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FATIGUE PROPERTIES OF SINTERED DIN SINT-D30 POWDER METAL BEFORE AND AFTER HEAT TREATMENT

LASTNOSTI SINTRANEGA KOVINSKEGA PRAHU DIN SINT-D30 PRI UTRUJANJU PRED TOPLOTNO OBDELAVO IN PO NJEJ

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The main focus of this study was to determine how heat treatment affects the dynamic properties of sintered steel. All the specimens were made of the DIN SINT-D30 metal powder, but only half of them were additionally heat treated. Flat specimens were cold pressed and sintered. The second set was additionally heat treated to increase the strength. After the static mechanical properties were determined, the fatigue strength was investigated in a pulsating machine with a load ratio of $R = 0$. Wöhler curves were plotted and the parameters for determining the fatigue life (σ_f' and b) were calculated.

Keywords: powder metallurgy, fatigue, $S – N$ curve

Glavni namen te študije je bil ugotoviti, kako toplotna obdelava vpliva na dinamične lastnosti sintranega jekla. Vsi vzorci so bili izdelani iz kovinskega prahu po DIN SINT-D30, vendar je bila samo polovica vzorcev dodatno toplotno obdelana. Ploščati vzorci so bili hladno stiskani in sintrani. Druga skupina je bila dodatno toplotno obdelana, da bi se povečala trdnost. Po ugotovitvi statičnih mehanskih lastnosti je bila preiskovana trdnost pri utrujanju na napravi za pulziranje z razmerjem obremenitve $R = 0$. Izrisana je bila Wöhlerjeva krivulja in izračunani so bili parametri za določanje časovne dinamične trdnosti (σ_f' in b).

Ključne besede: prašna metalurgija, utrujanje, $S – N$-krivulja

1 INTRODUCTION

Sintering of metal powders is becoming an interesting manufacturing process for large series, due to high performance, low costs, good accuracy and smooth surfaces. The whole process consists of three main phases (powder mixing, automatic die compaction and sintering) where different variables influence the mechanical properties of a sintered component that mostly depend on the porosity[1–7].

Like wrought-steel components, sintered-steel parts can also undergo additional heat treatment in order to improve mechanical properties. In[7], different measures are taken to improve the mechanical properties of a sintered gear. It is shown that sinter hardening is the most appropriate method for improving the wear resistance if the price and dimensional accuracy are considered as well.

In many studies of the fatigue behavior, sintered specimens were pressed into rectangular shapes and afterwards machined into cylindrical specimens[2,6,8]. In our study, as-pressed standard P/M tensile-test specimens with rectangular cross-sections (**Figure 1**) were tested. Sharp edges that were a result of the pressing were grinded down, but not polished. In order to avoid heating up the specimens due to the damping effects[8], the testing was done at $f = 10$ Hz. Consequently, after 10^6 cycles it became too expensive to test the fatigue properties, which is why it was not possible to determine if the fatigue limit for this powder mix exists, like the one from[5], or it is not to be determined even after 10^9 fatigue cycles, like in[8].

The main goal of this study was to determine the fatigue life of the specimens between 10^4 and 10^5 cycles with minimum machining. It was found that hardening significantly improves static mechanical properties, but

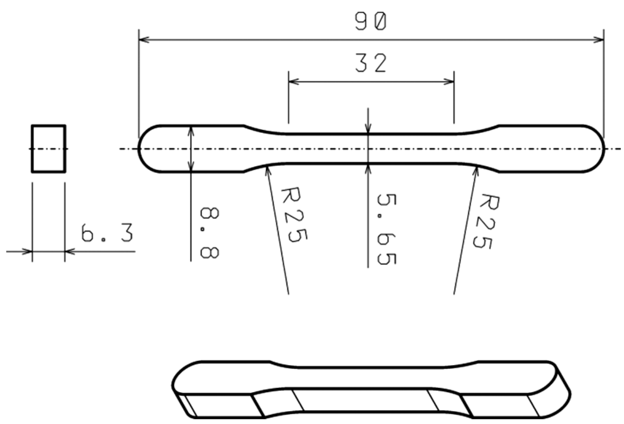

Figure 1: Test-specimen dimensions
Slika 1: Dimenzije preizkušancev

the difference gradually disappears when approaching 10^6 cycles of fatigue life.

2 MATERIALS AND METHODS

The powder mixture used in this study can be classified as SINT-D30 according to the DIN standard.[9] However, designations according to the other standards may be used: MPIF FD-0205[10] or JIS SMF 5040. The powder mixture used in this study was Höganäs Distaloy AB with an addition of the mass fractions w = 0.6 % of lubricant Kenolube P11 and w = 0.3 % of carbon in the form of graphite UF4. For a detailed chemical composition of the used powder mixture see **Table 1**, where it is compared to the standardized powders according to DIN and MPIF. Note that the MPIF standard suggests narrower limits for the alloying elements. In the last column of **Table 1**, the limits for the weight percentages of the alloying elements in powder mixture Höganäs Distaloy AB are also given.

Before the compaction of the specimens, the apparent density of the powder was 3.15 g/cm^3 and the Hall flow rate was 29 s for 50 g. Flat specimens (**Figure 1**) were cold compacted with a pressure of 585 MPa and sintered for 30 min in a 10/90 hydrogen and nitrogen atmosphere at 1120 °C. After the sintering, half of the specimens were austenitized at 915 °C, oil-quenched and tempered for 1 h at 175 °C. Both sets of specimens had the final density of 7.07 g/cm^3. Additional grinding of the specimens was done before the fatigue tests to remove the sharp edges, which were a result of the compaction process and could have significantly affected the results. However, the surfaces of the specimens were not additionally polished, thus, the average roughness at the thinned sections of the specimens was R_a = 0.76 µm.

Table 1: Chemical composition of the specimens compared to the standardized SINT-D30, FD-0205 and commercially available powder mixture

Tabela 1: Primerjava kemijske sestave vzorcev s standardiziranima SINT-D30, FD-0205 in komercialno mešanico prahov

w/%	Specimens	DIN SINT-D30	MPIF FD-0205	Höganäs Distaloy AB
Fe	Bal	Bal	Bal	Bal
C	0.29	< 0.3	0.3–0.6	< 0.01
Cu	1.47	1.0–5.0	1.3–1.7	1.35–1.65
Ni	1.69	1.0–5.0	1.55–1.95	1.57–1.93
Mo	0.50	< 0.6	0.4–0.6	0.45–0.55
Kenolube	0.58			

The static properties of the randomly chosen specimens from both sets were determined in a controlled environment at room temperature (22 °C) with a computer-controlled tensile-testing machine and a data-acquisition rate of 500 Hz. The displacement rate for all the quasi-static tensile tests was set to 0.50 mm/min. The stress-strain data was averaged and it is presented in the results section along with the static properties for each set of the specimens.

Although dynamic tests are normally performed on rounded and polished specimens[6], sintered components in practice usually do not undergo any machining before coming into use in service. Therefore, the specimens were only grinded to remove the sharp edges at the corners of the cross-sections.

Due to the rectangular section of the specimens, fatigue testing on a rotating-beam machine was not possible. Hence, it was performed on the same uniaxial machine where the static tests were done, but with a different configuration. To achieve the load ratio of R = 0, the load-control regime was induced in such a way that the maximum load was set. The loading frequency had to be set rather low, to f = 10 Hz, because the damping effects could have increased the temperature of the specimens and their cooling would not have been possible.

3 RESULTS AND DISCUSSION

The results of the static tensile tests show a good correlation to the values in the standards[9,10]. The Young's modulus of the sintered specimens is 130 GPa, which is the same as specified in the DIN standard and 10 % lower than in the MPIF standard for this material at a given density. For the hardened specimens a value of 142 GPa was recorded, which is 2 % lower than specified in the MPIF standard. The DIN standard does not give any value for this material after heat treatment, thus the values cannot be compared.

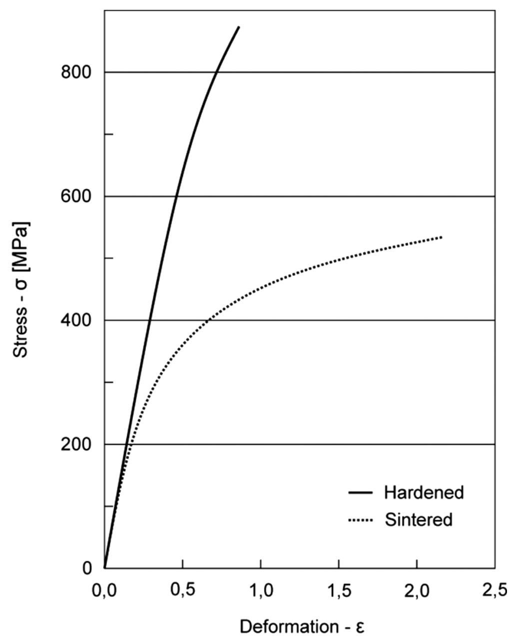

Figure 2: Comparison of static response for sintered and hardened specimens

Slika 2: Primerjava statičnega odgovora sintranih in toplotno obdelanih vzorcev

The average ultimate tensile strength for the sintered specimens was 532 MPa and the elongation at fracture was 2.16 %. The hardened specimens had a much higher ultimate tensile strength, averaging at 842 MPa, and their elongation at fracture was 0.86 %. Therefore, the heat treatment had a significant effect on the static tensile properties – increasing the tensile strength and reducing the ductility (**Figure 2**). A comparison of these values with the standards shows that the tensile strength is higher than specified in the DIN standard only for the sintered specimens and it is lower than specified in the MPIF standard for both sets of specimens. See **Table 2** and **Figure 2** for a detailed comparison of the static properties.

Table 2: Average static properties
Tabela 2: Povprečne statične lastnosti

	E/GPa	R_m/MPa	A/%
Sintered specimens	130	532	2.16
DIN D30	130	460	2
MPIF FD-0205-52.5*	145	575	1.75
Hardened specimens	142	842	0.86
MPIF FD-0205-130HT**	145	965	< 1

*Material designation code FD-0205-52.5 is not found in the MPIF standard. The values are linearly interpolated according to density between FD-0205-50 with a density of 6.95 g/cm^3 and FD-0205-55 with a density of 7.15 g/cm^3.
**Material designation code FD-0205-130HT is not found in the MPIF standard. The values are linearly interpolated according to density between FD-0205-120HT with a density of 6.95 g/cm^3 and FD-0205-140HT with a density of 7.15 g/cm^3.

Several dynamic tests were done at different load levels. Data points were plotted in a lg σ_a – lg N diagram and afterwards the method of least squares was used to find parameters A and b in the Basquin's equation (Eq.1), which suggests a straight-line relationship in a double logarithmic graph[11,12]:

$$\sigma_a = A(N)^b \tag{1}$$

where σ_a is the applied alternating stress for N cycles. Parameter A represents the amplitude fatigue strength for 1 cycle and it is only a theoretical value. Parameter b indicates the slope of the Wöhler line on a logarithmic scale.

For the sintered specimens, the calculated parameters were A_s = 494 MPa and b_s = –0.121. The calculated values for the parameters of the hardened specimens were A_h = 787 MPa and b_h = –0.153. However, Equation 1 is often written in a slightly different form[11]:

$$\sigma_a = \sigma_f' A(2N)^b \tag{2}$$

where parameter A is substituted with $2^b \cdot \sigma_f'$. Fatigue-strength coefficient σ_f' represents the theoretical amplitude stress at N = 0.5 and it is roughly equal to the actual tensile strength σ_f for most wrought-metal materials. It can be easily calculated from Equation 1, if parameters A and b are known, by inserting the value of 0.5 for N. Parameter b is the same in both Equations, (1) and (2). Fatigue-strength coefficients $\sigma_f'_s$ and $\sigma_f'_h$ were calculated for both sets of specimens and they are 537 MPa and 875 MPa for the sintered and hardened specimens, respectively.

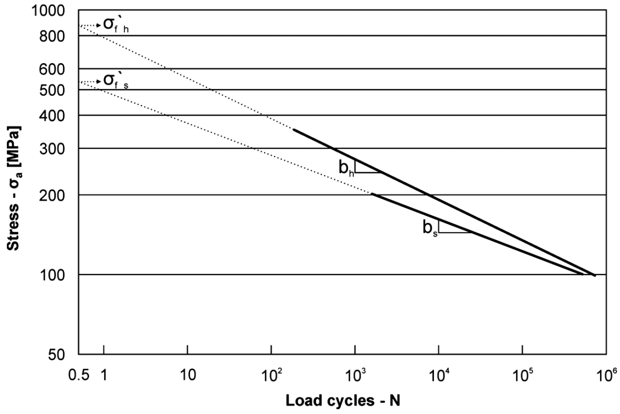

Figure 3: Comparison of S – N lines and marked parameters
Slika 3: Primerjava linij S – N in označeni parametri

The calculated S – N lines for the sintered and heat-treated specimens are compared in **Figure 3**, where the values of the fatigue-strength coefficients ($\sigma_f'_s$ and $\sigma_f'_h$) and slopes of both lines (b_s and b_h) are marked. When comparing the fatigue strengths at 10^4 cycles, the calculated value from the S – N line is 192 MPa for the hardened specimens and 162 MPa for the sintered specimens. From **Figure 3** it is evident that the difference in the fatigue strength gradually dissipates. The fatigue strength at 10^5 cycles is almost the same for both sets – 135 MPa for the hardened and 123 MPa for the sintered specimens. **Figure 3** also suggests that the S – N lines would cross each other after 10^6 cycles, but this is inconclusive, because there are no data points after 10^6 cycles. Therefore, on the basis of the available data, the amplitude strength cannot be determined at 10^6 cycles for either of the specimens and additional testing should be performed to find if the S – N lines cross each other after 10^6 cycles.

4 CONCLUSION

The main purpose of our study was to compare the median fatigue strengths of sintered and additionally hardened specimens between 10^4 and 10^5 cycles with a load ratio of R = 0. Before the dynamic testing, monotonic tensile tests were done comparing our values with the standard values for sintered materials[9,10]. The results showed a good correlation with the standard values, with some deviations that may have been caused by many variables in powder metallurgy (density, size, distribution of pores, chemical composition, sintering temperature, cooling rate from sintering temperature, etc.). The ultimate tensile strength for the sintered and hardened specimens was found to be 534 MPa and 842 MPa, respectively. Heat treatment also decreased the elongation at breakage from 2.16 % to 0.86 %. Therefore, for both wrought materials and sintered metals, hardening increases the strength and decreases the ductility.

Thereafter, the fatigue strength was investigated in a pulsating, load-control machine with the load ratio set to $R = 0$ at a frequency $f = 10$ Hz. The acquired data was then used to calculate the parameters in the Basquin's equation[12] with the least-squares method and $S - N$ lines for both sets of specimens were plotted in log-log diagrams. It turned out that, even though heat treatment increases the static strength with the difference being noticeable at 10^4 cycles, the slope of the $S - N$ line suggests that in the case of high-cycle fatigue, heat-treatment contributions to the fatigue strength of the chosen sintered material are negligible. However, more testing should be performed to investigate the fatigue behavior after 10^6 cycles because the data from this study alone is insufficient.

The fatigue limit was not determined in this study because the testing was interrupted when the cycle counter surpassed 10^6 cycles. Furthermore, the testing up to 10^7 cycles or beyond at the frequency $f = 10$ Hz would be very expensive. However, the MPIF standard does give a guiding value for FD-0205-HT regarding the axial fatigue limit for 90 % survival after 10^7 cycles, which is 310 MPa at a load ratio $R = -1$, determined at $f = 100$ Hz. A comparison of this value with the data from our study is not possible because the tension mean stress ($R > -1$) reduces fatigue life.[11]

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