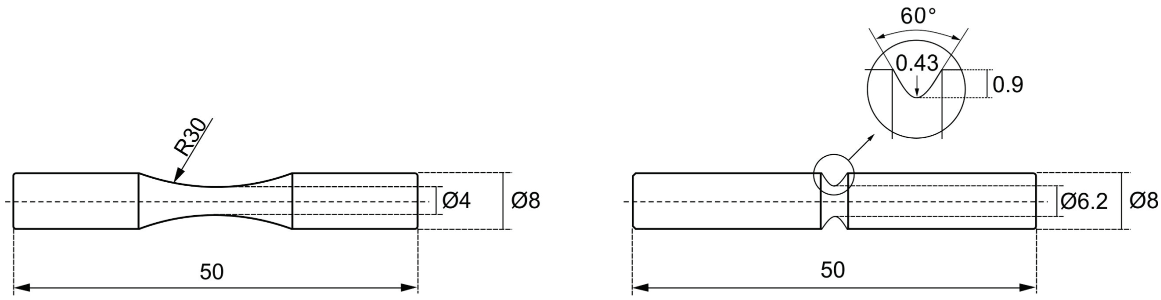
It is well known that reductions in cross sections or notches can markedly reduce the HCF strength of structural components. The stress concentration at a notch is usually described by the geometrical notch factor $k_t = \sigma_{max}/\sigma_{nom}$ which mainly depends on the notch root radius, the notch depth and the mode of loading. Experiments have shown that the HCF strength of a notched specimen not only depends on k_t but also on material properties such as grain size, yield stress and tensile ductility. Therefore, a fatigue notch factor k_f was introduced which relates the smooth HCF strength for a given number of cycles (e.g. 10^7) to the notched one: $k_f = \sigma_{a10^7 smooth}/\sigma_{a10^7 notched}$. Accordingly, the fatigue notch sensitivity q can be expressed as [1]:

$$q = (k_f - 1)/(k_t - 1)$$

Two limiting cases can occur: q equals 0 and q equals 1. The first case is given if $\sigma_{a10^7 notched} = \sigma_{a10^7 smooth}$, the latter if $k_f = k_t$. A simple relationship between the fatigue notch sensitivity q and other material properties does not exist. However, it is generally accepted that high strength materials with low ductility are more notch sensitive than low strength materials with high ductility. Low notch sensitivities are also typically observed in materials with defects such as pores or micro-cracks. For example, the fatigue notch sensitivity in cast iron depends very much on the morphology of the graphite being present. Lamellar cast iron is quite notch insensitive whereas ductile iron with a spherical morphology of the graphite is more notch sensitive. The low notch sensitivity of lamellar cast iron is due to the large number of internal notches only filled with graphite. Therefore, an additional external notch hardly affects the fatigue performance. Furthermore, the surface condition can additionally affect q. Industrial practice has demonstrated that mechanical surface strengthening of notched components results in an improvement in HCF performance superior to that observed on un-notched components [2, 3]. The experiments described below were conducted to investigate the variation in fatigue notch sensitivity of selected materials which differ with regard to crystal structure, grain size, phase arrangements and dimensions as well as work-hardening capability and ductility. A correlation between material properties and notch sensitivities will be assessed.

Experimental Methods

Materials studied include AISI 304 (Fe-18Cr-10Ni-0.05C), IMI 230 (Ti-2.5Cu), Beta C (Ti-3Al-8V-6Cr-4Zr-4Mo), AZ80 (Mg-8Al-0.5Zr), α-brass (CuZn30) as well as Al2024 (Al-4Cu-1Mg). Tensile tests were performed using threaded cylindrical specimens having gage lengths and diameters of 25 and 5mm, respectively. Initial strain rates were 6.7 x 10^{-4} s^{-1}. HCF tests were conducted in rotating beam loading (R = -1) on hour-glass shaped smooth (k_t = 1) specimens and notched (2.1 ≤ k_t ≤ 2.7) specimens. Both specimen types were electrolytically polished to serve as reference. The hour-glass shaped specimens had a minimum diameter of 4mm. The notched specimens with a minimum diameter of 6.2mm had a notch depth of 0.9mm, a notch angle of 60° and a notch root radius of 0.43mm (**Fig.1**).



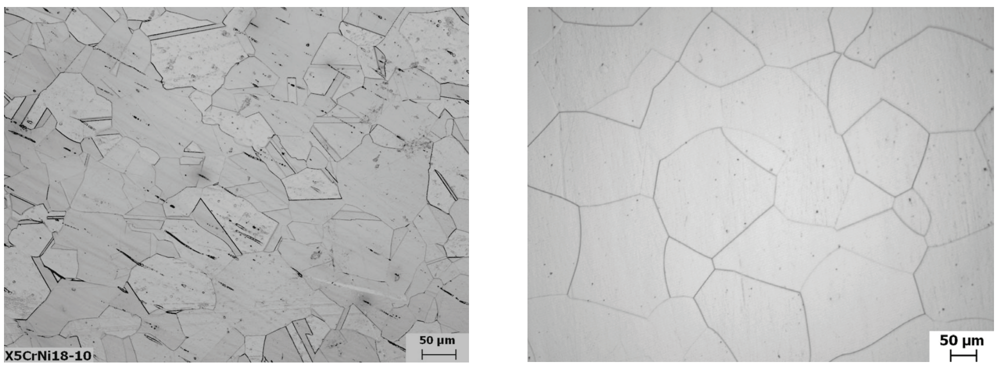
a) smooth b) notched

Figure 1: Geometry of the fatigue specimens

Ball-burnishing (BB) of the smooth specimens was done using a conventional lathe and a hydrostatically driven tool from Ecoroll Company (HG3) working with a hard metal ball of 3mm in diameter. Roller-burnishing (RB) of the notched specimens was conducted using a roller tool with a tip radius of 0,35mm. For BB, the burnishing pressure was kept constant at 350 bar while for RB this pressure amounted to 50bar.

Results

Figure 2 shows the microstructures of the two alloys AISI 304 (**Fig. 2a**) and Beta C (**Fig. 2b**) which differ very much with regard to fatigue notch sensitivity as will be shown below. These two alloys also exhibit very different work hardening capabilities and HCF responses to BB.



a) AISI 304 c) Beta C

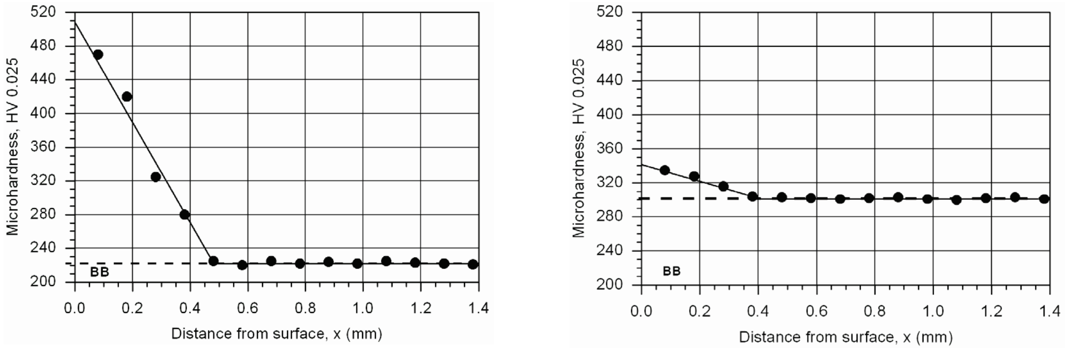
Figure 2 Microstructures of selected alloys

The equiaxed γ-grain size in AISI 304 and the β-grain size in Beta C are about 60 and 150μm, respectively. Tensile properties of all investigated alloys are listed in **Table 1**.

Table 1 Tensile properties of the various alloys

Material	**YS (MPa)**	**UTS (MPa)**	**UTS – YS (MPa)**	**El (%)**	ε_F = **ln (A_0/A_F)**
AISI 304	270	660	390	81.5	0.97
Ti-2.5Cu	685	770	85	9.1	0.57
Beta C	850	860	10	21.3	1.15
AZ80	245	340	95	12.1	0.15
CuZn30	125	310	185	67.4	0.81
Al2024-T4	305	460	155	26.2	0.39
Al2024-T6	390	470	80	13.1	0.27

Figure 3 illustrates micro-hardness depth profiles after BB of the two extremes, AISI 304 and Beta C.

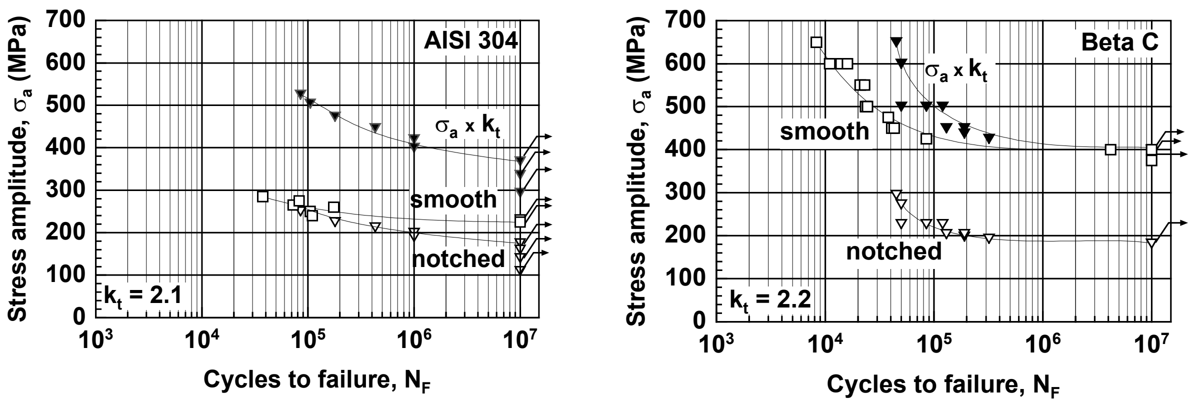


a) AISI 304 b) Beta C

Figure 3: Micro-hardness depth profiles after BB

AISI 304 with its marked work-hardening (**Tab. 1**) also demonstrates high increases in micro-hardness values in the near-surface regions (**Fig. 3a**). Beta C with the lowest degree in work-hardening UTS - YS (Tab.1) also illustrates the slightest increase in micro-hardness after BB (**Fig. 3b**).

The fatigue performance of smooth and notched conditions is illustrated in **Figure 4** comparing AISI 304 (**Fig. 4a**) with Beta C (**Fig. 4b**). For the notched specimens, the maximum stress amplitude at the notch root (σ_a x k_t) is also plotted.



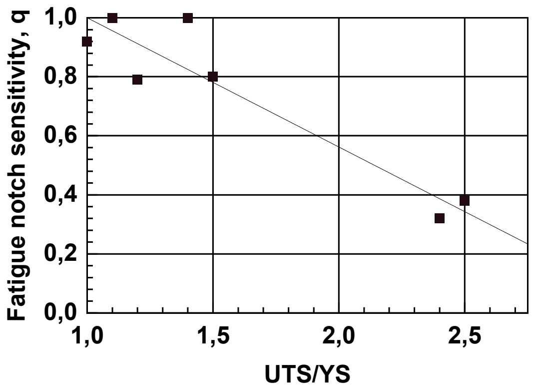
a) AISI 304 b) Beta C

:Figure 4: S-N curves in rotating beam loading (R = -1) comparing smooth and notched conditions

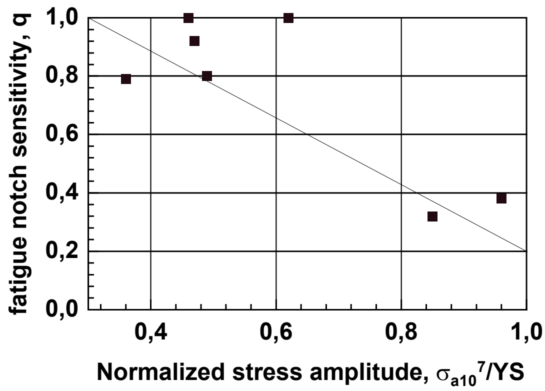
While the HCF performance of AISI 304 is only slightly deteriorated by the notch (q = 0.32), Beta C is much more affected. Since the curves $\sigma_a - N_F$ of the smooth and $\sigma_a \times k_t - N_F$ of the notched conditions in Beta C converge (**Fig. 4b**) Beta C is almost fully fatigue notch sensitive (q = 0.92, $k_f \approx k_t$). The fatigue results of all tested materials [4-10] together with the calculated k_f and q values are listed in **Table 2**.

Table 2: Fatigue performance of the various alloys

Material	**UTS/ YS**	σ_{a10^7} **smooth (MPa)**	σ_{a10^7} **smooth / YS**	σ_{a10^7} **notched (MPa)**	k_t	k_f	**q**
AISI 304 [4]	2.4	230	0.85	170	2.1	1.35	0.32
Ti-2.5Cu [5]	1.1	425	0.62	185	2.3	2.30	1.00
Beta C [6]	1.0	400	0.47	190	2.2	2.11	0.92
AZ80 [7]	1.3	100	0.46	37	2.7	2.70	1.00
CuZn30 [8]	2.5	120	0.96	80	2.3	1.50	0.38
Al2024-T4 [9]	1.5	150	0.49	80	2.1	1.88	0.80
Al2024-T6 [9]	1.2	140	0.36	75	2.1	1.87	0.79



a) q vs. UTS/YS

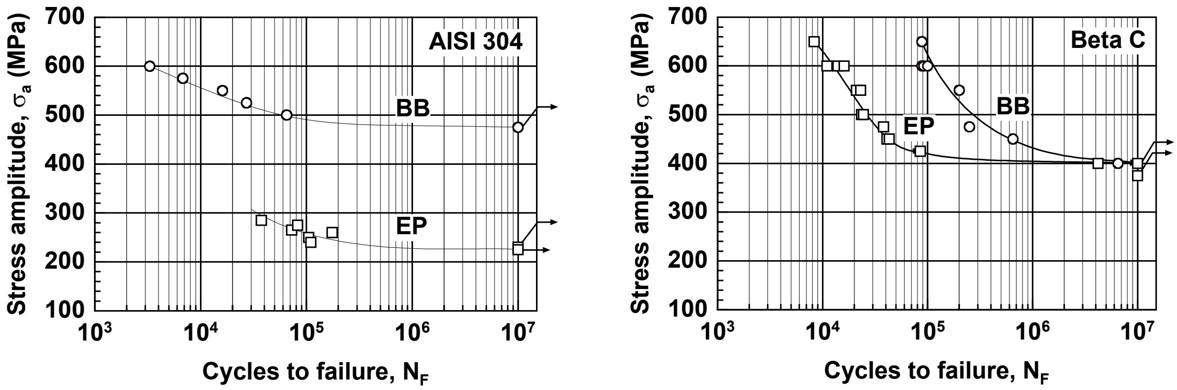


b) q vs. σ_{a10^7}/YS

Figure 5: Fatigue notch sensitivity dependencies

As seen in **Figure 5**, materials with low degrees of work hardening (**Fig. 5a**) or with low normalized HCF strength values (**Fig. 5b**) are quite notch sensitive whereas materials with high degrees of work hardening are much less notch sensitive. Interestingly, materials with face centered cubic (fcc) crystal structure such as AISI 304, α-brass and Al2024 exhibit fatigue notch sensitivities lower than materials with body centered cubic (bcc) crystal structures (Beta C) or hcp structures (IMI 230, AZ80).

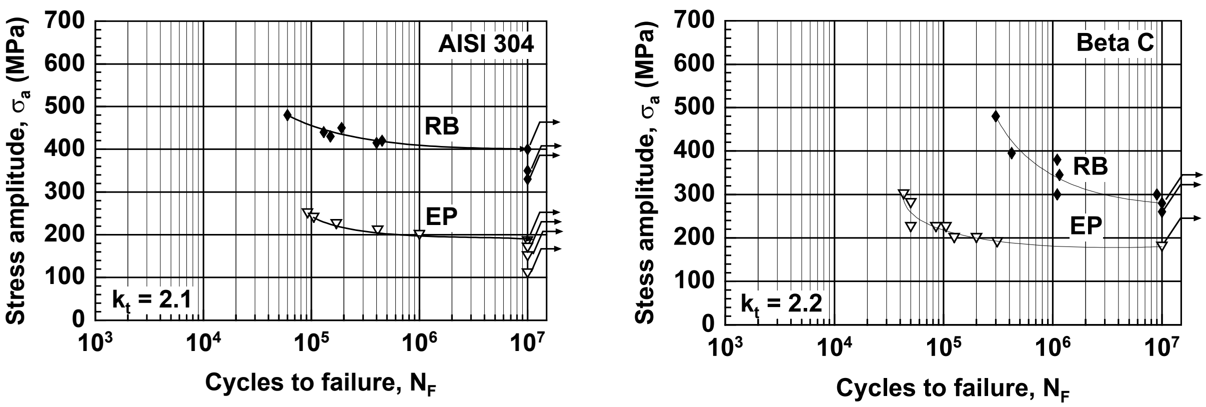
Figure 6 shows the influence of BB on the smooth HCF performance of AISI (**Fig. 6a**) and Beta C (**Fig. 6b**). While the HCF strength of AISI is clearly improved by BB, there is no improvement in case of Beta C.



a) AISI 304 b) Beta C

Figure 6: Effect of BB on smooth fatigue performance

Presumably, the marked work hardening in AISI gives rise to the observed very high improvement of the HCF strength by BB (**Fig. 6a**). Similar beneficial responses to BB were found on α-brass [10]. On the contrary, the very low work hardening in Beta C may cause the detrimental response of this alloy to BB (**Fig. 6b**).
The notched fatigue results after RB of both alloys are illustrated in **Figure 7**.



a) AISI 304 b) Beta C

Figure 7: Effect of RB on notched fatigue performance

It is clearly seen that the HCF strength improvement due to RB on AISI 304 (**Fig. 7a**) is much more pronounced than in Beta C (**Fig. 7b**). As opposed to smooth specimens, where no HCF strength improvement due to BB was observed (**Fig. 6b**), a significant improvement of the HCF strength due to RB was found on notched specimens **Fig. 7b**.

Conclusions

Fatigue notch sensitivities can be correlated quite well with the work hardening capabilties (UTS/YS) or normalized HCF strengths (σ_{a10^7}/YS) of the studied materials: The higher the work hardening capability or the normalized HCF strength, the lower is the fatigue notch sensitivity. While the smooth HCF strengths of materials with low work-hardening capability such as metastable beta-titanium alloys can even be detrimentally affected by surface strengthening through BB, notched specimens always respond with an increase in the HCF strength. Work is needed to shed some light on possible contributing factors such as multi-axiality of the stress state or differences in residual stress stability as opposed to smooth specimens.

Acknowledgements
One of the authors (J.A.) would like to thank the Ministry of Higher Education of the Syrian government for supporting his stay at IWW of TU Clausthal for obtaining a Dr.-Ing. degree.

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