# Shape Distortion and Tooth Root Bending Fatigue Strength Obtainable with Various Hardening Process Routes of Ring Gears made of PM Material.

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**ABSTRACT:** Ring gears are used in a planetary gear system to transfer torque from one axis to another. During this transfer the resulting gear forces cause tensile, compressive and contact stresses, which must not exceed permitted values and fatigue stress limits of the material used. To reach necessary fatigue stress levels on gears, i.e., on flank and root, and also to improve tribological performance during gear contact, a number of well-known processes such as heat treatments can be selected. However, this selection can be limited by the impact on possible distortion of the gear geometry. It is therefore important that both the strength and the geometry, such as dimensions, shape and runout can meet the given specifications. Today, ring gears are in general made from steel forged preforms and undergo a substantial number of expensive machining processes prior to heat treatment. The ring gear design and its critical tolerances, such as runout, are set in order to also minimize gear noise. Ring gears made from PM can be made near to net shape and help to substantially reduce the machining and total cost per unit. In this investigation, different hardening processes have been applied on gears and the influence on shape distortions and fatigue stress limits were determined.

***Key words*:**
Ring Gear, Fatigue, Powder Metallurgy

## 1. Introduction

A planetary gear system, such as epicyclic gearing, consists in its basic form of four components (sun gear, annulus gear, planet gear and planet carrier) that, when interacting, are able to generate a wide range of speed ratios in a very compact design. Compared with a parallel shaft gear, the planetary gear system design means savings both in weight and space [1].

The planetary gear system has been widely used for a long time in the automotive industry for transmissions, especially in passenger cars for automatic transmission (AT). The AT is the most common and dominant type of transmission in the US and will most likely be so until 2025, where today six-speed transmissions are regarded as standard in the market, while seven-, eight-, nine-speed transmissions are also in production, all using several planetary gear systems [2].

The largest gear component of the planetary gear system, in terms of diametric dimension, is the annulus gear, also called the ring gear, where the teeth are situated on the ring inside, i.e., an internal gear. A common way to manufacture gears includes some type of machining, often from a wrought steel preform. However, internal gears are more complex to machine, compared with a plain and “normal” external gears, and the type of suitable machining tools are fewer. Internal gears like the ring gear, are not subject to being machined and shaped with a “hob” tool [3]. When gear teeth geometries become more complex, for example, from rake spur to helical, the machining ways, i.e., cutting methods and tools, have to be further developed and thus are often more expensive to for achieving high production rates and volumes. This constant development has brought machining types from gear shaper, to broaching, pinion skiving and to super skiving [4][5].

A way to get around the expensive, complex and time-consuming machining of every manufactured ring gear is by using PM technology. By manufacturing one tool of complex geometry, this single pressing tool can generate a large number of ring gears in near net shape at a high production rate by powder compaction.

Regardless of manufacturing method, whether from wrought or PM steel, the requested performance of the ring gear must be fulfilled in terms of properties such as fatigue stress, stiffness and surface hardness. Feasible ways to increase and improve these properties are usually found with some kind of heat treatment process. These

heat treatments could be divided into processes with the addition of external element diffusion techniques such as surface hardening with carburizing or nitriding, but without external diffusion like plain heating followed by quench and tempering in order to establish through hardening [6][7][8][9]. Depending on the choice of heat treatment, beneficial compressive residual stress, with respect to improved fatigue properties, could be established close to the surface of important parts such as gear teeth, flank and root.

Some diffusion heat treatment techniques are found to be suitable for PM components. With furnaces equipped with low pressure carburizing (LPC) it is possible to control carbon profiles but also handle oxidation-sensitive materials such as Cr-alloys [10][11]. By selecting plasma nitriding, a process also carried out at a very low gas pressure, the nitrogen diffusion can be controlled in a much better way compared with ordinary gas nitriding [12]. The importance of a suitable heat treatment, necessary to achieve mechanical and fatigue properties, also concerns to what degree the total distortion of ring gear dimensions, shape and position become after the hardening processes. In this investigation, different hardening processes have been applied on gears and the influence on shape distortions and fatigue stress limits was determined.

## 2. Experimental Procedure

The experimental procedure was based on the following activities:

- Selection of heat treatment processes.
- Selection of PM material corresponding to the selected heat treatment processes.
- Powder mixing.
- Compaction of gear components.
- Sintering of gear components.
- Heat treatment of gear components.
- Measuring of dimensional change of gears in CMM, on green, sintered and heat treated.
- Metallographic examination.
- Determination of hardness.
- Determination of tooth root bending fatigue (TRBF).

The measuring of dimensional changes was carried out on the ring gear component, but the determination of TRBF was however carried out on another gear geometry, (R&D gear), due to technical and geometrical reasons in the measuring setup. Both gears, with related data, are shown in Figure 1.

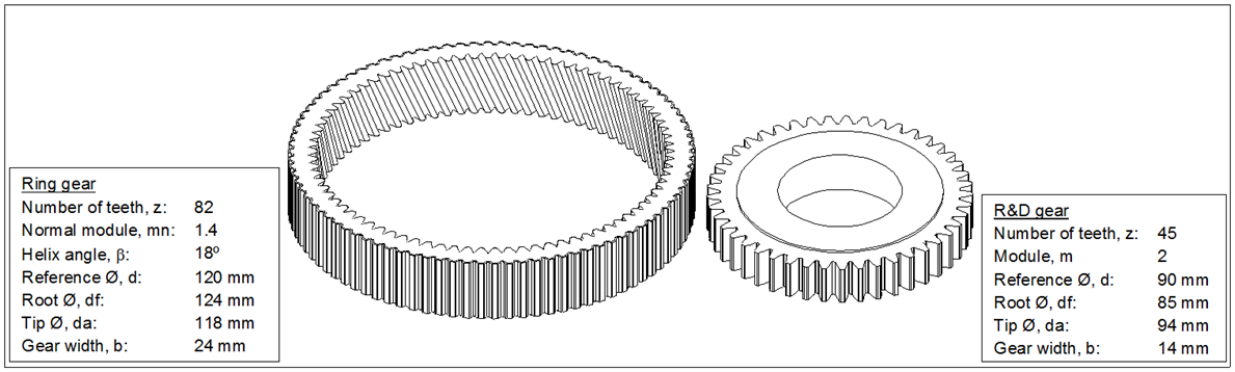



***Figure 1**. PM experiment components: ring gear and R&D gear.*

***Selection of heat treatment processes, with or without diffusion of elements, e.g., from atmosphere***
The selected heat treatments are all standard industrial processes.

*a. Case hardening processes*
Two types of case hardening are of interest, shown in Table 1, where one is carried out as traditional carburizing following oil quench and the second as LPC following gas quench. The LPC technique is suitable with respect to oxidation-sensitive materials e.g., chromium alloyed steels.

***Table 1****. Selection of case hardening processes.*

| **Case hardening** | **Process parameters** |
|---|---|
| CQT | Carburizing at 920ºC for 20 minutes with 0.8% carbon potential atmosphere. Oil quenching and subsequent tempering at 200ºC for 60 minutes in air. |
| LPC | Low pressure carburizing in a two-chamber furnace (Fulgura Duo from ECM Technology) with separate heating/carburizing and high-pressure gas quench cell. Carburizing in $C_2H_2$ diluted with $N_2$ as backfill. Quenching in $N_2$ under 20 bars pressure and subsequent tempering at 200ºC for 60 minutes in air. |

*b. Through hardening processes*
Two types of through hardening are of interest, shown in Table 2, where one is carried out with a traditional oil quenching and tempering (QT) process and the second one as part of the sintering process, as sinter hardening, of the green gear components.

***Table 2****. Selection of through hardening processes.*

| **Through hardening** | **Process parameters** |
|---|---|
| Traditional QT | Austenitizing temperature at 920ºC for 30 minutes with 0.55% carbon potential atmosphere. Oil quenching with subsequent tempering at 200ºC for 60 minutes in air. |
| Sinter hardening | Sintering in laboratory belt furnace at 1120ºC for 30 minutes in 90% of $N_2$ and 10% of $H_2$ atmosphere. Discontinuous belt drive to increase gas cooling i.e., sinter hardening, and subsequent tempering at 200ºC for 60 minutes in air. |

*c. Plasma nitriding processes*
Two types of plasma nitriding, shown in Table 3, are of interest, where one is carried out in a gas mix of nitrogen and hydrogen and the second one with the same gases together with a hydrocarbon gas (free of oxygen), e.g., methane. The process parameters are settled to maximize the diffusion zone, i.e., where the beneficial compressive residual stresses can be found [9], and to control the hard nitride rich compound layer close to the surface and minimize its propagation further down, to avoid brittleness in the pore structure. Molybdenum and especially chromium represent good nitride formers and are used in typical nitriding steels [6].

***Table 3****. Selection of plasma nitriding processes.*

| **Plasma nitriding** | **Process parameters** |
|---|---|
| Plasma nitriding (PN) | PN at 540ºC for 16 hours in 98% of $H_2$ and 2% $N_2$. |
| Plasma nitro carburization (PNC) | PNC at 570ºC for 4 hours in 70% $H_2$, 25% $N_2$ and 5% $CH_4$. |

***Selection of PM material to correspond to the selected heat treatment processes***
Three pre-alloyed and water atomized PM materials, shown in Table 4, were selected to be used together with the heat treatment processes.

***Table 4****. Selection of PM materials.*

| PM material | Composition |
|---|---|
| Astaloy Mo | 1.5% Mo (Fe bal.) |
| Astaloy 85 Mo | 0.85% Mo (Fe bal.) |
| Astaloy CrA | 1.8% Cr (Fe bal.) |

By combining the three selected PM materials with different carbon content (later added as graphite) with the six selected heat treatment processes, nine combinations were created, shown in Table 5.

***Table 5****. Combinations of PM material with carbon content and heat treatment process.*

| Heat treatment process | Selection of PM material + carbon | Designation |
|---|---|---|
| CQT | Astaloy Mo + 0.25% C | CQT-Mo |
| LPC | Astaloy Mo + 0.25% C | LPC-Mo |
| LPC | Astaloy CrA + 1% Ni + 0.25% C | LPC-CrA |
| QT | Astaloy Mo + 0.6% C | QT-Mo |
| Sinter hardening | Astaloy CrA + 2% Ni + 0.6% C | SH-CrA |
| PN | Astaloy CrA + 1% Ni + 0.5% C | PN-CrA |
| PN | Astaloy 85 Mo + 1% Ni + 0.4% C | PN-85Mo |
| PNC | Astaloy CrA + 1 %Ni + 0.5% C | PNC-CrA |
| PNC | Astaloy 85 Mo + 1% Ni + 0.4% C | PNC-85Mo |

***Powder mixing***
Powder mixes were based on selection of PM material and carbon, shown in Table 5, and manufactured as premixes by adding the corresponding amount of graphite and 0.70% of lubrication (LubeE).

***Compaction of gear components***
All gear components were compacted in a Dorst TPA800/2 hydraulic press. The complex shape of the ring gear geometry, with helical inner gears and splines on the outer diameter, required a higher compaction pressure (850 MPa) compared with the R&D gear (700 MPa). The obtained green densities, GD, are shown in Table 6. The nominal green weight of the ring gear was 565 g and the R&D gear 535 g.

***Table 6****. Obtained green density (GD) of compacted gear component.*

| Powder mix "ready to press" | GD of gears [g/cm$^3$] |
|---|---|
| Astaloy Mo + 0.25% C + 0.70% LubeE | 7.15 |
| Astaloy CrA + 1% Ni + 0.25% C + 0.70% LubeE | 7.15 |
| Astaloy Mo + 0.60% C + 0.70% LubeE | 7.13 |
| Astaloy CrA + 2% Ni + 0.6% C + 0.70% LubE | 7.10 |
| Astaloy CrA + 1% Ni + 0.5% C + 0.70% LubeE | 7.10 |
| Astaloy 85 Mo + 1% Ni + 0.4% C + 0.70% LubE | 7.20 |

***Sintering of gear components***
All gear components were sintered before any heat treatment process was carried out. Sintering, and a single sinter hardening, were carried out in a laboratory belt furnace at 1120ºC for 30 minutes in an atmosphere gas mixture of 90% $N_2$ and 10% $H_2$, without addition of hydrocarbons.

***Measuring of dimensional change of ring gears in CMM, on green, sintered and heat treated***
All measurements and characterization of dimensions, shape and positions on the ring gears were carried out in a Zeiss DuraMax coordinate measuring machine equipped with Calypso software. The deviations of flatness, roundness and runout, shown in Figure 2, were determined with nominal values, i.e., zero-values, as reference. The roundness and runout values were both generated from the half of the ring gear height, i.e., 12 mm. The coordinate reference axis, seen in Figure 2, also indicates the compaction direction of the ring gear component, i.e., in z-axis.

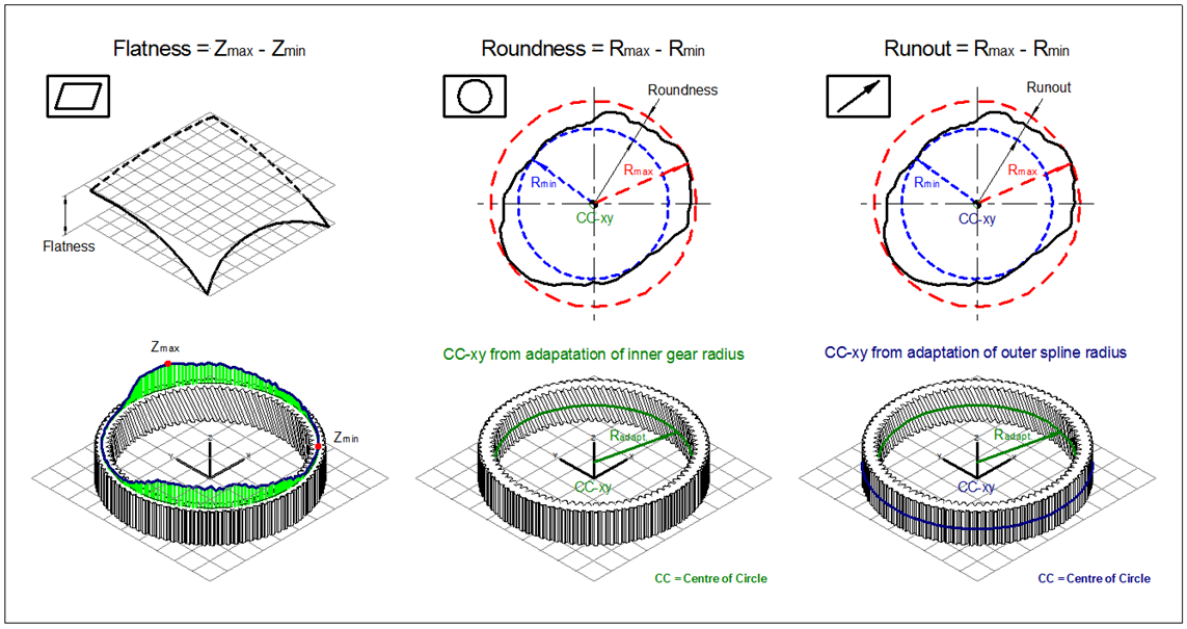



***Figure 2****. Definition of flatness, roundness and runout on ring gear.*

***Metallographic examination***
Metallography inspections and shooting were carried out with a light optical microscope (LOM).

***Determination of hardness***
Micro hardness profiles (MHV0.1) were conducted on the heat treated ring gears with a Matsuzawa MMT-7 hardness tester. The procedure to measure hardness of gear flank and root was carried out according to ISO 4507, and the determination of the same according to ISO 6336-5.

***Determination of tooth root bending fatigue (T.R.B.F.)***
The tooth root bending fatigue stress was evaluated on the R&D gears, according to ISO 6336-5, using the staircase method, according to MPIF Standard 56, for determination. No previous or additional gear treatment, e.g., grinding or polishing, are required or necessary before the measuring of TRBF is started. This was of course a prerequisite where the direct and unaffected influence of heat treatment was of interest.

## 3. Results and Discussion

***Dimensional distortion of ring gears***

The dimensional distortion in green state was found to be relatively small, seen in Figure 3 - 5, but by studying the distortions in the z-axis, i.e., the direction of the punches into the die during compaction, these values were smaller as seen with flatness values, compared with the distortions in xy-axis, here represented by roundness and runout values. The cause of this difference could probably be found in the powder filling sequence of the die, due to powder distribution, where small differences became clearer in xy-axis of the green ring gear. This behavior could most likely be minimized with an improved filling shoe setup, e.g., adjustments of shoe geometry and kinematics.

Compared with the changes in green state, the changes in sintered state were of a higher magnitude, also seen in Figure 3 - 5. The smallest distortions in sintered state were observed with the two low carbon content materials, i.e., Astaloy Mo + 0.25% C and Astaloy CrA + 1% Ni + 0.25% C. A large distortion in flatness was found with the Astaloy CrA + 1% Ni + 0.5% C ("PN-CrA" and "PNC-CrA") but not in roundness or runout values for the same material. The distortion in the sintered state was larger compared with the same in green state, and this could most likely be explained by the sintering conditions. These include the laboratory belt furnace sintering capacity and possible temperature gradients, where the limited furnace cross section, compared with relatively large outer diameter and small thicknessnes of ring gear could be of and crucial importance. In an industrial sintering furnace, more suitable for handling large geometries and volumes, the dimensional distortion would probably be more positively affected.

The distortions of the heat treated ring gears seen in Figure 3 - 5, with respect to the geometry z- or xy-axis, showed different behaviors. In z-axis, i.e., flatness values, the changes from sintered to heat treated state were small, sometimes even a little better ("PN-CrA" and "PN-85Mo"). The change in flatness of "SH-CrA", where the ring gear in green state underwent heat treatment in one step, i.e., sinter hardening, was found to be large. For all heat treated ring gears, except for the nitrided ones, the roundness and runout values increased significantly. The largest distortions of the values were found with the "QT-Mo" and "SH-CrA". The small distortions from sintered to heat treated state, found with the plasma nitride and the plasma nitro carburized ring gears in both z- and xy-axis, were undoubtedly due to the process temperature at 540°C – 570ºC, i.e., a surface hardening process temperature in the ferritic area, together with a considerably slower cooling rate from this already moderate working temperature.

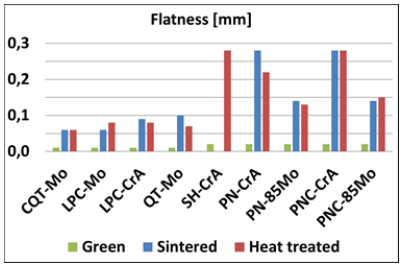



***Figure 3****. Flatness of ring gears.*

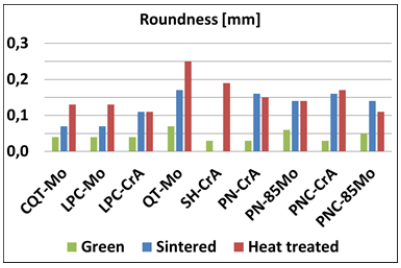



***Figure 4****. Roundness of ring gears.*

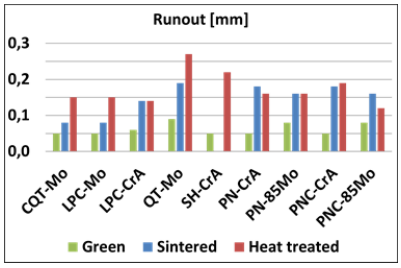



***Figure 5****. Runout of ring gears.*

In order to minimize distortion of flatness, roundness or runout a calibration pressing operation, after the sintering process, could be recommended. This operation could actually also be possible for some of the heat treated ring gears, i.e., the surface hardened ones with less core hardness.

***Metallography work on microstructure of heat treated ring gears***

The ring gears were cut perpendicular to the flank of the tooth, shown in Figure 6 – 8, where these figures also represent the three different hardening methods, i.e., the case hardening (Figure 6), through hardening (Figure 7) and plasma nitriding (Figure 8). Since both case hardening and plasma nitriding are based on diffusion processes the appearances shows some similarities.



***Figure 6**. LPC-Mo.*

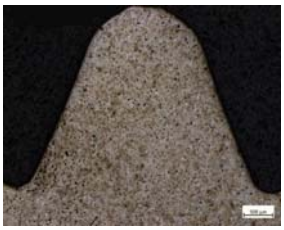


***Figure 7**. SH-CrA.*

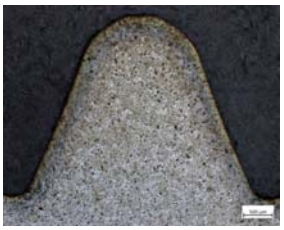


***Figure 8**. PN-CrA.*

A clear difference in microstructure was found when the two types of nitriding processes, i.e., plasma nitriding (PN) and plasma nitro carburization (PNC), were compared together with same PM material, shown in Figure 9 (close-up from Figure 8) and Figure 10. A significant difference was found in the occurrence of an established nitride rich compound layer and this was found to be thicker and more continuous with the PNC process.

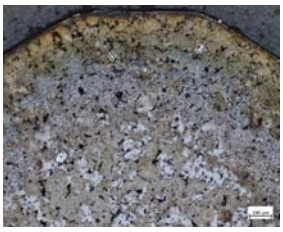


***Figure 9**. PN-CrA (tooth top).*

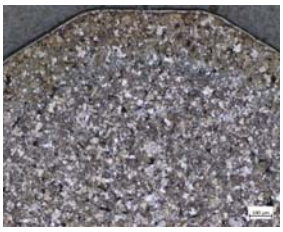


***Figure 10**. PNC-CrA (tooth top).*

Depending on the carburization method, the CQT carried out in a 0.8% carbon potential atmosphere, exhibit larger diffusion, compared with the LPC method, and thus after quenching in oil obtained a higher amount of martensite in the center of the ring gear, i.e., between the outer and inner diameter. All microstructures and phases of the heat treated ring gears are described and explained in Table 7.

***Table 7**. Microstructures and phases of heat treated ring gears.*

| **Designation** | **Microstructure of heat treated ring gear** |
|---|---|
| CQT-Mo | Martensitic surface (flank/ root/tooth top) and center. |
| LPC-Mo | Martensitic surface (flank/ root/tooth top). Center with dense high temperature (HT) bainite. |
| LPC-CrA | Martensitic surface (flank/ root/tooth top). Center with HT bainite in dense low temperature (LT) bainite. |
| QT-Mo | Martensitic surface (flank/ root/tooth top) and center. |
| SH-CrA | Martensitic surface (flank/ root/tooth top) and center with some areas of Ni-rich austenite. |
| PN-CrA | Very thin discontinuous layer of nitrides (compound layer) on surface (flank/ root/tooth top). Diffusion zone a mix of tempered martensite, pearlite, bainite and needles of nitrides. Beneath a mix of bainite and tempered martensite and a network of nitrides. Center with bainite, pearlite and Ni-rich austenite areas. |
| PN-85Mo | Very thin discontinuous layer of nitrides (compound layer) on surface (flank/ root/tooth top), beneath of bainite, Ni-rich austenite and small amount of fine bainite/tempered martensite. |
| PNC-CrA | Thin continuous layer of nitride (compound layer) on surface (flank/ root/tooth top) and thin darker nitride layer beneath. Diffusion zone of pearlite and network of nitrides. Center with a mix of bainite, pearlite and a small amount of tempered martensite around Ni-rich austenite. |
| PNC-85Mo | Thin discontinuous layer of nitride (compound layer) on surface (flank/ root/tooth top), beneath (to center) of bainite, Ni-rich austenite and small amount of fine bainite/tempered martensite. |

***Micro hardness of heat treated ring gears***

The micro hardness of the CQT and LPC treated ring gears are shown in Figures 11 – 13. As described earlier, the CQT treated ring gear was found to be fully martensitic and this was confirmed with the hardness profile, shown in Figure 11. The hardness profile patterns of the LPC-treated ring gears are similar, but the CrA material obtains higher hardness values. Overall, the flank hardness profile values were larger compared with the root

values, undoubtedly a combination of diffusion and quenching possibilities, due to the exposed surface area on gear tooth compared with the root.

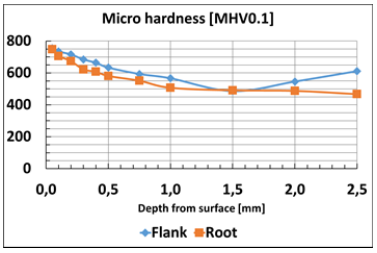



***Figure 11**. CQT-Mo.*

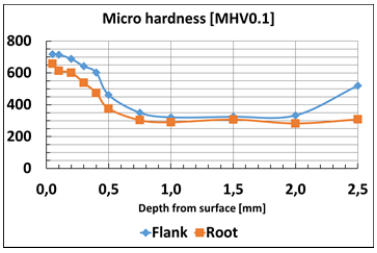



***Figure 12**. LPC-Mo.*

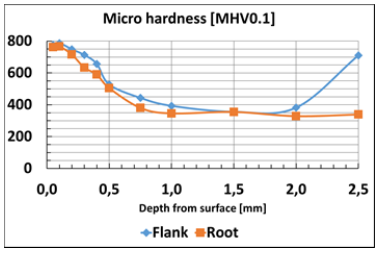



***Figure 13**. LPC-CrA.*

The hardness profiles of the through hardened ring gears were very similar (Figure 14 and 15), thus, in this case, independent heat treatment or material.

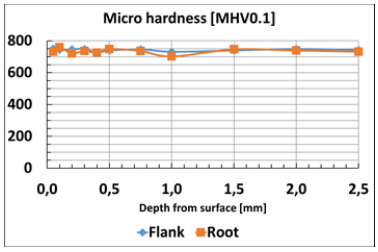



***Figure 14**. QT-Mo.*

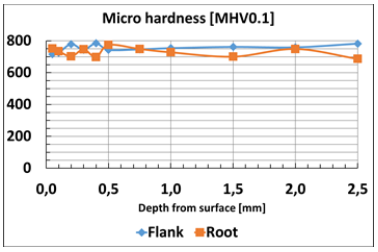



***Figure 15**. SH-CrA.*

The hardness of the nitrided ring gears, shown in Figure 16 – 19, possesses considerably lower values compared with the other heat treated gears. Comparing the PM material selection, clear benefits could be seen with the chromium alloyed material, here represented by PN-CrA and PNC-CrA. The influence of the process with respect to hardness, i.e., PN versus PNC, could be observed by comparing PN-CrA with PNC-CrA. The PNC-CrA ring gears reached higher hardness on surface but the PN-CrA kept a higher hardness a bit further down from the surface.

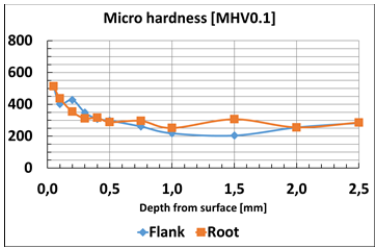



***Figure 16**. PN-CrA.*

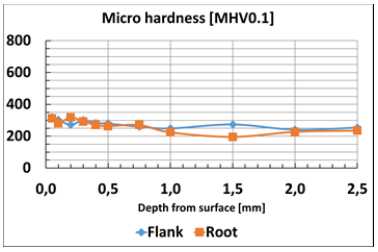



***Figure 17**. PN-85Mo.*

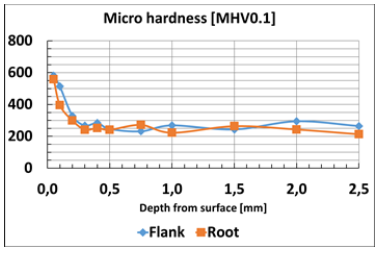



***Figure 18**. PNC-CrA.*

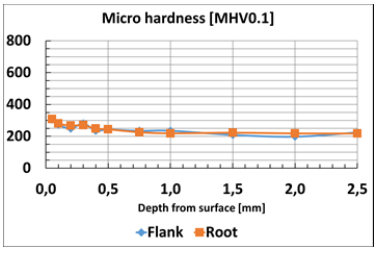



***Figure 19**. PNC-85Mo.*

***Tooth root bending fatigue of heat treated R&D gears (TRBF)***
The average fatigue stress ($\sigma_{50}$) values of the tooth root bending are shown in Figure 20. The highest values were found with gears treated with the case hardening processes i.e., CQT-Mo, LPC-Mo and LPC-CrA were all between 625 – 655 MPa. The fatigue stress of the through hardened QT-Mo (528 MPa) was more than 27% higher compared with others through hardened such as the SH-CrA (412 MPa). The highest values of the nitrided gears were found with the plasma nitro carburized ones, i.e., PNC-CrA (471 MPa) and PNC-85Mo (424 MPa). By comparing the fatigue stress achieved by PNC with those achieved by through hardening, i.e., QT and SH, we can see the micro hardness profile has no influence, but was this was most likely due to the level of residual compressive stress and its location.

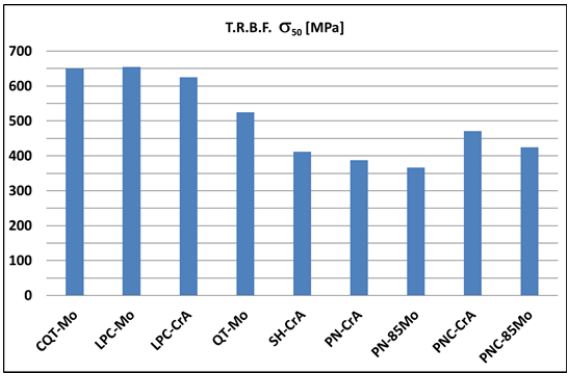



***Figure 20****. TRBF of heat treated R&D gears.*

A possible procedure to improve the TRBF of the plasma nitrided and nitro carburized gears could be with a previous hardening, e.g., a sinter hardening, and a following tempering just above the subsequent nitriding process temperature. This would hopefully increase the core strength and at the same time retain the beneficial residual compressive stresses.

## 4. Conclusions

Through a selection of different types of heat treatments, applied on gears made of six different PM materials, the effects on dimensional distortion, microstructure, hardness profile, and on fatigue stress were investigated.

The lowest overall dimensional change on ring gears in green, sintered and heat treated condition were found with case carburized and quenched materials, i.e., CQT of Astaloy Mo + 0.25% C, LPC of Astaloy Mo + 0.25% C and LPC of Astaloy CrA + 1% Ni + 0.25% C.

The heat treatment process with the lowest influence on dimensional distortion was found with the nitriding processes, i.e., plasma nitriding and plasma nitro carburization.

The highest tooth root bending fatigue (TRBF) on R&D gears was found with case carburized and quenched materials, i.e., CQT of Astaloy Mo + 0.25% C, LPC of Astaloy Mo + 0.25% C and LPC of Astaloy CrA + 1% Ni + 0.25% C.

Lastly, a high value hardness profile is not a guarantee of achieving high tooth root bending fatigue and this is shown by comparing through hardening and fully martensitic material with plasma nitro carburized material with less hardness.

## References


1. R. August et al. *Dynamics of Planetary Gear Trains.*
   NASA Contractor Report 3793
   https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19840017959.pdf [Retrieved 2018-03-28]
2. National Research Council, 2015. *Cost, Effectiveness and Deployment of Fuel Economy Technologies for Light-Duty Vehicles Committee on the Assessment of Technologies for Improving Fuel Economy of Light-Duty Vehicles, Phase 2.*
   Chapter 5 (Transmissions)
   https://www.autonews.com/assets/PDF/CA100105618.PDF [Retrieved 2018-03-28]
3. D.W. Dudley. *Handbook of Practical Gear Design.*
   CRC Press 1994
   ISBN: 1-56676-218-9
4. H.J. Stadtfeld. *Power Skiving of Cylindrical Gears on Different Machine Platforms.*
   Gear Technology, January/February 2014
   https://www.geartechnology.com/issues/0114x/power-skiving.pdf [Retrieved 2018-03-27]
5. Y. Yanase et al. *Development of MSS300 Super Skiving Machine - Realization of High-Precision, High-Efficiency Gear Cutting Method*
   Mitsubishi Heavy Industries Technical Review Vol. 53 No. 4, December 2016
   http://www.mhi.com/company/technology/review/pdf/e534/e534055.pdf [Retrieved 2018-03-27]
6. Swerea IVF. *Steel and its Heat Treatment – a Handbook.*
   Publication No. 12801, 2012
   ISBN: 987-91-86401-11-5
7. D.H. Herring. *Atmosphere Heat Treatment – Volume 1.*
   BNP Media II, LCC. Custom Media Group.
   ISBN: 978-0-692-28393-6
8. M.J. Schneider et al. *Introduction to Surface Hardening of Steels.*
   ASM Handbook, Volume 4A, Steel Heat Treating Fundamentals and Processes
   2013 ASM International
9. E.J. Mittemeijer. *Fundamentals of Nitriding and Nitrocarburizing.*
   ASM Handbook, Volume 4A, Steel Heat Treating Fundamentals and Processes
   2013 ASM International
10. M. Dahlström et al. *High performance PM Components Heat Treated by Low Carburizing and Gas Quench.*
    Presented at EURO PM in Gothenburg, Sweden, 2013.
11. M. Dahlström. *Influence of Alloying Content on Low Pressure Carburized and Gas Quenched PM Components.*
    Presented at WorldPM in Hamburg, Germany, 2016.
12. A. Molinari et al. *Plasma Nitriding of C-alloyed Astaloy CrM Processed in Different Conditions.*
    Presented at PM2Tec in New Orleans, USA, 2001