Suitability of High Density Powder Metal Gears for Gear Applications

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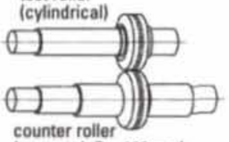
Introduction

The implementation of powder metal (PM) components in automotive applications increases continuously, in particular for more highly loaded gear components like synchromesh mechanisms. Porosity and frequently inadequate material properties of PM materials currently rule out PM for automobile gears that are subject to high loads. By increasing the density of the sintered gears, the mechanical properties are improved. New and optimized materials designed to allow the production of high-density PM gears by single sintering may change the situation in the future.

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 phased (α-phase). That finding inspired the development of the QMP MSP3.5Mo material, a water-atomized, pre-alloyed steel powder with a molybdenum content of 3.5 percent. Based upon that material, two new steel powders with a molybdenum content of 4.0 percent by weight have been developed. Because of the increased molybdenum content of 0.5 percent, the sintering behavior of the material is constant during the high temperature sintering process. With these materials—QMP MSP4.0Mo and MSP4.0Mo-0.1Nb steel powder—in collaboration with QMP Metal Powders GmbH and the Laboratory for Machine Tools and Production Engineering (WZL), investigations regarding the load-carrying capacity and the suitability as future materials for sintered gears were conducted. The investigations were carried out as a part of a project sponsored by the German Federal Ministry of Education and Research (BMBF, Project No. 03N3024).

The report covers investigations concerning the macropitting resistance under Hertzian pressure and sliding of sintered rollers made from the new developed steel powders MSP4.0Mo and MSP4.0Mo-0.1Nb. Tests on the tooth root and tooth flank load-carrying capacities of sintered gears have been conducted on gears with a module of 3.5 mm. The influence of shot peening on the properties of sintered gears made from MSP4.0Mo and MSP4.0Mo-0.1Nb was also investigated. The results of the sintered rollers and gears are directly compared to the fatigue properties of rollers and gears made from wrought steel. The single sintered PM gears with densities between 7.5 g/cm³ and 7.7 g/cm³ can attain tooth root and flank load capacities



combination of rollers:

test roller – counter roller

V1 – Reference
V2 – Reference
Reference – Reference

Reference: 20MnCr5

		V1	V2	Reference
alloy system		MSP4.0Mo	MSP4.0Mo -0.1%Nb	20MnCr5
compacting	P_1	P_1=650 MPa		
sintering (mixed gas H_2/N_2)	t_s, S_1	t_s=30 min, S_1=1290°C		
density (g/cm³)		7.58	7.63	7.86
Young's modulus E (N/mm²)		185,000	186,000	210,000
E (N/mm²)	$\bar{E} = \frac{2E_1E_2}{E_1+E_2}$	196,700	197,200	210,000

Figure 1—Work material variants and production parameters of the test rollers.

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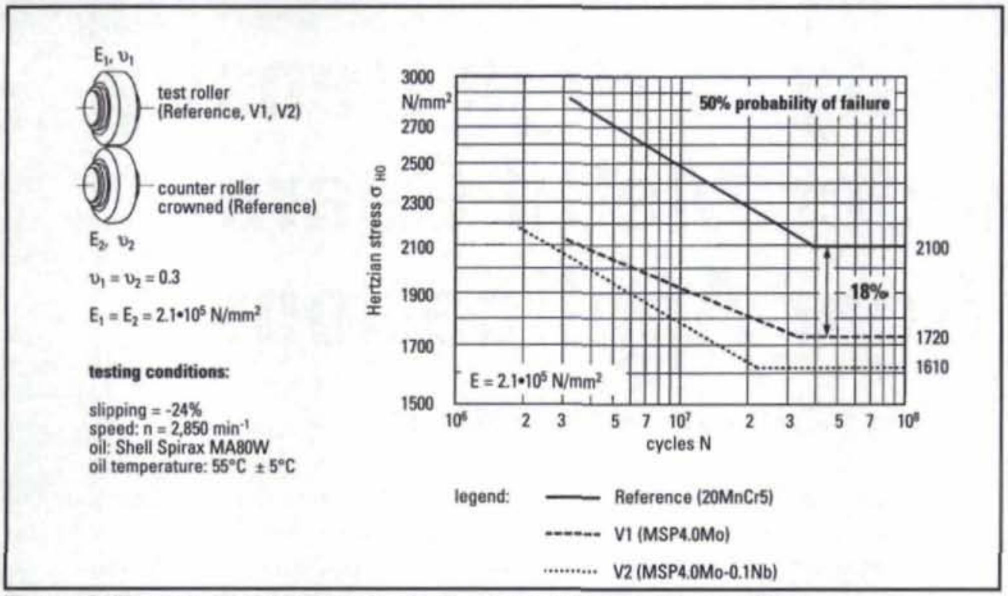

Figure 2: Rolling strength of the sintered variants as compared to the reference variant

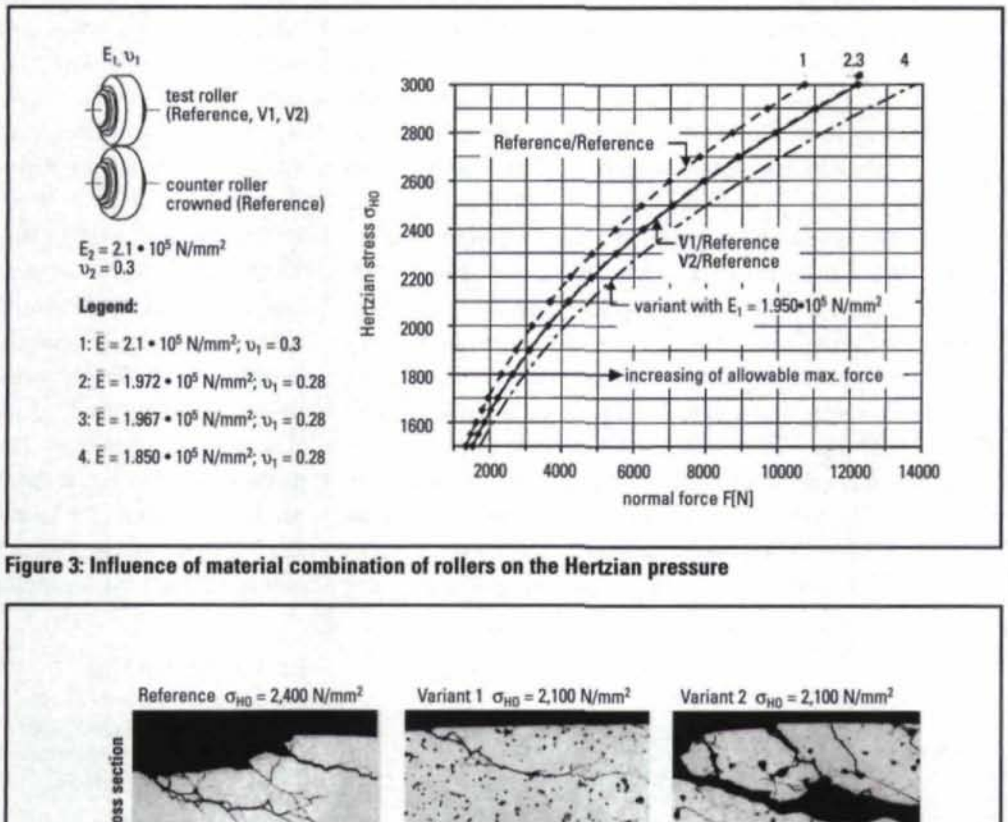

Figure 3: Influence of material combination of rollers on the Hertzian pressure

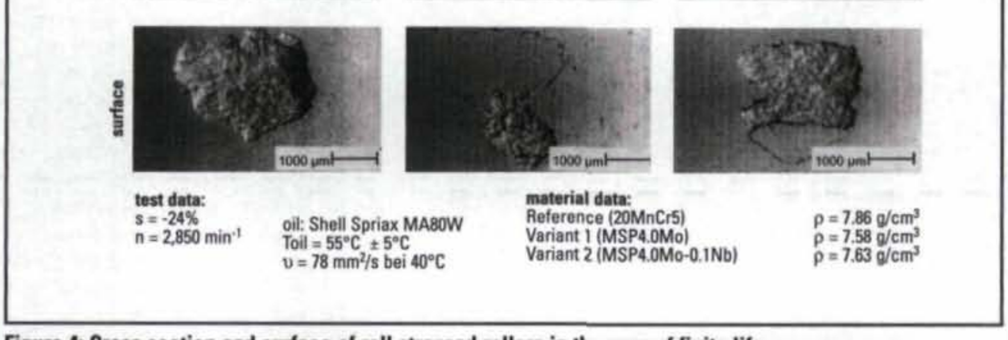

Figure 4: Cross section and surface of roll stressed rollers in the area of finite life

that are comparable to those obtained with DIN steels. Based on those results, high density PM materials could be suitable for future gear applications.

Investigation of rolling strength of sintered rollers

Material variants and geometry of rollers. Figure 1 shows the material and production parameters of the test rollers used in the WZL tests. The sintered test rollers were pressed from cylindrical circular blanks and plasma-carburized. The bores and running surfaces of the test rollers were then ground in the circumferential axis and the finished test rollers were shrunk onto steel shafts. The counter-rollers, manufactured solely from the case hardening steel ZF7B (20MnCr5) reference material, and the reference test rolls were machined as a single part and were case hardened. The sintered test pieces were pressed at P_1 = 650 MPa. The sintering temperature was 1290°C at a sintering time of t_s = 30 min. in an H_2/N_2 gas atmosphere. The density of the α-phase sintered materials is already very high, at 7.58 g/cm³ (V1) or 7.63 g/cm³ (V2). Figure 1 also shows the modulus of elasticity of the V1 and V2 sintered material variants and the mean modulus of elasticity used to calculate the Hertzian pressures encountered in the rolling tests.

Test procedure and results. The rolling strength tests on the PM rollers were conducted under typical gear conditions using a twin-disc test stand. The contacting materials in the running tests on variants 1 and 2 were a sintered cylindrical test roller and an embossed counter-roller made from the 20MnCr5 reference material (Figure 1). Two 20MnCr5 rollers were used in the reference test. Figure 2 shows the results of the roller tests.

The Hertzian pressure that can be withstood continuously by the single-sintered rollers is roughly 82 percent of the load-carrying capacity of the conventional 20MnCr5 case-hardening steel. The S/N-curves for variants V1 and V2 in Figure 2 are somewhat flatter than the reference variant, suggesting greater sensitivity to overload peaks. In Figure 2, the Hertzian pressures of the sintered variants were corrected with the aid of a standardized modulus of elasticity ($2.1 \cdot 10^5$ N/mm^2) in order to achieve greater comparability of the load-carrying capacities of the various material combinations. For that correction, the diagram in Figure 3, which shows the Hertzian pressure depending on the applied normal force for different material combinations, was used.

The damage patterns for all materials in the tests were, however, approximately identical and resulted partly from the high density and homogeneous microstructure of the sintered rollers. Contrary to previous tests with rollers at densities of max. 7.2 g/cm^3, in these investigations no wear at the sintered rollers occurred, and the failure mode was macropitting in all cases. As an example, Figure 4 shows the typical failure in the area of finite life for the investigated materials. The damages to the reference wrought steel and to the sintered variants V1 and V2 show similar forms of

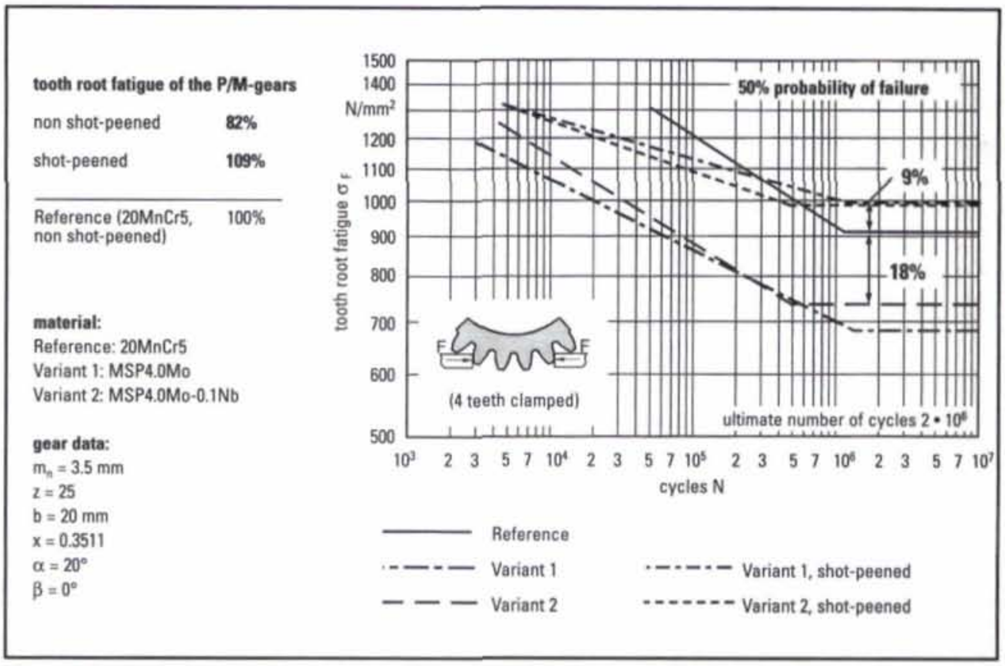

Figure 5: Tooth root load-carrying capacity of the sintered variants compared to the reference variant

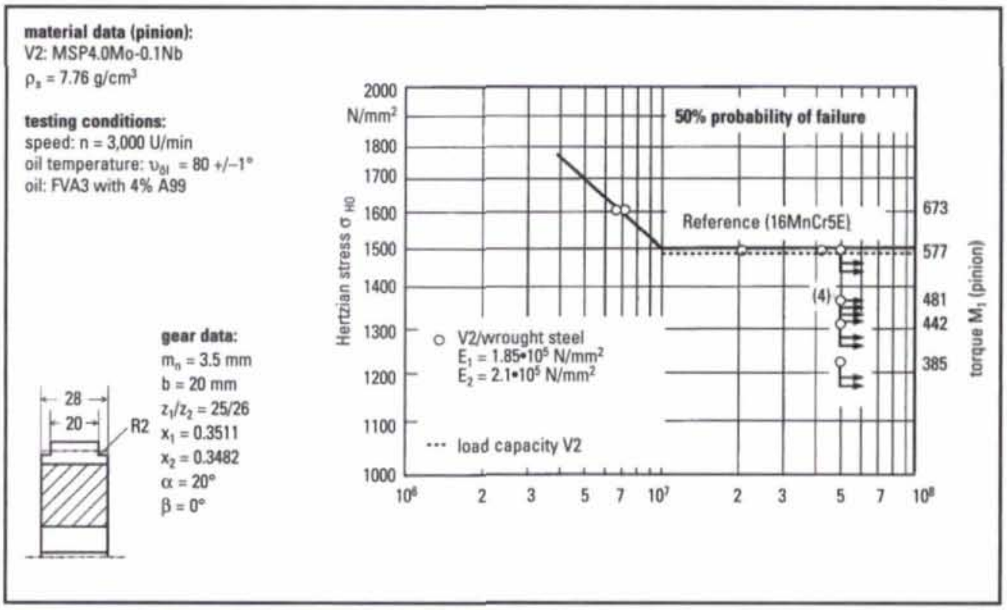

Figure 6: Tooth flank load-carrying capacity of Variant 2

appearance. In the photos of the cross section, the cracks, starting below the surface in the area of the maximum equivalent stress, are shown. The surface shots show the macropitting at test end.

Gear Tests

Additional gear tests (m_n = 3.5 mm; b = 20 mm; ß = 0°) for Quebec Metal Powders GmbH were performed using the molybdenum-containing materials listed in Figure 1 as part of the BMBF project. 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 plasma-carburized 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/cm^3 for Variant 1 and ρ_2 = 7.76 g/cm^3 for Variant 2. As in the rolling strength tests on the twin-disc test stands, S/N-curves for the case hardened 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

MEANINGS OF METALLURGICAL WORDS

compact—an object produced by the compression of metal powder, generally while confined in a die, with or without the inclusion of nonmetallic constituents.

density ratio—the ratio of the determined density of a compact to the absolute density of metal of the same composition, usually expressed as a percentage.

sintering—the bonding of adjacent surfaces of particles in a mass of metal powders or a compact, by heating.

Source: *Definitions of Metallurgical Terms*, ASM International.

***high density**—density higher than 7.5 g/cm³, which allows* higher loads compared to conventional, single sintered powders.

shrinkage—a pressed part will shrink during the sintering process, due to the bonding of the powder particles, such as the decreasing of diameter and height of a pressed circular blank.

Source: Dr.-Ing. Rainer Link, Dipl.-Ing. Gerd Kotthoff

20MnCr5 reference variant tooth root was not tested in the shot-peened state.

Figure 5 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 $\sigma_{F0} = 900$ N/mm². The equivalent value for the Variant 1 sintered gears is roughly 25 percent below that figure, at $\sigma_{F0} = 685$ N/mm². The value for Variant 2 is $\sigma_0 = 745$ N/mm², or about 18 percent 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 $\sigma_{F0} = 1000$ N/mm² approximately, which is 9 percent above the tooth root load-carrying capacity of the unpeened reference variant.

Finally, load carrying capacity tests were carried out with the sintered variant V2. In the tests, the sintered test pinion was mating with a 16MnCr5 wrought steel gear, in order to investigate the sintered material V2 at the pinion. Figure 6 contains the test points already covered for variant V2, 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 ($\rho = 7.63$ g/cm³) was employed. An S/N-curve for 16MnCr5 wrought steel determined in earlier tests is also shown to indicate the comparative load-carrying capacities of sintered gears and 16MnCr5 wrought steel gears.

The results of the running tests show the slope of the S/N curve for Variant 2 is comparable with that for steel. The continuously withstandable Hertzian pressure for Variant 2 is roughly 97 percent of that for the steel material (50 percent probability of failure).

Conclusion

Innovative iron-molybdenum-based powder metallurgical materials were produced on the laboratory and production scale as part of the BMBF project on *New PM Materials.* The strength behavior of the materials was initially examined in extensive materials science test programs. Surface macropitting rolling tests and pulsator tests were then carried out at the WZL on sintered gears made with the newly-developed PM materials, in order to determine tooth-root load-carrying capacity. Rolling test results show that single-sintered, high-density PM rollers can achieve a continuously withstandable Hertzian pressure σ_{H0} representing some 82 percent of the rolling strength of the reference material. An analysis of available test roll damage patterns indicated no significant differences between damage to the high-density sintered rollers and the reference rollers. Of interest in this context is the fact that that high rolling strength was attained by single-sintered test rollers which had not been subjected to additional shot peening treatment. 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 percent 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 percent higher than that of the reference variant. Tooth-flank load-carrying capacity tests on Variant 2 (MSP4.0Mo-0.1Nb) PM gears show that fatigue strength values comparable to those for wrought steel can be expected from the high-density sintered gears.

Acknowledgment

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