DYNAMIC PROPERTIES OF PRE-ALLOYED MOLYBDENUM STEEL POWDERS FOR GEAR APPLICATIONS

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Abstract
The implementation of PM components in automotive applications increases continuously. Especially applications in heavy-duty components like gears, pistons and connecting rods that are exposed high cycle dynamic loads can be realised with new developed materials and processes [1]. It is known that the dynamic properties of P/M parts are a complex phenomena which are influenced by numerous factors like pores, microstructure, heat treatment, etc. [2]. In several studies it has been proved that the porosity of a P/M part has the greatest influence [3, 4]. It can generally be assumed that raising the density leads to a more or less linear increase of the static mechanical properties, while the fatigue and impact strength increase exponentially [5]. The pre-alloyed Mo-steel powder MSP 3.5 Mo comes very close to meeting the stringent requirements of highly-loaded P/M parts, such as gears.

1. Introduction
A conventional method of attaining high component density is shrinkage during sintering. The most effective way of increasing shrinkage with sintered steels is to execute sintering in the ferrite phase (α-phase). This finding inspired the development of the QMP MSP 3.5 Mo water atomised, pre-alloyed steel powder with a molybdenum content of 4.0 wt-%. Because of this molybdenum content the sintering behaviour of the material is constant during the high temperature sintering process. The outstanding property of this material is the component density of 7.5 to 7.6 g/cm³ (approx. 95% of the theoretical density) that can be achieved by single sintering without a liquid phase.
With this material in collaboration with QMP Metal Powders GmbH and the Laboratory for Machine Tools and Production Engineering (WZL) investgations regarding the load carrying-capacity and the suitabilty as future material for sintered gears were conducted. The investigations were carried out as a part of a project sponsored by the Federal Ministry of Education and Research (BMBF, Project No. 03N3024).

2. Establishing suitable alloy systems
The fact that molybdenum extends the ferritic zone of iron is known in literature. Therefore the Fe-Mo system seems promising for P/M materials sintering exclusively in the α-phase. The Fe-Mo phase diagram was established on the basis of dilatometric tests and thermodynamic calculations. As the material MSP 3.5 Mo is to sinter fully in the α-phase, knowledge of the exact boundaries of the different phases is indispensable. A phase diagram can be designed by means of dilatometric curves, see figure 1. With rising molybdenum content, the phase region $\alpha + \gamma$ is increasingly restricted. Up to a molybdenum content of 3.5 mass-%, a phase transformation $\alpha \rightarrow \alpha + \gamma \rightarrow \alpha$ takes place

while the material is heating up. With a molybdenum content of 4.0%, the dilatometer printouts did not show any transformation. With this Mo-content, the material is purely ferritic over the entire temperature range. The programs Chemsage and Thermocalc of the Institute of Ferrous Metallurgy (RWTH Aachen/Germany) [6] were used to calculate the ternary phase diagram Fe-Mo-C. On the one hand, the diagram is intended to provide information on the stability of the α-phase during carbon-free processing. On the other hand, the purpose of the calculation was to clarify how much of the alloying element carbon may be added at the very most to achieve nothing but the ferritic phase during the sintering process. In addition, the various phases undergone by the material in the course of case hardening, as a function of the austenitising temperature, were to be demonstrated.

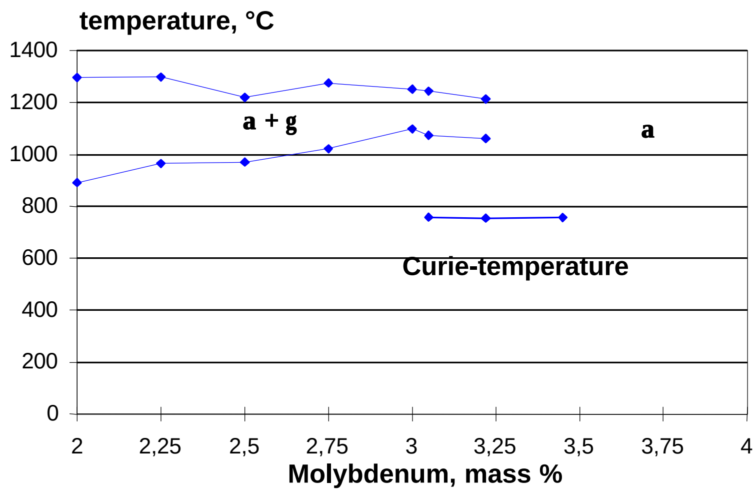

Figure 1. Fe-Mo phase diagram established on the basis of dilatometric curves

The effect of carbon on the Fe-Mo system is extremely complex. For the Fe-Mo-C phase diagram, quasi-binary sections at 3.5 mass-% were calculated (figure 2). The molybdenum content was kept constant in each case to avoid complicating the diagrams unnecessarily. On the one hand, the α-zone is extremely restricted by carbon, with a maximum possible extension of the a-phase up to around 940°C and approximately 0.01% carbon. Sintering must therefore be practically carbon-free in order to take advantage of effect of the high self-diffusion coefficient of iron in the α-phase. Carbon should therefore be introduced into the material after sintering, for example by case hardening. On the other hand, the phase diagram shows that the usual austenitising temperatures of 850 – 950°C are not sufficient to decompose the M_6C carbides and to austenitise the material completely. Case hardening must be done at temperatures above 1050°C in order to avoid carbide precipitation. The strength of MSP 3.5 Mo at about 350 MPa is still low. Therefore niobium and phosphorus were added to the basic powder to increase its strength. These elements do not constrict the ferritic phase. It was found out that merely partial alloying with phosphorus improves strength with elongation after fracture it´s remaining the same. Niobium also seems promising although ist strength-increasing effect only shows after carbon is added by a thermochemical treatment (case hardening), but not in the as-sintered condition.

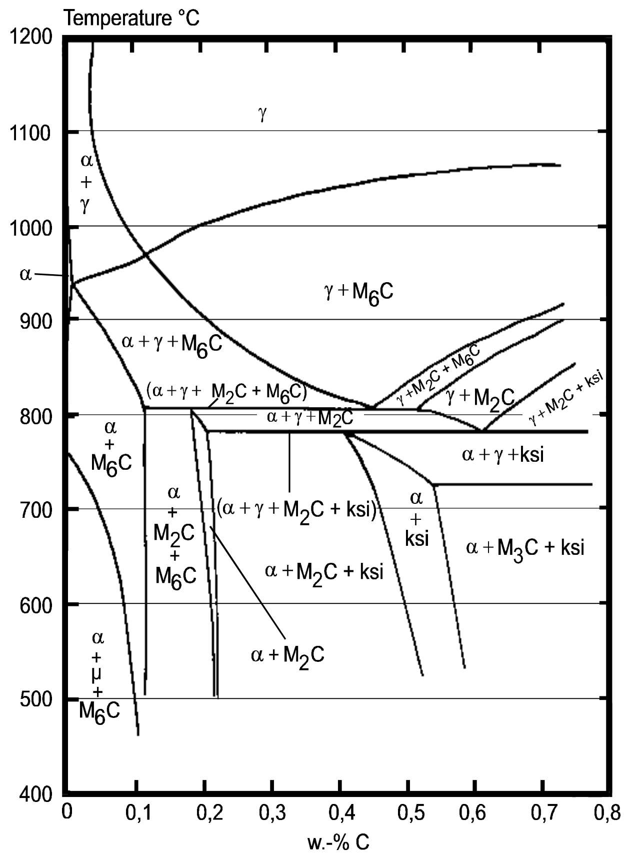

Figure 2. Quasi-binary section through the Fe-Mo-C-phase digram at an molybdenum content of 3.5 mass-%

3. Optimisation of case-hardening

The solution temperature of the carbides is essential for case hardening since carbides at the grain boundaries substantially reduce strength and toughness properties. If low austenitising temperatures are selected for case hardening special carbides of the M_6C type appear at the grain boundaries. The decomposition of the carbides can be subdivided into different stages. At an annealing temperature of 900°C, the carbide network still exists, but the carbides already start to coalesce as round structures (1st stage). The 2nd stage emerges after an annealing treatment at 1000°C. Now nothing but round, coalesced and coagulated carbides are visible. In the 3rd stage, individual carbides start to disintegrate, and from a temperature of 1050°C the percentage of carbides decreases noticeably. If an annealing temperature above 1100°C is selected, all carbides will disintegrate. Therefore an austenitising temperature of more than 1050°C must be chosen for case hardening to prevent the formation of special carbides at the grain boundaries.

4. Gear tests

Gear tests (m_n = 3.5 mm; b = 20 mm; ß = 0°) for were performed using the molybdenum-containing materials listed in figure 3. For reasons of time and cost, circular blanks of the sintered materials were pressed in a simple die, the gear teeth were machined and the parts were heat-treated and ground. The circular blanks were manufactured at a pressure of P_1 = 750 MPa. Sintering was carried out for t_s = 30 min at 1290 °C in an H_2/N_2 atmosphere. The density of the sintered rollers was ρ_1 = 7.72 g/cm³ for Variant 1 and ρ_2 = 7.76 g/cm³ for Variant 2. S/N-curves for the 20MnCr5 reference variant and the two sintered material variants (V1 and V2) were determined in pulsator tests. Some of the sintered gears were additionally shot-peened using compressed air in order to enhance the load carrying capacity of the tooth root and likewise tested in the pulsator. To save time and cost, the load-carrying capacity of the 20MnCr5 reference variant tooth root was not tested in the shot-peened state.

combination of gears:

test gear - counter gear

V1 - Reference
V2 - Reference
Reference - Reference

Reference: 20MnCr5

		V 1	V 2	Reference
alloy system		MSP3.5Mo	MSP3.5Mo -0,1%Nb	20MnCr5
compacting	P_1	P_1 = 750 MPa		
sintering (mixed gas H_2/N_2)	t_S, S_1	t_S = 30 min S_1 = 1290 °C		
density (g/cm³)		7,72	7,76	7,86
Young's modulus E (N/mm²)		185.000	186.000	210.000
$\bar{E}$ (N/mm²)	$\bar{E} = \frac{2E_1E_2}{E_1+E_2}$	196.700	197.200	210.000

Figure 3. Work material variants and production parameters

Figure 4 shows the S/N-curves for the conventional 20MnCr5 case-hardening steel reference variant and the V1 and V2 PM variants. The tooth root stress continuously withstood by the 20MnCr5 reference variant is approximately σ_{F0} = 900 N/mm². The equivalent value for the Variant 1 sintered gears is roughly 25 % below this figure, at σ_{F0} =

685 N/mm². The value for Variant 2 is σ_{F0} = 745 N/mm², or about 18 % below the reference variant. Shot peening increases the tooth root load-carrying capacity of the PM gears. Both PM variants achieve a continuously withstandable tooth root stress of σ_{F0} = 1000 N/mm² approx., which is 9 % above the tooth root load-carrying capacity of the unpeened reference variant.

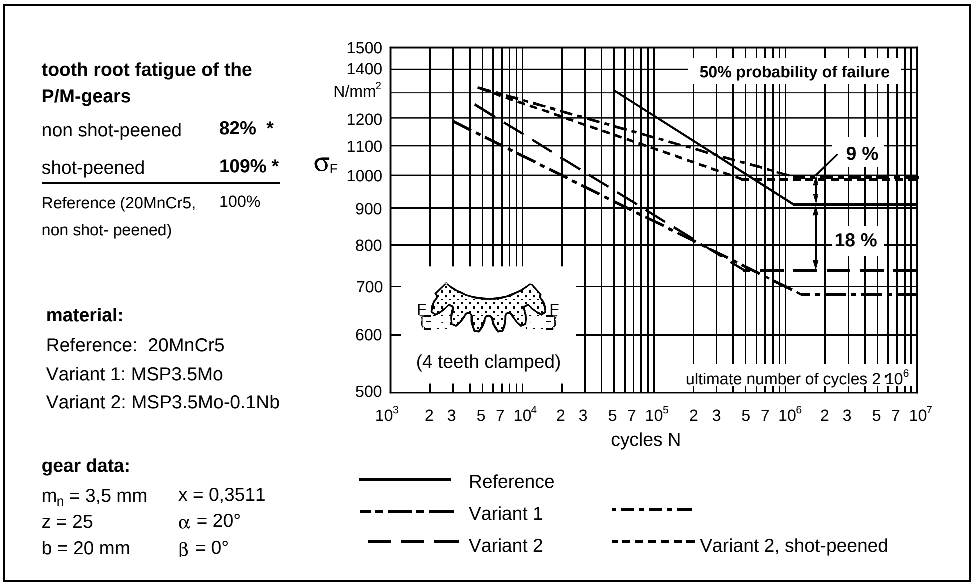

Figure 4. Tooth root load-carrying capacity of the sintered variants compared to the reference variant [7]

Figure 5 contains the test points covered for Variant 2, indicating the hertzian pressure σ_{H0} and the torque M_1 applied to the pinion. The varying moduli of elasticity for the pinion (z_1 = 25) and the gear (z_2 = 26) were taken into account in calculating the hertzian pressure. In the case of the sintered material, the modulus of elasticity determined ultrasonically on the sintered rollers (ρ = 7.63 g/cm³) was employed. An S/N-curve for 16MnCr5 compact steel determined in earlier tests is also shown to indicate the comparative load-carrying capacities of sintered gears and 16MnCr5 compact gears. Results of the running tests show that the transition zone from fatigue strength to creep strength is comparable with that for steel. The continuously withstandable hertzian pressure for Variant 2 is roughly 97 % of that for the steel material (50 % probability of failure).

5. Conclusion

The sintered steel MSP 3.5Mo is characterised by its very high density of 7.5 g/cm³ as a result of sintering in the α-phase. The strength behaviour of this materials was initially examined in extensive materials science test programmes. Pulsator tests were carried on sintered gears made from MSP 3.5 Mo in order to determine tooth-root load-carrying capacity. The tooth-root load-carrying capacity of the sintered gears was examined on gears with a module m_n = 3.5 mm in the unpeened and shot-peened states. The high-density PM gears attain roughly 80 % of the load-carrying capacity of the reference gear in the unpeened state. Following additional shot peening, the tooth-root load-carrying capacity of the PM gears is 9 % higher than that of the reference variant. Tooth-flank load-carrying capacity tests on Variant 2 (MSP3.5Mo-0.1Nb) PM gears show that fatigue strength values comparable to those for compact steel can be expected from the high-density sintered gears.

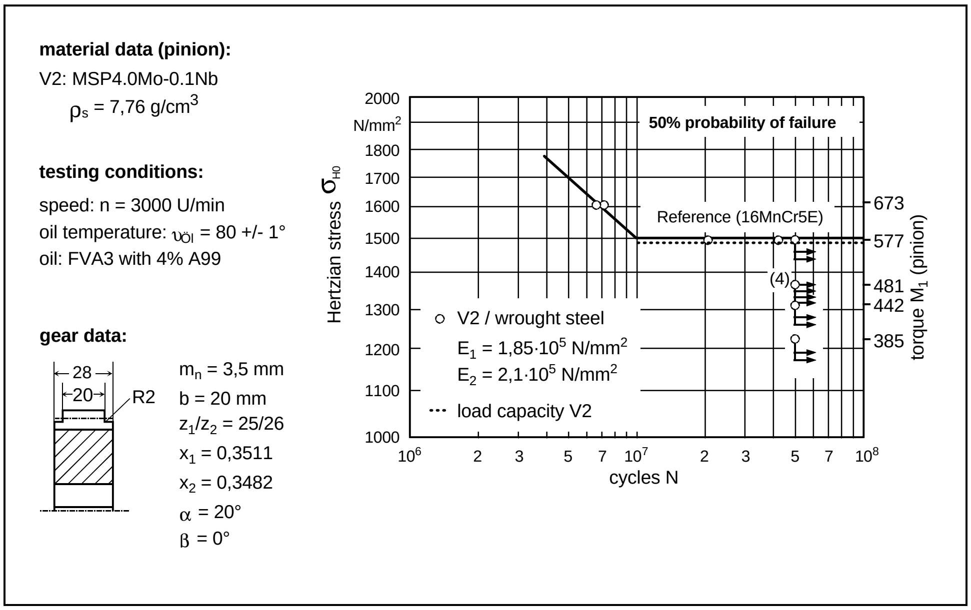

Figure 5. Tooth flank load-carrying capacity of Variant 2 [7]

Acknowledgement

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