High Performance PM Components Heat Treated by Low Pressure Carburizing and Gas Quenching.

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Abstract
High performance components are often case hardened to have high surface hardness and fatigue strength. Low pressure carburizing and gas quenching is an increasingly popular process method for conventional steels but so far not commonly used for PM steels. Besides the benefits offered for conventional steels, such as less distortion and clean parts after heat treatment, low pressure carburizing enables surface hardening of chromium alloyed PM steels which is not possible with conventional gas carburizing. This paper presents results for low pressure carburized and gas quenched PM steels. The control of the case profiles is demonstrated together with related micro structures and initial fatigue strength results are presented.

1. Introduction

Low Pressure Carburizing (LPC) followed by high pressure gas quenching is a novel heat treatment process for PM components. In conventional gas carburizing the load is exposed to a process gas during the entire carburizing cycle. In the LPC process carburizing gas is introduced under low pressure, typically 5-10 mbar, in short boost cycles where the surface of the component is saturated with carbon. The carbon then diffuses into the material during a diffusion cycle while under low pressure with nitrogen backfill. The final carbon profile can then be controlled by varying length and number of boost and diffusion cycles thus enabling a precise control of case profiles. The use of high pressure gas cooling brings more freedom during the cooling cycle by the possibility to adjust gas pressure and turbine speed and thus enabling control of the cooling rate. Also the use of gas instead of oil as cooling medium removes the need to clean the quenched parts.

It is well-known that a hard case and softer core is beneficial for fatigue properties in terms of residual compressive stresses in the near surface region [1]. Higher carbon content in the carburized area will postpone the martensitic transformation by lowering the M_s temperature. Once the martensitic transformation starts, the increase in volume will give rise to compressive residual stresses. A large difference in carbon content between carburized area and base material will result in a more beneficial residual stress distribution. However, depending on the given load condition the softer core could be exposed to significant stress levels. It is therefore crucial to tailor the material composition of the component in order to have enough hardenability of the core for the required application.

Chromium alloyed materials is difficult to harden due to its strong affinity to oxygen. The atmosphere used in conventional Gas Carburizing (GC) is oxidizing to chromium alloyed materials. The open porosity of low to medium density PM parts in combination with long exposure time allows the oxygen to penetrate deep into the component and form oxides not only at the surface but also in the core. The use of low pressure carburizing which is an oxygen free process enables hardening of these materials without forming oxides.

In this paper the results of a number of LPC experiments is presented focusing on control of case profile, core hardness and case hardening of chromium alloyed material.

2. Experimental

Chemical composition of the materials used in the investigation is summarized in Table 1. All three base powder included in the study are water atomized, pre-alloyed iron powders. Graphite was added to the mixes in various contents which are reported for each experiment.

Table 1. Chemical composition of base materials used in this investigation.

	Mo [%]	Cr [%]
Astaloy 85Mo	0,85	
Astaloy CrA		1,80
Astaloy CrL	0,20	1,50

The powder mixes of Astaloy 85 Mo and Astaloy CrL were pressed to standardized tensile (ISO 2740) and fatigue (ISO 3928) test bars to a density of 7.20 g/cm³. From the Astaloy CrA mix spur gears with a gear modulus of 1.6 and outer diameter of 32 mm were pressed. Sintering was done in a conventional belt furnace at 1120°C for 30 minutes. Atmosphere was 90% nitrogen and 10% hydrogen.

The low pressure carburizing was carried out in a two chamber furnace with high pressure gas quench, Fulgura Duo manufactured by ECM Technologies. Acetylene was used as carburizing gas and the samples were quenched under 20 bar pressure of nitrogen if nothing else is specified. Each load was charged with 250 kg of parts in order to have production like conditions.
Gas carburizing and oil quench was done in a conventional case hardening furnace. Methanol diluted with nitrogen was used as process gas and a carbon potential of 1% was used. The carburizing was done at 920°C for 20 min and the parts were then quenched in oil.
All components used in the investigation were tempered after the case hardening at 180°C for 60 minutes in air atmosphere. Fatigue strength was tested by 4 point plane bending with R-1 and calculations were made by the stair case method according to MPIF Std 56.

3. Results and discussion

3.1 Control of case profiles

The possibility to case-harden components without affecting the core carbon content can be highly beneficial in some cases. The magnitude of compressive residual stresses in the surface is related to difference in carbon content and microstructure between carburized surface and core. Low pressure carburizing enables case hardening without affecting the core carbon content even for large targeted CHD. This is illustrated in Figure 1.

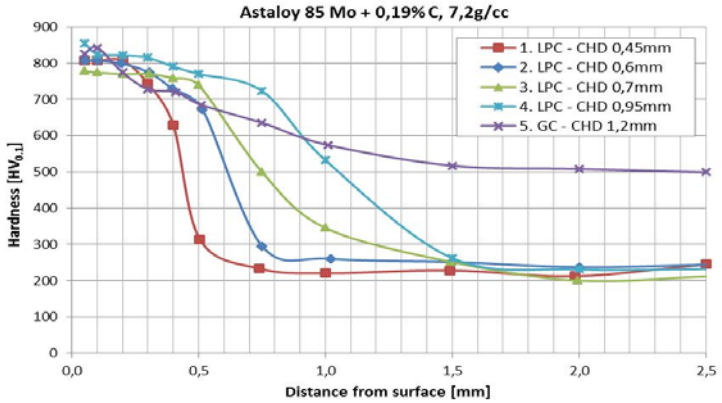


Figure 1. Case hardened profiles measured on tensile strength test bars carburized by low pressure carburizing and gas carburizing: Graph 1-4 LPC, Graph 5 GC.

Figure 1 show examples of well-defined case profiles achieved by LPC and that it is possible to achieve different Case Hardened Depth (CHD) without affecting the core hardness. The short controlled boost cycles do not enable the process gas to penetrate into pore system of the component to the same extent as in gas carburizing. Low to medium density components with open porosity can in gas carburizing exhibit the problem with through carburizing. The higher cooling rates of oil quench and especially in combination with excessive carburizing can lead to through hardening. In Figure 2 the core microstructure of sample 4 (left) and sample 5 (right) from Figure 1 are shown.

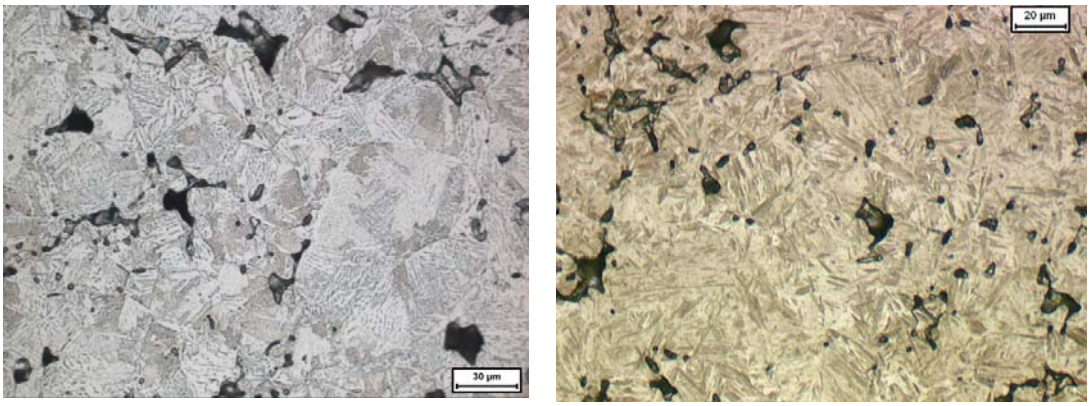


Figure 2. Comparison of core microstructure of tensile bars case hardened by LPC and gas quenched (left) and gas carburizing with oil quench (right).

The low pressure carburized and gas quenched sample had a bainitic microstructure in the core while the gas carburized and oil quenched sample had a low carbon lath martensitic structure in the core. Since the difference in hardness between case and core was relatively small the desired residual compressive stresses and toughness might be reduced.
In Figure 3 another example of case profiles of a small spur gear treated by LPC is presented. This gear was made of Astaloy CrA with 0.20% sintered carbon content.

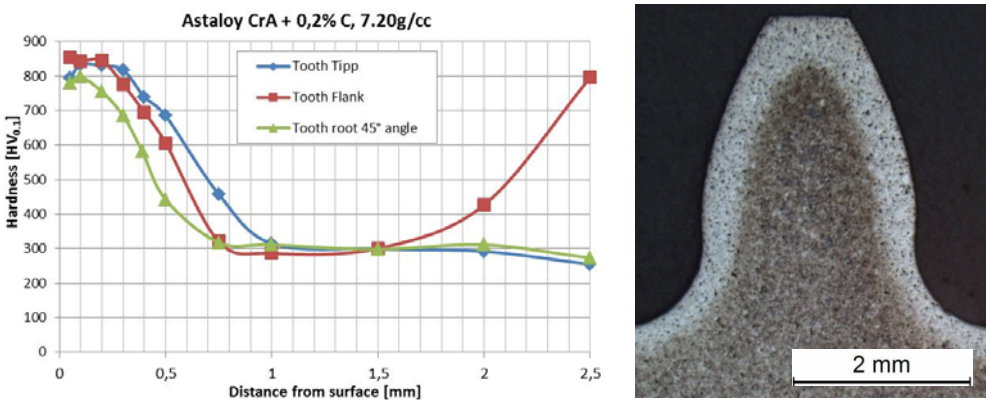


Figure 3. Hardness profiles measured in three different locations of small spur gear (left) and overview of low pressure carburized case (right).

The desired hard case and soft core was achieved on a small modulus gear tooth. The core hardness was measured to approximate 300 $HV_{0.1}$ on the different locations. The results show that LPC in combination with gas quench enabled a well defined case profile even in the relatively small teeth of the gear. The difference in CHD measured on the small spur gear depending on location is related to geometrical effect [2]. Due to the small gear modulus the hardness profile measured on the tooth flank was almost measured

across the entire width of the tooth. This explains the increase in hardness seen in the tooth flank after 2 mm. In Figure 4 below the microstructures of carburized surface and core are shown.

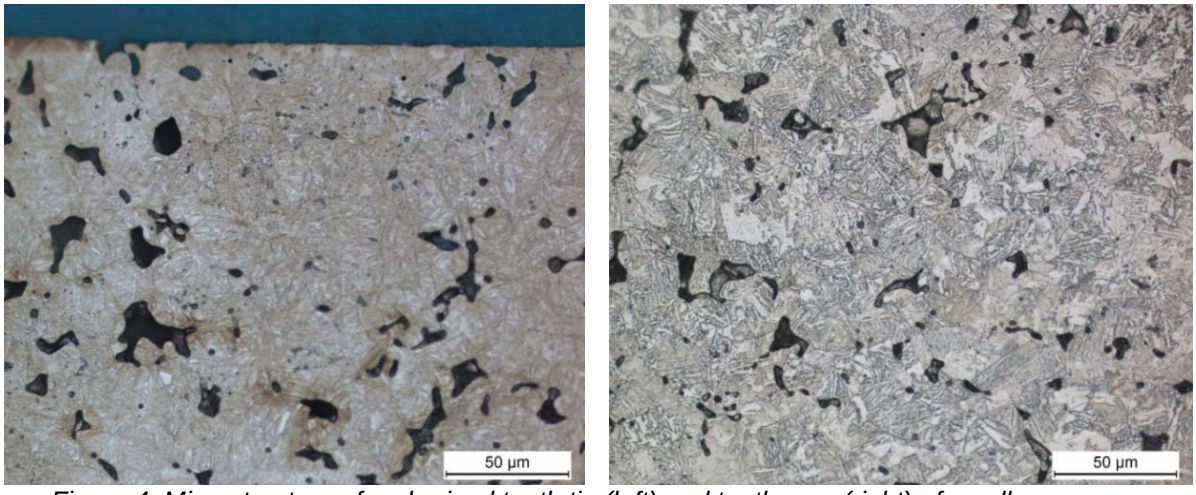


Figure 4. Microstructure of carburized tooth tip (left) and tooth core (right) of small spur gear.

The results show that it was possible to case harden small components without the risk of through hardening. In order to increase the core hardness to desired level the carbon content of the base material can be optimized which is illustrated in next paragraph.

3.2 Influence of base carbon content on core hardness

The hardenability of a PM material is governed by type and amount of alloying elements as well as admixed carbon content. To be able to fine tune the carbon content in the material is a degree of freedom for PM steels which is not possible for conventional steels. Optimum core hardness depends on type of load case the component is subjected to and the case depth. However, core hardness in the range of 400-450 $HV_{0.1}$ is typically considered as optimum for bending fatigue [1].

To investigate the influence of carbon content on core hardness of Astaloy 85 Mo, tensile bars with varying carbon contents were quenched using 15 bar nitrogen pressure, without any prior carburization. The micro hardness of the specimens was measured and is plotted versus the analyzed carbon contents in Figure 5.

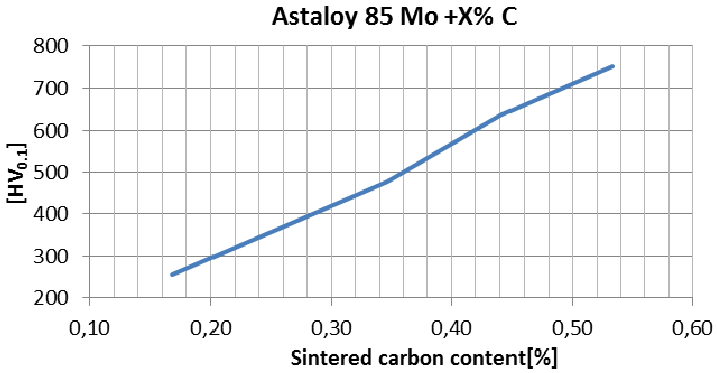


Figure 5. Core hardness as a function of carbon content.

The results show that the core hardness can be fine-tuned by means of admixed graphite content. Based on these findings a new trial with low pressure carburizing was done with the sintered carbon content increased to 0.26%, see Figure 6 below for results.

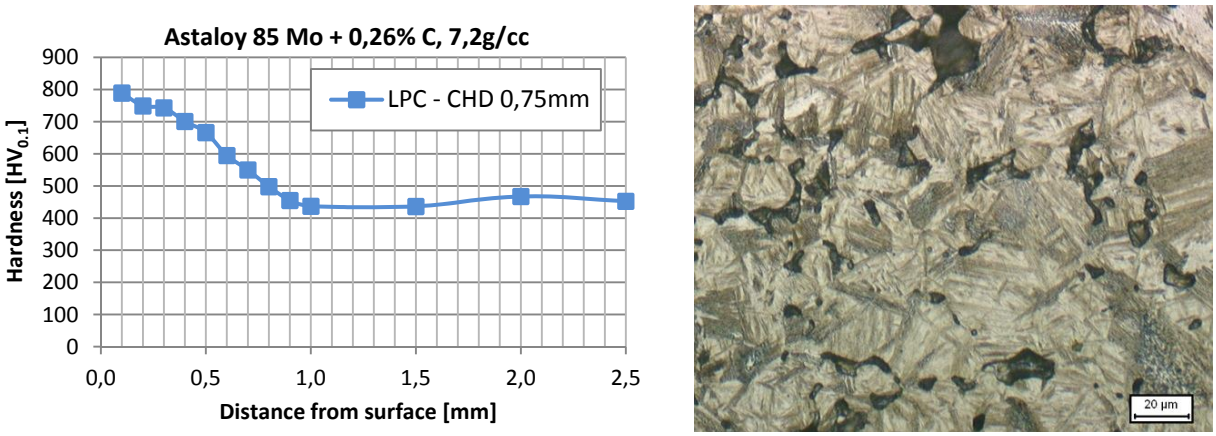


Figure 6. Hardness profile (left) and corresponding core microstructure (right) measured on a TS bar.

The hardness profile show that a sintered carbon content of 0,26% results in the desired microhardness of the core of 450$HV_{0.1}$. The somewhat higher hardness compared to what to be expected from Figure 5.1 can be explained by the use of 20 bar quench pressure used in this experiment. The achieved core hardness was now in the desired range according to literature. The obtained microstructure is a mixture of lower bainite and martensite in an approximate 50/50 relation.

3.3 Fatigue strength of LPC and GC chromium alloyed material

The fatigue strength of Astaloy CrL heat treated by LPC and by conventional gas carburizing was compared. Sintered carbon content before carburizing was 0.17% for both processes. The corresponding microhardness profiles obtained from by the two hardening methods are shown in Figure 7.

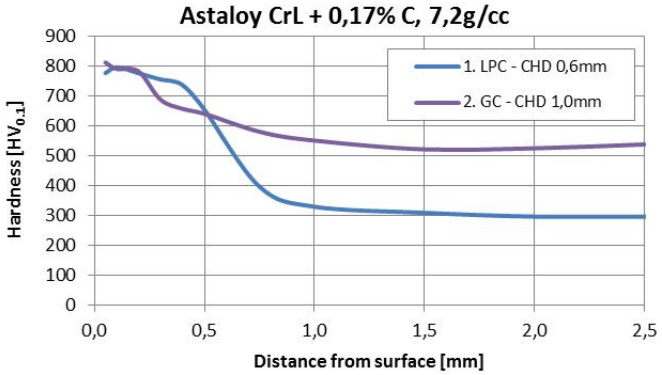


Figure 7. Microhardness profiles measured on fatigue strength test bars carburized by LPC and GC.

The fatigue strength of LPC and GC Astaloy CrL was 379MPa and 398MPa, respectively. However, these are only initial results and do not show the full potential of the material with respect to fatigue strength. Process parameters and carbon content needs to be further optimized in regards of CHD, case profile and core hardness. Even though there was a large difference in obtained core hardness and CHD of the samples case hardened by the two processes the bending fatigue was similar.

Chromium alloyed materials are sensitive to oxygen which presents a problem during conventional gas carburizing. The use of low pressure carburizing enables chromium containing materials to be carburized without formation of Cr-oxides. This can be seen in the microstructures of the fatigue bars from this study, see Figure 8.

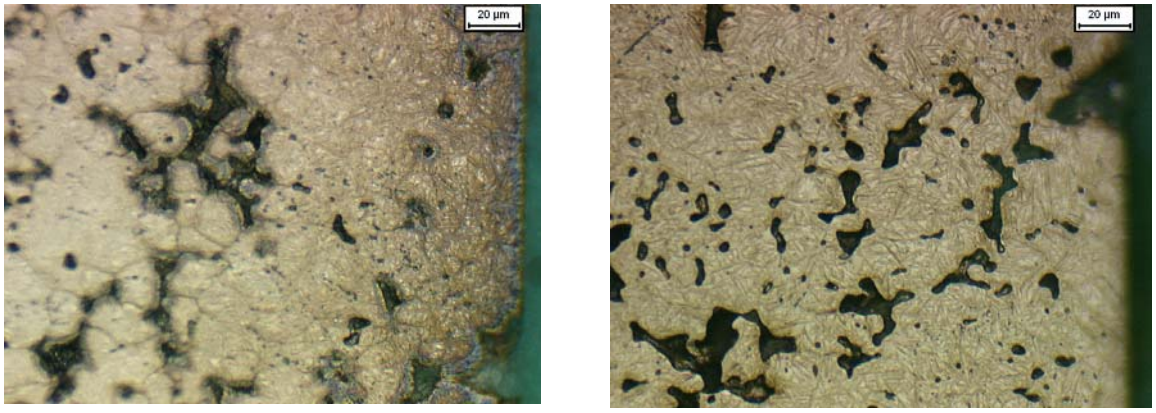


Figure 8. Microstructure of Astaloy CrL: Presence of Cr-oxides near the surface left) of GC samples compared to LPC samples without Cr-oxides (right).

The samples which were gas carburized contained of chromium oxides in the grain boundaries at both surface and center. In the surface region the chromium oxides can be seen as darker grain boundaries. Also in the center, chromium oxides could be found. The oxygen content was analyzed before and after carburization, see Table 2.

Table 2. Comparison of oxygen content of fatigue test bars before and after carburization.

	Sintered	LPC	GC
Oxygen contnet [%]	0,081	0,085	0,31

The results clearly show that no oxygen was picked during the LPC process while the oxygen content was significantly increased by the GC process. A microstructure free from Cr-oxides and no increase in oxygen content makes LPC a suitable heat treatment process for case hardening also of chromium alloyed PM materials.

4. Conclusions

Well defined case profiles on test bars and gear tooth treated by low pressure carburizing and gas quenching have been demonstrated.

With low pressure carburizing it is possible to achieve similar level of surface hardness and microstructure of carburized layer as with conventional gas carburizing. Case depth and case profile can be tailored by the LPC process while the core hardness can be controlled by alloying and carbon contents. High pressure gas cooling does not offer the same cooling speed as oil but offers more flexibility to control the cooling rate during the quench.

The use of chromium alloyed PM materials is attractive due to the use of cost efficient alloying elements and good hardenability. The results presented here show that low pressure carburizing is a suitable process for PM materials and especially for chromium alloyed materials. Samples which were treated by LPC did not show any presence of Cr-oxides in contrast to GC samples which contained Cr-oxides and significantly increased oxygen content.

The fatigue strength of Astaloy CrL was similar for the two different carburizing processes even though the core hardness was too low for the low pressure carburized samples. Case profile and core hardness needs to be further optimized for the LPC process to show the full potential of the material and process.

References

[1] Swerea IVF. (2010). Steel and its Heat Treatment - a handbook

[2] IVF. (1973). Material properties of carburized and carbonitrided steels.