Application requirements and material selection of surface densified P/M gears for automotive gearboxes

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ABSTRACT

The high dimensional and mechanical requirements have in the past limited or prohibited the use of gears produced by powder metallurgy for automotive transmissions. The introduction of a technique for selectively densifying the highly loaded regions of the gear provides a production route for high performance gears. The present work is part of a larger program that aims at demonstrating the feasibility, quality and economics of producing surface densified P/M gears for automotive gearboxes. The selected gear is the 5th gear (fixed) from a line of gearboxes for Renault passenger cars. It is characterised by a helical angle of 30^{o}, it has 31 teeth and internal splines. In order to select a material a series of surface densified rollers were manufactured and tested for rolling contact fatigue strength. The results show that the Distaloy DC1 can match the solid steel reference material. The investigations were carried out as part of a project funded by the European Commission under the "Competitive and Sustainable Growth" program (Project No: GRD1-1999-10674).

BACKGROUND

In the past decades the power transmission gears have been required to survive increasing engine power and higher car weights. At the same time there is an increased pressure on costs. This means that not only must the performance and quality be very high, the gears must also be less expensive for the end user.

Traditionally, powder metal technology has provided a successful path towards lower component cost for mass produced high quality components. However, the very high demands on performance, especially in terms of fatigue life at high loads, could not be met so far [1-5]. By introducing surface densification as a means to increase performance to solid steel levels, a new class of cost effective components can be created [6, 7].

The HIGHDENS project was started with the aim of demonstrating the critical steps in the production of surface densified PM transmission gears. The project consortium consists of a powder manufacturer, two parts producers, two end users and a university that together provides wide knowledge base of all steps in the proposed manufacturing chain.

The gear selected for investigation is the 5:th fixed gear in a 5-speed gearbox manufactured by Renault. Some of the requirements on the gear are shown in Table 1 together with selected gear data. The current manufacturing process was analysed and a process for the production of surface densified PM gears was proposed as shown in Table 2.

Type of gear	5:th speed fixed gear
Number of teeth	31
Centre distance (mm)	66
Helix angle	30°
Module (mm)	1,6

Table 1. Gear selected for the investigation.

There are two major factors governing the behaviour of P/M components; microstructure and density. Most gears are case hardened, resulting in a very hard martensitic surface layer and a tougher core. The heat treatment also results in compressive residual stresses, further increasing fatigue performance. The remaining option to improve fatigue performance is to increase density, preferably to full density. Selective densification is an alternative where the most loaded regions are densified to virtually full density, while maintaining the advantage of high dimensional accuracy of powder metal components. One of the objectives of this study is to investigate how effective the densification is in increasing the fatigue properties [6-8]. Other secondary objectives are to show how the application requirements relate to the powder properties and the process.

	Wrought steel gears *(current situation)*	**Sintered and rolled gears** *(target of the project)*
Material:	Forged blank	Powder mix
Forming:	Turning Hobbing Broaching	Compacting Sintering
Fine forming:	Shaving	Rolling
Heat treatment:	Case hardening	Case hardening
Hardfinishing:	-	Required?

Table 2. Major production steps for current and proposed manufacturing processes. Cleaning, deburring and marking steps are not shown in the table.

APPLICATION REQUIREMENTS

The fatigue requirements on the selected gear are quite high. The currently used gear is manufactured by a typical case hardening steel using mature, well optimised, machining and heat treatment processes. This means that the performance and quality of the gear is quite high. The major requirements are durability, expressed as tooth root and tooth flank fatigue endurance, and geometrical quality, expressed as e.g. DIN gear quality class.

SURFACE DENSIFICATION

The performance of pressed and sintered P/M components cannot reach these levels without special processes. One such process is surface densification by rolling as shown in Table 2. The gear is rolled between two gear-like tool rollers plastically forming the flank, root and sometimes the tip of the teeth. The gear is rolled in a soft (as-sintered) state and normally a case hardening operation is performed to carburize the surface and create the desired microstructure. As a consequence the stresses from rolling are annealed out. The result of the process is a selective densification of flank and root and an improvement of the gear quality.

MATERIAL SELECTION

The process routes of the current process as well as the proposed process for surface densification are shown in Table 2. A systematic material selection process is shown in Table 3. In a real case more aspects of powder properties must be taken into account. More general powder properties can be found in [9]. The critical property is in this case the durability of the gear during operation. However, tooth root and tooth flank fatigue data are not available, while rolling contact fatigue data are. The rolling contact fatigue test is designed to simulate the most loaded region in the gear contact [1-5] and the data is intended to be used for process and material selection purposes.

Process step	Property	Result
Compaction	Higher compressibility	Higher core density
	Better lubricant	Defect free parts with good surfaces
	Faster flow	Better density distribution and higher productivity
	Higher apparent density of powder	Lower fill height → easier ejection → better surfaces
Sintering	Lower scatter in dimensional change	Lower scatter in part dimensions
	Higher sintering temperature	Better core strength, higher modulus
	Lower sintering temperature	Smaller scatter in part dimensions
Rolling	Lower hardness	Smaller elastic deflection → easier calculation of tooling → faster development Higher densification near the surface → better fatigue performance
	Small dimensional scatter	Better process robustness
Heat treatment	Alloy chemistry	Higher hardenability →Lower cooling rate needed → Larger parts are possible Higher hardness in the core Should suppress formation of carbides Should not oxidize during heat treatment Should be possible to carburize to 0.8 wt.C in the surface

Table 3. Powder selection chart for the process outlined in Table 2. Some important parameters for material selection and their influence on various aspects for surface densified components

In the project a number of materials were selected for screening. In Table 4 the candidate materials are listed with some characteristic data. The base powders are selected from different types of powders. The N1 is a pre-alloyed powder with relatively low compressibility while the hardening behaviour is quite good. The microstructure near the surface of a case hardened part is martensitic with some retained austenite. Further into the part the microstructure changes into a pure bainitic structure. The N2 powder is based on pure iron powder with Ni, Cu and Mo diffusion bonded to the iron particles. This powder has excellent compressibility while the hardening behaviour at high densities is more uncertain. The resulting microstructure is heterogeneous with martensite, austenite, bainite and pearlite. Generally a homogeneous microstructure is desired for hardened components at high densities. In the N3 powder Ni is also diffusion bonded, but in this case to pre-alloyed powder

(1.5% Mo). This powder has good compressibility and high hardenability. The degree of heterogeneity is smaller than for the N2 powder. The microstructure is martensitic near the surface with some Ni-stabilized austenite. Moving further into the part the martensite turns first into a mixture of martensite and bainite (with some Ni-stabilized austenite) and finally into bainite (also with austenite).

Code	Material	Compacted density (g/cm^3)	Sintered density (g/cm^3)	Densification depth* (mm)	50% Endurance limit (MPa)
W1	16MnCr5 (0.16C + 0.8Cr + 0.8Mn + 0.25Si)	(solid)	(solid)	-	**100%**
R1	Distaloy DC-1+0.3wt.% C ($2Ni^{+} + 1.5Mo^{++}$)	7.05	7.10	-	78%
N1-A	Astaloy A + 0.2 wt.%C ($1.9Ni^{++} + 0.55Mo^{++} + 0.2Mn^{++}$)	6.90	6.95	0.3	(92%) **
N1-B				0.6	(96%) **
N1-C				1.0	101%
N2	Distaloy AE + 0.15wt.%C ($4Ni^{+} + 1.5Cu^{+} + 0.5Mo^{+}$)	7.10	7.16	1.0	96%
N3	Distaloy DC-1+0.15 wt.%C ($2Ni^{+} + 1.5Mo^{++}$)	7.05	7.12	1.0	105%

* defined as the point where 98% of full density is reached.
** The number of tests is not enough to establish a reliable endurance limit.
\+ Diffusion bonded to the base powder particles
++ Pre-alloyed

Table 4. Endurance limit of the tested material and densification variants. The compacting pressure was 550 MPa and sintering was performed at 1120 ^{o}C for 30 min in endogas atmosphere using a carbon potential of 0.3 wt%C

Rolling contact fatigue tests

The materials were compacted at a moderate compaction pressure of 550 MPa in order to simulate the density levels that were believed to be achievable using a helical gear tool with a high helix angle (30^{o}). The densities achieved are shown in Table 4. Cylinders with the geometry shown in Figure 2 were used for the densification, hardenability and rolling contact fatigue tests. The surface densification was performed by compressing the blank between two tool rollers while rotating. The target densification depth was set to 1 mm for the rollers and by using different rolling parameters the target was met. The densification profile for the N1-C variant is typical of the profile for the other materials. An attempt was also made to investigate the influence of "incomplete" densification of the rolling contact fatigue performance as shown in Figure 2.

The materials were case hardened in a commercial furnace using a standard heat treatment cycle. The resulting hardness profiles are shown in Figure 3.

The selected materials were tested in a rolling contact fatigue test rig [3, 4]. The test rig is designed to simulate the gear contact at a point where pitting damage occurs. It is lubricated with SAE 80 oil at $80^{o}C$ at the contact point. Two of the tests were not completed; the samples with "incomplete" densification, N1-A and N1-B, were interrupted before a reliable endurance limit was reached. However, the results are very clear with the reference material at 2075 MPa as shown in Figure 4. This value was actually exceeded by the N3 at 2175 MPa followed by N1-C and N2 materials. The N1-B and N1-A trailed at approximately 2000 and

1900 MPa respectively. The failure mode was in all cases pitting on the tested surface. The P/M reference material (without densification) exhibited an endurance limit of 1625 MPa.

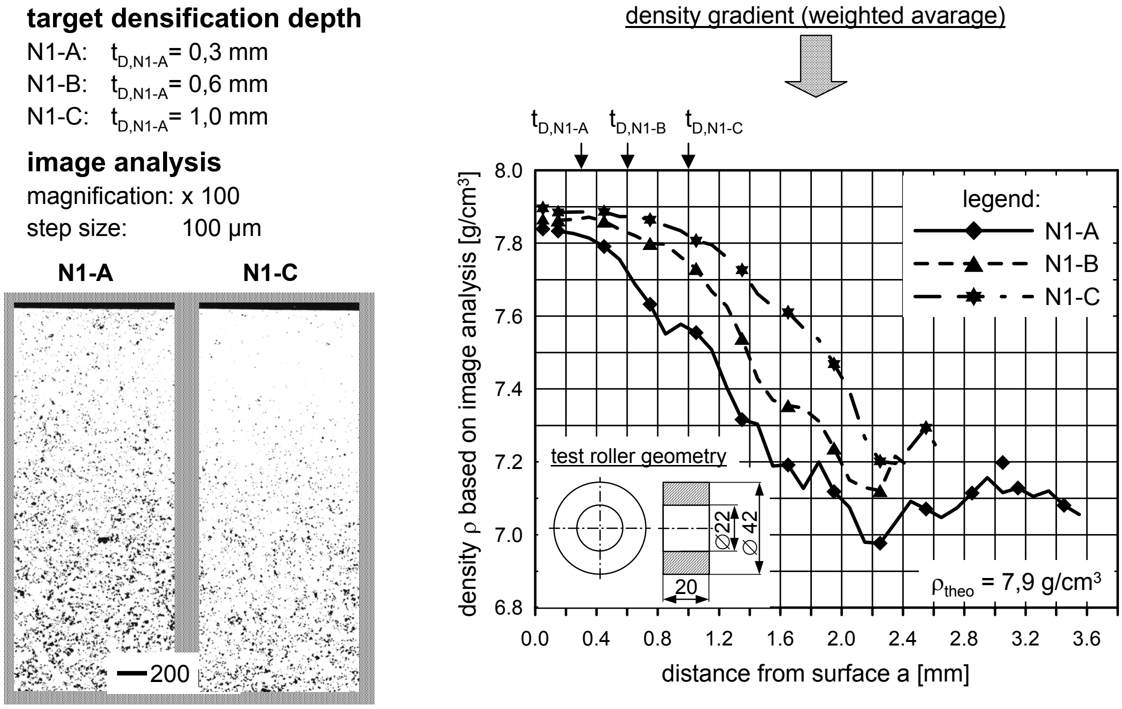

Figure 2. Density gradient measured by image analysis of variants N1-A,B,C

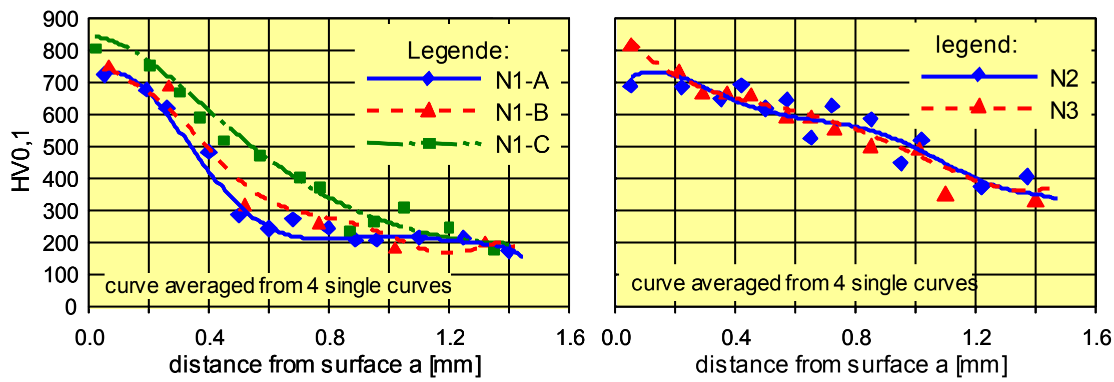

Figure 3. Micro hardness profiles of the tested materials.

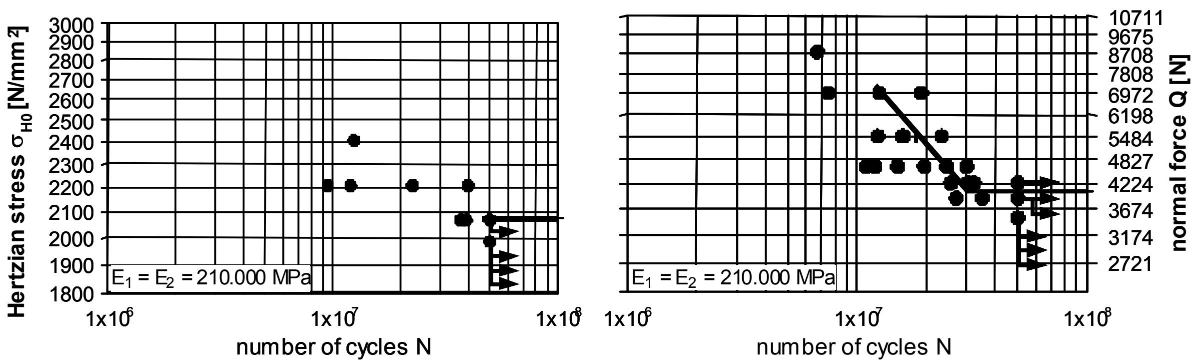

Figure 4. S/N diagrams of the reference material, 16MnCr5 (left) and the N3 material (right).

SURFACE DENSIFIED GEARS

The homogeneous material N1 should perform well at high densities, but its low compressibility is a drawback, especially for the properties of the core. The N2 has a higher compressibility but due to its inhomogeneous microstructure it is less well suited for case hardened applications. The N3 material is less inhomogeneous compared to the N2 material while the compressibility is quite high. It has the best RCF performance of the tested materials and is selected for further tests with gears.

CONCLUSIONS

- It was shown that surface densified rollers could be successfully manufactured and that they exhibit excellent fatigue properties.
- The performance of different materials was investigated and criteria for materials selection was presented.
- The pre-alloyed based powders performed well with the Distaloy DC material even exceeding the RCF endurance limit of the wrought steel reference material by 5%.

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REFERENCES

1 Lipp, K; Hoffmann, G, Design For Rolling Contact Fatigue, International Journal of Powder Metallurgy. Vol. 39, no. 1, pp. 33-46. Jan.-Feb. 2003.

2 Sonsino, C M; Lipp, K, Rolling contact fatigue properties of selected PM-materials for gear-box applications, SAE Transactions: Journal of Materials & Manufacturing. Vol. 108, pp. 250-261. 1999

3 Dautzenberg, N; Lindner, K H; Strehl, R, Comparison of conventionally manufactured gears with PM gears manufactured in single or double sinter process--technical and economical aspects, Powder Metallurgy World Congress (PM '94). Vol 1; Paris; France; 6-9 June 1994. pp. 43-46. 1994

4 Klocke, F.,Kotthoff, G., Wälzfestigkeits- und Tragfähigkeitsuntersuchungen an gesinterten hochdichten Rollen und Zahnrädern, Bericht zur 39. Arbeitstagung „Zahnrad- und Getriebeuntersuchungen", RWTH Aachen 1998

5 Petersen, J; Beiss, P, Effect of the core carbon content and density on the rolling contact fatigue of Distaloy HP-1, EURO PM2001: 2001 European Congress and Exhibition on Powder Metallurgy; Nice; France; 22-24 Oct. 2001. pp. 356-362. 2001.

6 Y. Takeya, T. Hayasaka, M. Suzuki, ”Surface rolling of sintered gears” , Met. Powder Rep., 37, (1982), pp467-470.

7 P.K. Jones, K. Buckley-Golder and D. Sarafinchan, “Developing P/M gear tooth and bearing surfaces for high stress applications” , Advances in Powder Metallurgy and Particulate materials (1997), Vol 1, pp33-43.

8 R. Lawcock, K. Buckley-Golder and D. Sarafinchan, “ Testing of High Endurance PM Steels for automotive gearing components” , SAE conf., Int. Congress & Exposition, March 1999, Detroit, MI, USA, pp15. (SAE No: 1999-01-0293)

9 Höganäs Iron and Steel Powders for Sintered Components, Materials data book published by Höganäs AB, Höganäs, Sweden.