Material aspects of selectively densified transmission gears

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Abstract - In order to increase the fatigue properties in the flank and the tooth root regions of PM gears a selective densification can be performed. Previous investigations have shown a substantial improvement of gear performance by utilising this technology and commercial production has been established. This paper describes the relation between material properties and densification as well as some results with powders of different types and alloying systems. The feasibility and influence on quality of the processing steps were also considered and the fatigue life of gears was discussed.

KEYWORDS: POWDER METALLURGY, GEARS, SELECTIVE DENSIFICATION, GEAR LOAD CAPACITY.

I. INTRODUCTION

Gears made from wrought steel are used in many types of applications. The properties of the gears are designed to meet the requirements of the respective applications. Powder metallurgy (P/M) gears can compete with wrought gears when the requirements are low or moderate. High performance gears were until recently exclusively made from case hardened wrought steel. The key properties are the tooth root (bending) endurance limit and the gear flank endurance limit. By selectively densifying the flank and the root, these properties can be improved to a level comparable to wrought steel, see e.g. [1-4].

The process anticipated for the surface densified gears includes; compaction, sintering, selective densification, case hardening and possibly a final grinding depending on quality level required.

The successful rolling process requires a soft material with sufficient core hardness in order to allow the densification of the surface region while macro deformation is prevented. In order to reach a high final hardness, the material must exhibit good hardenability and case hardening behaviour. These demands are to a degree contradictory, since good hardenability is usually associated with high hardness for a given carbon level. Furthermore, when the density of the surface layer increases towards full density, some other properties, such as notch sensitivity and surface roughness become more significant.

One of the inherent advantages of P/M material is the possibility to tailor the powder mix to the application. In the present work the properties influenced by the P/M process and the selective densification are reviewed with emphasis on the properties depending on the material itself.

II. MANUFACTUING PARAMETERS

Rolling capability

The ability to deform without creating cracks or other defects during the selective densification process depend to a significant degree on the type and character of the densification process itself. Since P/M materials normally exhibit a limited deformation to fracture in a tensile test, processes with mainly compressive stresses are preferred. In this case, the hardness is the most important parameter. A lower hardness gives lower forces and less elastic deformation of the component. However, if the elastic deformation of the components can be constrained, it is possible to selectively densify relatively hard materials. The relation between applied force and the decrease in work piece diameter is shown in Figure 1. If the number of passes increases to much, a fatigue type defect may occur. Furthermore, the strength of the core must be sufficient to endure to loads created by the densification.

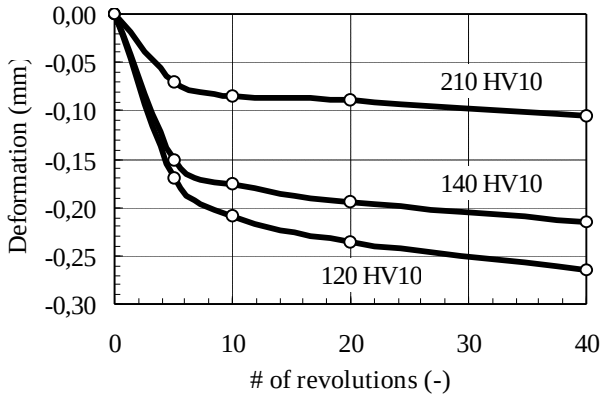


Fig. 1. Decrease in diameter versus number of revolutions during the densification of 10 mm wide rolls for three different materials. The diameter of the work piece was approximately 30 mm and the tool rolls 170 mm.

Dimensional scatter

The tolerances for pressed and sintered components under favourable conditions (IT6-7) do not impart any restrictions for the material selection. However, if the conditions are unfavourable or if high temperature sintering with extensive liquid phase formation is employed (IT8->) there may be a problem with the scatter in dimensions. If the process requires the component to be densified to measure, a scatter of a few hundreds of a millimetre may be significant. The severity of this restriction depends on the geometry of the component. If there is a

lot of material that can be densified, it will be less serious, while if the volume and strength of the material is low it may turn out to be a limiting restriction.

Case hardening

The case hardening of a selectively densified material must be performed with some care. The densified layer is created in order to bear the load and must therefore have a high carbon content. However, the diffusion rate in the core is significantly higher compared to the densified layer. If the combination of geometry, surface and core density is unfavourable, it may happen that the diffusion path through the sides and the centre hole will be quicker than through the densified layer. This may result in a hardness profile that will show a dip at the inner portion of the densified layer, see Figures 2 to 4. This phenomena can be counteracted in a number of ways; the sides and the centre hole can be masked, so that the carbon diffusion is stopped or the core density can be increased so that interconnected porosity is not present.

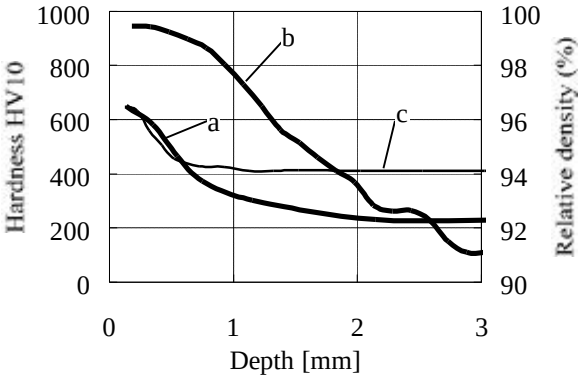


Fig. 2. a) Hardness profile for Astaloy A + 0,2C, b) Density profile for Astaloy A + 0,2C, c) Hardness profile for the reference material case hardening steel DIN 16MnCr5.

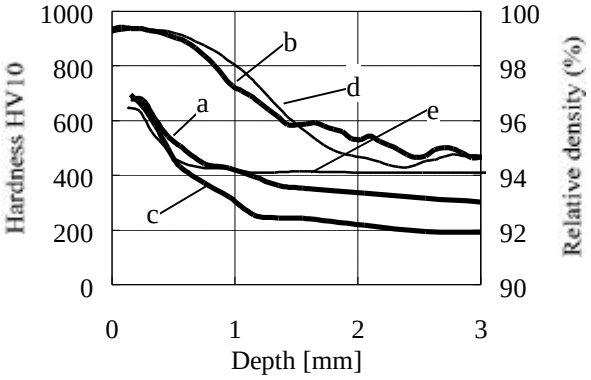


Fig. 3. a) Hardness profile for Astaloy Mo + 0,25C, b) Density profile for Astaloy Mo + 0,25C, c) Hardness profile for Astaloy 85 Mo + 0,25C, d) Density profile for Astaloy 85 Mo + 0,25C e) Hardness profile for the reference material case hardening steel DIN 16MnCr5,

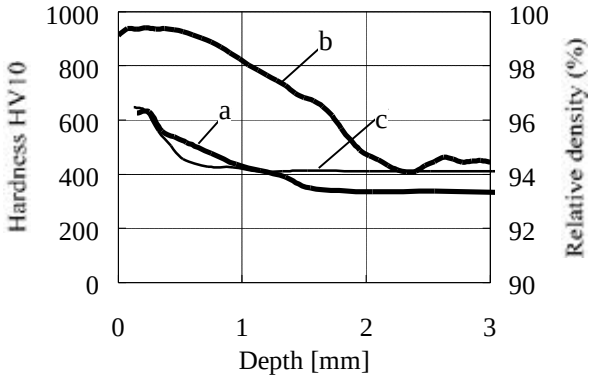


Fig. 4. a) Hardness profile for Distaloy DC + 0,25C, b) Density profile for Distaloy DC + 0,25C, c) Hardness profile for the reference material case hardening steel DIN 16MnCr5.

The hardness profiles for four different selectively densified P/M materials are shown in Figures 2 to 4. It can be seen that the maximum hardness at the surface matches the reference material well. The Astaloy Mo (Fe+1,5Mo) and Astaloy 85 Mo (Fe+0,85Mo) based materials exhibit an almost identical maximum hardness level, see Figure 3. The Astaloy A (Fe+1,9Ni+0,55Mo+0,2Mn) exhibits a slightly lower maximum hardness due to the lower graphite content, see Figure 2. The Distaloy DC also exhibits a slightly lower maximum hardness, but in this case due to the presence of retained austenite. The Astaloy 85 Mo exhibits a lower hardness in the core due to the lower level of hardenability resulting from the lower level of alloying elements.

III. GEAR PERFORMANCE FACTORS

The load capacity of P/M gears is not yet covered by national- or international standards, as it is comprehensively done for wrought gears. An opportune way to calculate the load capacity of P/M gears may be to conduct an approximate calculation according to standards for wrought gears, focusing mainly on the factors influenced by the material selection and the densification process. The uncertainty of such an approach is of course not known at present and must be estimated by gear testing.

By using a part of the gear calculation standard [5], the factors limiting the gear performance can be structured. The safety factor against gear flank pitting (S_H) and tooth strength (S_F) can be used as figures of merit. Both safety factors are defined as the "corrected" endurance limit divided by the nominal stress. These "corrections" take into account a number of factors and influences. In this report, only factors special to using selectively densified P/M gear are taken into account. A more detailed presentation of the factors is found in the standard [5].

$$S_H = \frac{\sigma_{HG}}{\sigma_H} = \frac{\sigma_{Hlim}\, Z_{NT}\, Z_L\, Z_V\, Z_R\, Z_W\, Z_X}{Z_B\, \sigma_{H0} \sqrt{K_A\, K_V\, K_{H\beta}\, K_{H\alpha}}} \qquad (1)$$

$$S_F = \frac{\sigma_{FG}}{\sigma_F} = \frac{\sigma_{Flim}\, Y_{ST}\, Y_{NT}\, Y_{\delta\, rel\, T}\, Y_{R\, rel\, T}\, Y_X}{\sigma_{F0}\, K_A\, K_V\, K_{F\beta}\, K_{F\alpha}} \quad (2)$$

$$\sigma_{H0} = Z_H\, Z_E\, Z_\varepsilon\, Z_\beta \sqrt{\frac{F_t}{d_1\, b}\,\frac{u+1}{u}} \quad (3)$$

$$\sigma_{F0} = \frac{F_t}{b\, m_n}\, Y_F\, Y_S\, Y_\beta \quad (4)$$

$$Z_E = \sqrt{\frac{1}{\pi\left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}\right)}} \quad (5)$$

The major factors that are directly related to density, material and heat treatment are σ_{Hlim} and σ_{Flim}, the gear flank endurance limit and tooth root endurance limit respectively. Both these properties improve with increasing density [6,7]. If the rate of improvement from axial fatigue can be considered, an increase in density from 7,25 to 7,35 g/cm^3 can increase the axial fatigue strength with 10 to 20% [8], the smaller value for high strength materials. This means that since the densification can increase the density from 7,2 g/cm^3 to near full density, substantial improvements in fatigue behaviour can be expected. The two load cases that are considered here, flank and root, are both strongly influenced by residual stresses. It is possible to create compressive residual stresses in the zones that have the highest tensile stresses during operation. This means that the heat treatment (case hardening) must be optimised for the material and the density profile obtained, in order to create the desired residual stresses.

The load distribution on the teeth and gear mesh ($K_{H\beta}$, $K_{F\beta}$, $K_{H\alpha}$, and $K_{F\alpha}$), are related to the elastic modulus and therefore the density. The nominal stress as described by σ_{H0} depends strongly on the elasticity factor Z_E. In fact, because the contact area increases when the modulus decreases, the nominal load decreases. This means that the contact stress on the gear will be lower for a P/M gear compared to a fully dense gear. It also means that when comparing the gear flank endurance limit or rolling contact fatigue values, the Hertzian stress values must be recalculated into load transferred by the gear. The Z_E factor decreases by 5% if a selectively densified gear with core density of 7,3 g/cm^3 is run against a fully dense gear compared to a situation with two fully dense gears.

The material combination factor (Z_W) depends on the material selected. However, the information available regards typical wrought case hardening steels and the properties of typical P/M steels are not known at present.

The notch sensitivity factor ($Y_{\delta\, rel\, T}$) and surface notch sensitivity factor ($Y_{R\, rel\, T}$) are controlled by the manufacturing process. It is well known [9] that the notch sensitivity for P/M components is low for low to moderate densities, an advantage that decreases as the density increases. The surface notch sensitivity factor can be improved by reducing the surface roughness in the tooth root and or by shot peening of the tooth root.

Pitting resistance test

The rolling contact fatigue is the test parameter that is most closely related to the tooth flank endurance limit with the exception of gear tests. In order to evaluate a selectively densified material a rolling contact fatigue test was performed. The test is set-up as a pitting resistance test. It was performed on an SKF-ERC roller to roller test rig. The counter roller is indented with a Vickers hardness indenter in order to create defects on the roller surface that will accelerate the start of the pitting of the test roller.

The test material was pressed to 800 MPa in order to achieve a sintered density of 7,2 g/cm3. The test pieces were sintered at 1120 ^{o}C for 30 min in a 90% N_2 and 10% H_2 gas. The rollers were densified to a depth of 0,9 mm, see Figure 2a. In the "fully dense" region, there are a few pores with significant distances between them. The density measured by image analysis in this region above 99% is probably to low. The real density is very near 100%. The density gradually falls to a distance of 3 mm from the surface were the bulk density is reached. The specimens were solution treated at 920 ^{o}C in carburizing atmosphere (C-potential 0,8%C) for 30 min, quenched to RT in oil and tempered at 160 ^{o}C for one hour in air.

The tests were made as a comparison test. The DIN standard 16MnCr5 wrought case hardening steel was used as a reference material. This was compared to the sintered material Astaloy A with 0,2% graphite. The test parameters are shown in Table 1.

Table 1. Test parameters

Parameter	**Value**
Radius of load ring	45,25 mm
Crowning radius of load ring	30 mm
Radius of test ring	15,25 mm
Crowning of test ring	∞
Lubricant	Shell Spirax HD80W/90
Lubricant temperature	80 ^{o}C
Velocity of test ring	10045 rpm
Slip on the test ring	-8%
Applied force	1,7 kN
Number of revolutions	$7 \cdot 10^6$

The same load was applied for the two materials. This means that the contact pressure for the P/M roller is somewhat lower due to the lower elastic modulus. It requires a detailed analysis to estimate how much lower it is since the surface layer has a density profile according to Figure 2 and the contact pressure analysis becomes complicated.

The damage, see Figure 5, was evaluated using the damage length as an approximation of total damage. A line was drawn in the middle of the running track of the test ring. The parts of the line that were damaged were

measured and added together to get the total damage length of the test ring.

The damage lengths were 5,6 and 5,5 mm for the Astaloy A and reference materials, respectively. The damage in both cases is pitting.

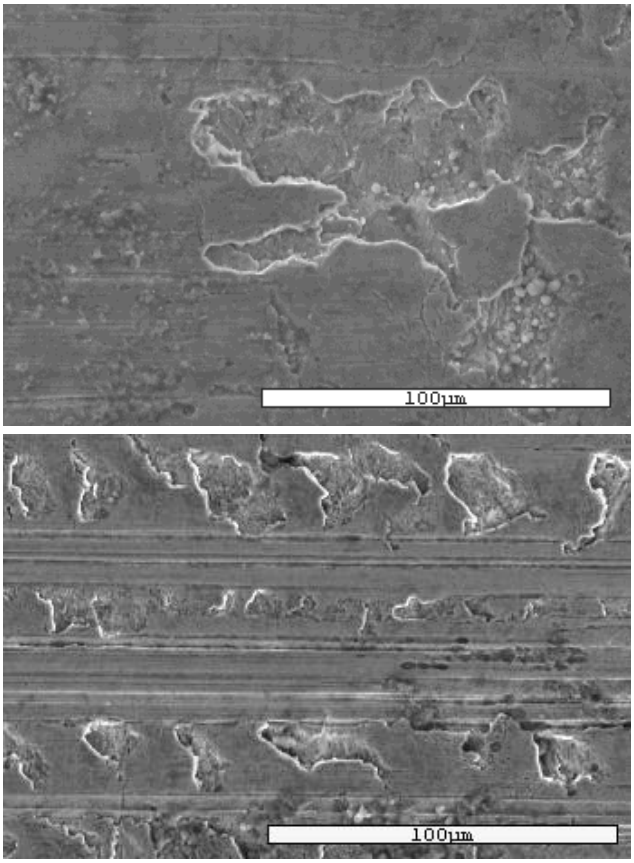


Fig 5. SEM micrograph of damage on tested rollers. Top: Selectively densified Astaloy A. Bottom: Reference material 16MnCr5.

IV. CONCLUSIONS

The selectively densified and case hardened P/M material is compared to a wrought case hardening steel commonly used for gears (DIN 16MnCr5).

- The gear flank endurance limit and the tooth root endurance limit are strongly improved by the densification. The selection of material plays also an important role.
- Selectively densified and case hardened rollers can achieve the same pitting resistance as the reference material.
- The material must be relatively soft for the densification to be successful. If the component is weak, the material must be very soft.
- The hardenability of the pre-alloyed powders is utilised in the case hardening operation. In fact the degree of hardenability can be used control the hardness profile for a particular component.
- The pressed and sintered dimensional scatter should be low enough for the rolling operation to take place without any finishing prior to densification.
- The hardness profile of the reference material can be matched by the selectively densified P/M material by optimising the case hardening and the carbon content and density of the core material.

References

[1] Y. Takeya, T. Hayasaka, M. Suzuki: Surface rolling of sintered gears, Met. Powder Rep., **37**(1982), pp467-470.

[2] C. M. Sonsino, R. Mueller: Int. J. Fatigue, **14**(1992), pp3-13.

[3] Y. Itoh, Y. Takeda, N. Motooka, Y. Kureha: Met. Powder Rep., **44**(1989), pp702-706.

[4] P.K. Jones, R. Buckley-Golder, R. Lawcock, R. Shivanath: In: Advances in Powder Metallurgy & Particulate Materials - 1996, Vol 4, Part 13, (1996), pp13.439-13.451.

[5] German standard DIN 3990 (December 1987) - Calculation of load capacity of cylindrical gears. Beuth Verlag, Berlin.

[6] K. Lipp, C. M. Sonsino, D. Pohl, W. Brandt: In: Powder Metallurgy Worl Congress (PM 94'). Vol, 2, Paris, France, 6-9 June, (1994), pp831-834.

[7] M. Kobayashi, A. Kamada, R. Iwamura, T. Hayasaka: Int. J. Powder Metall., **21**(1978), pp143-148.

[8] S. Bengtsson: In: 2000 International Conference on Powder Metallurgy & Particulate Materials, Part 6, NewYork, May 31-June 3, (2000).

[9] C. M. Sonsino: Powder Metall., **33**(1990), pp235-245.