Rolling Contact Fatigue Design Aspects of Surface Densified PM Components

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Abstract
The PM industry is permanently expanding the applications into new and challenging fields. Sintered components are becoming more and more frequent for highly loaded components also under rolling contact conditions. Gears are successfully introduced for applications such as oil pumps. An important field of future expansion for PM materials are highly loaded gears in e.g. vehicle transmission and power train gears.

To ensure that PM materials have the ability to compete with wrought steels, rolling contact fatigue investigations have been performed on molybdenum pre-alloyed PM materials. A summary of design aspects under rolling contact conditions for surface densified PM components will be discussed studying the surface and sub-surface stress distribution.

1 Introduction

PM technology is a cost effective method of producing components with complicated geometries like gears. Transmission gears are subjected to rolling contact fatigue at the gear flanks and tooth bending fatigue. The development of new PM materials and processes lead to a potential for substituting conventional cast or wrought products by PM. Material properties for fatigue and rolling contact fatigue must be known in order to assess the stresses including the Hertzian pressure on the gear flanks, Fig. 1 [1, 2, 3].

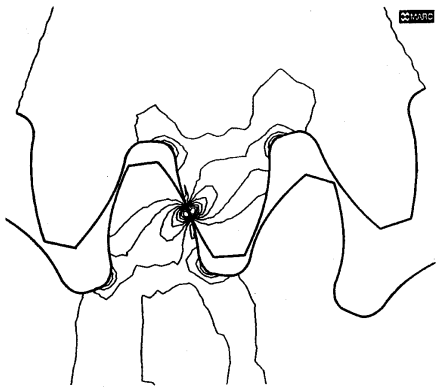


Fig. 1: Stresses on mating gears

PM parts manufactured by single pressing, single sintering can reach densities up to 7.2-7.4 g/cm^3. The application of the more expensive double pressing, double sintering technique or warm

compaction will not necessarily result in a better rolling contact fatigue behaviour [2, 4, 5]. However, highest endurable Hertzian pressures will be achieved by full density, e.g. powder forging [2, 4].

The surface densification technique has been developed in order to increase the load bearing capacity of PM gears [6-13]. For highly loaded gears, advantages will be given by a surface densification, where the economic single pressing, single sintering process is combined with the properties of the full density in the highly loaded areas of the gear flank and the tooth root [8, 11]. The technique can hence be an alternative to conventional methods to manufacture highly loaded gears to a low cost with properties comparable to wrought steel.

2 Materials and manufacturing of test specimen

Rolling contact fatigue test specimens were manufactured by cold compaction, sintering at 1120°C for 30 minutes in $90H_2/10N_2$ and soft machining to the required shape with an over measure on the diameter of test surface. The surface densification was performed by radial rolling in a two-roll burnishing machine at Escofier Technologie SA in France. The diameter was reduced by 0.5 mm during rolling; resulting in full or near full density in the surface while the core material remained unchanged. Also the shape and the surface roughness of the component were improved by the rolling. The surface densified rollers were case carburised, quenched in oil and tempered. The base powders and the reference wrought steel that were used in this study are listed in Table 1 together with their chemical composition.

Table 1: Characteristics of investigated test specimens

	Base powder	Graphite (%)	Density (g/cm^3)	As-sintered hardness (HV10)	Densification depth^{+} (mm)	Case depth (mm)
A	Astaloy 85Mo (0,85%Mo)	0.5	7.1	165	1.0	Not defined^{++}
B	Distaloy DC-1 (2%Ni diffusion bonded, 1,5%Mo pre-alloyed)	0.15	7.0	142	0.9	0.75
C	Astaloy Mo (1,5% Mo pre-alloyed)	0.6	7.2	189	1.0	Not defined^{++}

$^{+}$ Distance from the densified surface where the density drops to 98% of theoretical, measured by image analysis. $^{++}$The hardness exceeded 550HV0.1 throughout the cross section [14].

3 Economical aspects

The benefits of combining PM technology and surface densification compared to conventional manufacturing methods are mainly economical. Fig. 2 shows a comparison of the estimated cost of some gear manufacturing routes, i.e. (1) cold compaction and sintering, (2) cold compaction, sintering and surface densification [15], (3) powder forging [15-17] and (4) machining of wrought steel. As can be seen in Fig. 2, the additional cost for the surface densification operation is comparable to pressing and sintering. The cost for the rolling operation is significantly lower compared to a powder forging procedure. It can be seen that hobbing, turning and shaving are very costly operations in contrast to pressing sintering and rolling. Into the bargain, the surface finish will be radically improved by the rolling operation compared to shaving [12].

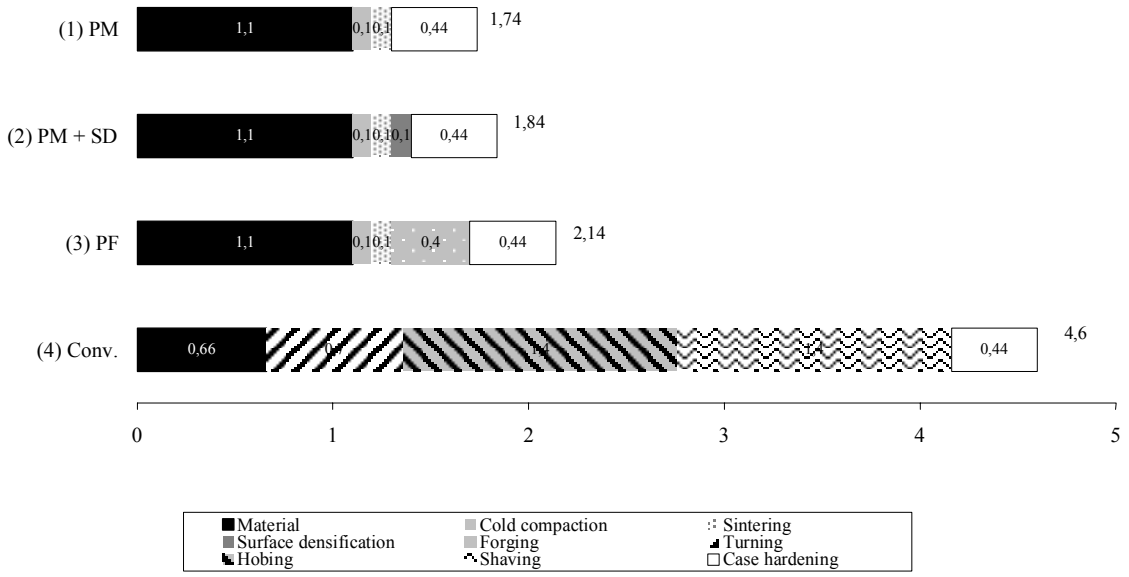


Fig. 2: Cost comparison of (1) cold compaction, sintering and case hardening, (2) cold compaction, sintering, surface densification and case hardening, (3) cold compaction, sintering, powder forging and case hardening (4) turning, hobbing, shaving and case hardening.

4 Rolling contact fatigue testing

4.1 Testing conditions

The tests were performed in a ZF-RCF test bench with the loading principle and specimen geometry shown in Fig. 3. The advantage of this testing principle is its ability to realistically simulate the load conditions on gear flanks [18]. The testing conditions were Hertzian pressure with additional sliding of -24% as the most severe condition on gear flanks, gearbox oil SAE 80 (MIL-L 2105 = GL4) and an oil temperature at the surface of the specimens of 80°C. The test is terminated either when pitting failures are detected or when the specimens has endured 10^8 cycles without failure. A vibration sensor detects pitting failures.

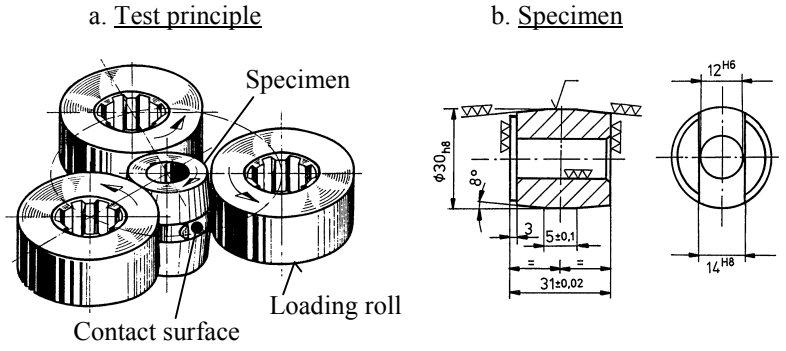


Fig. 3: Test principle and specimen

4.2 Endurable Hertzian Pressures of surface densified materials

The results of rolling contact fatigue for the tested materials are presented in Fig. 4 using double logarithmic diagrams. The endurable Hertz pressure, estimated by linear regression and extrapolated to 10^8 cycles (endurable Hertzian pressure with a probability of survival of 50%), and the hardness characteristics are shown for all investigated materials in Table 2.

Whereas the results of materials A and B will show a small scatter, the results of material C is showing a significant larger scatter in rolling contact fatigue.

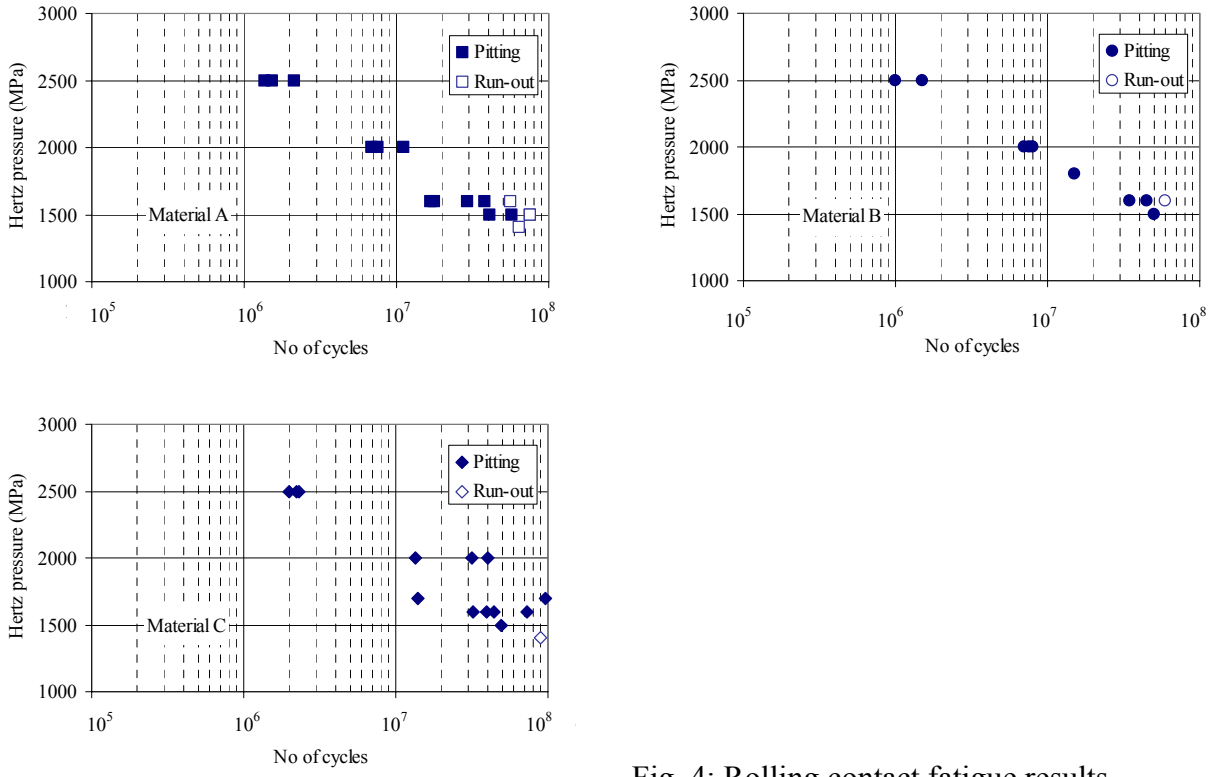


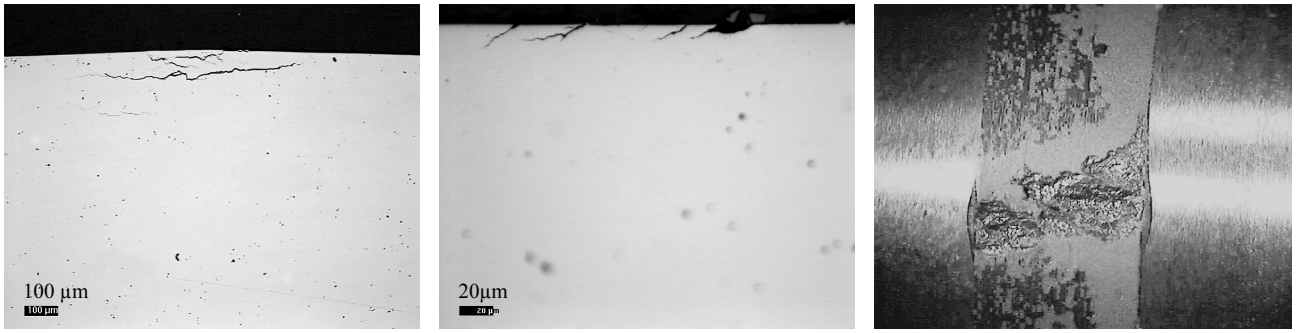
Fig. 4: Rolling contact fatigue results

Table 2: Endurable Hertz pressure and hardness characteristics

		Surface hardness (HV0.1)	Core hardness (HV0.1)	Case depth (mm)	Endurable Hertz pressure for 10^8 cycles (MPa)
A	Astaloy 85Mo+0.5% C	870	630	Not defined[+]	1350
B	Distaloy DC-1 + 0.15%C	945	400	0.7	1410
C	Astaloy Mo + 0.6%C	935	720	Not defined[+]	1500
Reference	16MnCr5				1600[++]

[+]The hardness exceeded 550HV0.1 throughout the cross section [++]source ZF Friedrichshafen and [4]

All surface densified PM materials failed by pitting. The pittings look very similar to the damages in the wrought steel reference material [4]. Two types of cracks were found in the tested surface densified PM materials, i.e. small surface cracks and longer subsurface cracks running parallel to the surface, Fig 5. All the cracks were found within the densified zone. It is believed that the subsurface cracks develop to pitting damages. The small surface cracks are propagating due to the shear stresses at the surface (sliding of –24%) with a defined angle of approximately 30° into the material, Fig. 5.



Sub surface cracks Surface cracks Pitting damages

Fig. 5: Subsurface cracks, cracks at the surface and pitting damages

5 Subsurface stress distribution

The subsurface stress distribution can be calculated for homogeneous materials using analytical formulas [20]. The contact pressure results in a three-dimensional stress field beneath the contact surface with a maximum stress in a certain depth [21, 22] taking into account only low friction forces. The subsurface stress distribution is often expressed in terms of the von Mises stress in order to give an indication about the depth of the stress maximum and the allowable load. The subsurface stress distribution is mainly effected by the geometry of the mating bodies, the density respectively the Young's modulus and the Hertzian pressure itself.

In order to calculate the stress distribution of such surface densified materials with inhomogeneous Young's moduli the analytic formulas cannot be used. For this application the stress distribution was calculated using a Finite-Element-Model. Fig. 6 shows the density and the hardness distribution for the surface densified rollers of Distaloy DC-1 (B). The Young's modulus distribution was calculated on basis of the density distribution by using the formula for sintered steels [23]:

$$E = E_0 \cdot (\rho / \rho_t)^{3.4}$$

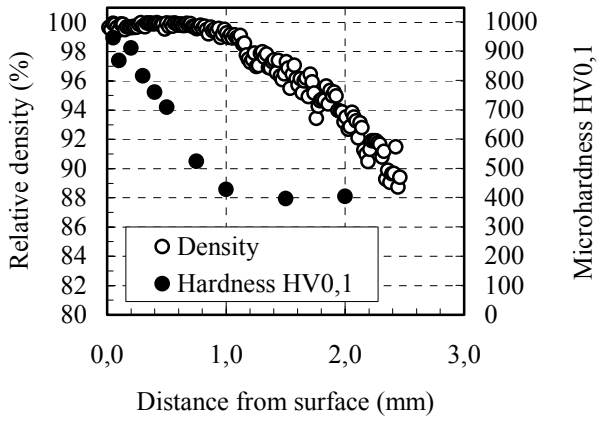


Fig. 6: Density and hardness distribution for the investigated alloys

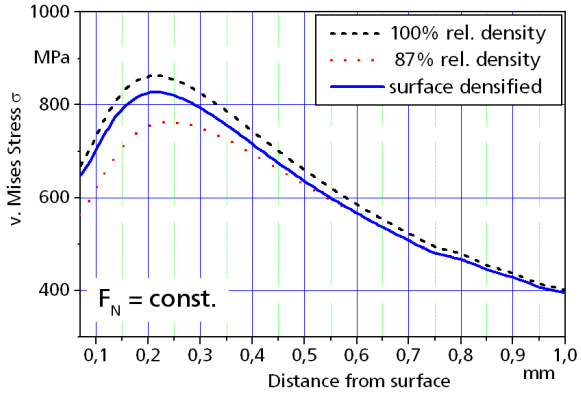


Fig. 7: Comparison of the sub surface stress distribution of fully dens, surface densified and porous (relative density of 87%) material.

The stress distribution is shown in Fig. 7 for homogeneous full density (100%), a relative density of 87%, which is the relative density in the core of the investigated samples, and for the surface densified PM material. For all calculations the same load was applied. The stresses distribution of the full density material result in the highest subsurface stresses whereas for the relative density of 87% the stresses are lower. For the densified PM material the maximum subsurface stress is about 4% lower than for the full density material applying the same load. In a depth of about 0.5 mm the stress distribution of the densified material converge at the stress distribution of the as sintered one.

6 Discussion on design aspects for rolling contact fatigue conditions

Comparing Materials A and B indicates that it is more important to have a high surface hardness than core hardness. However, material C that endured the highest Hertzian pressure of the investigated materials is characterised by high core and surface hardness. Unfortunately, the results are showing a high scatter. The results indicate that high core and surface hardness is beneficial for the rolling contact fatigue properties.

Fig. 8 compares the endurable Hertz pressure of PM materials manufactured by cold compaction, warm compaction, surface densification and powder forging. The wrought steel reference material is also included. The rolling contact fatigue performance of surface densified and case hardened materials are radically improved compared to the performance of the non-densified PM materials with similar compositions. It can also be seen that surface densified PM components performs

similarly under Hertzian pressure as powder forged components. That leads us to believe that a moderate density level (7.0-7.2g/cm^3) is sufficient for components that are to be surface densified.

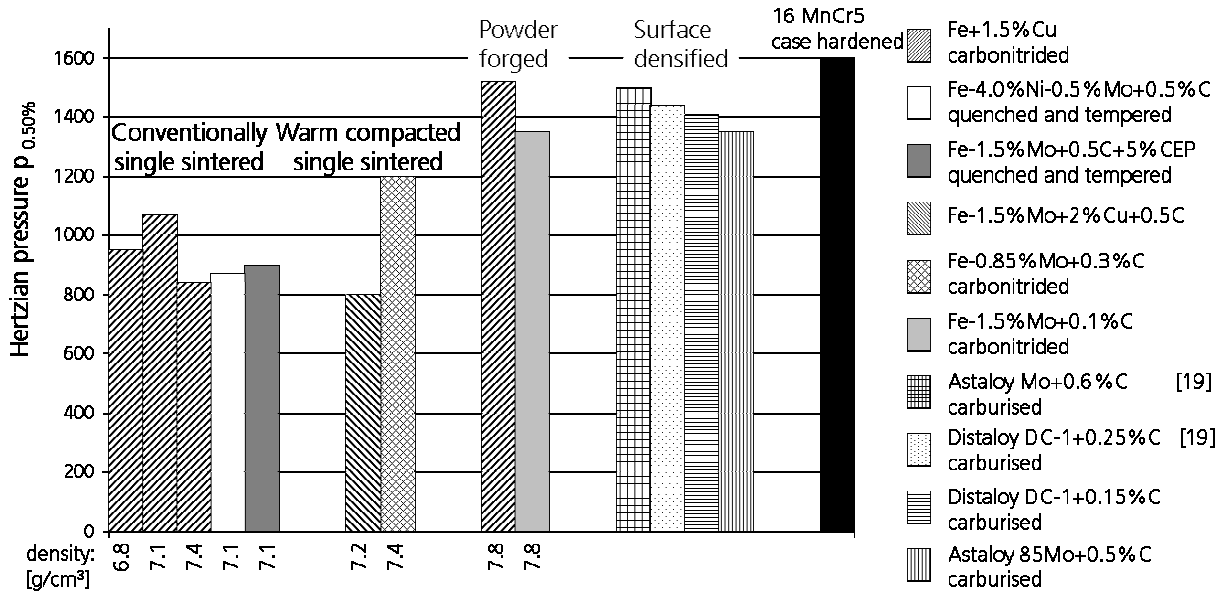


Fig. 8: Comparison of endurable Hertzian pressure

The surface densified materials result in the same endurable Hertzian pressure than for the powder forged PM steels and both are very close to the case hardened wrought steel. Based on the endurable load, the surface densified PM-steels are superior compared with the powder forged PM-steels due to the stress distribution. The same endurable Hertzian pressure results in higher transferable loads, which is relevant for service applications.

7 Conclusions

The presented results show that the rolling contact fatigue behaviour of selectively densified and case hardened PM materials is very close to wrought steels. The more expensive powder forging procedure will not result in higher endurable Hertzian pressures.

For real applications the gap between PM-materials and wrought steel regarding rolling contact fatigue behaviour will be smaller based on the transferable loads and therefore surface densified gears should be considered as a possible and economic alternative to wrought steels.

Following conclusions can be summarized:

- The rolling contact fatigue behaviour of PM components is radically improved by surface densification and approaches the level of wrought steels.
- Surface densified PM components have very similar subsurface stress distribution under contact pressure steels as wrought steel. Hence, the same guidelines regarding for example case depth, surface hardness, residual stresses and other design parameters can be used for surface densified components as for wrought steel.
- The failure mechanisms for surface densified components that are exposed to rolling contact fatigue are very similar to the failures in wrought steel.
- The surface densification technique is an economic procedure compared to conventional machining and also to powder forging.

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