Carburizing of Low-Alloyed Chromium Materials
– An Overview

Sven Bengtsson[1], Theodora Marcu[2], Alexander Klekovkin[3]

[1]Höganäs AB, Höganäs, Sweden, [2] University of Trento, Trento, Italy, [3]North American Hoganas Inc, Hollsopple, PA, USA

ABSTRACT

Case carburizing followed by quench and temper is a well established method of reaching very high properties for components like gears and sprockets. The well established materials on Fe-Cu-Mo-Ni base can all be case hardened using standard equipment and processes. Cr-containing PM materials, with their increased sensitivity to oxidation (and local carbon level), require special considerations.

In this paper an overview of how different methods to carburise low alloyed chromium alloyed PM steels will be presented. Among methods discussed are gas carburizing, carbonitriding and vacuum carburizing. Specific emphasis is on selection of appropriate process with regard to density of the components and the formation of carbides.

INTRODUCTION

In many practical cases the performance of the structural component depends on the mechanical properties of the surface [1,2]. There are many heat treatment methods that focus on improving the properties of the surface. In this paper Gas Carburizing [3-6], Carbonitriding [3,5] and Vacuum Carburizing [3,7-12] will be discussed. These processes aim at achieving a high carbon concentration of carbon at the surface, gradually decreasing towards the core [3]. After austenitizing and quenching high-carbon martensite is formed at the surface while the core will transform into low-carbon martensite, bainite, pearlite, ferrite or a mixture thereof depending on cooling rate and alloy system. A secondary, but very important effect is that the high-carbon martensite will expand on formation and it will expand more than low-carbon martensite or any of the other structures that may form in the core. With a thin expanded surface region compressive stresses will form that are balanced by tensile stresses in the core, but since normally the core is much larger in cross-sectional area the tensile stresses will be lower while the compressive stresses will be significant. These compressive stresses will improve especially the fatigue performance of structural parts loaded in bending; a typical example is bending fatigue of a gear tooth.

In case carburizing, a process developed for solid steel, a low carbon (0,15-0,25 wt.% C) low alloy steel is heated to carburizing temperature in the austenite regime (typically 925 ^{o}C / 1700 ^{o}F) in a gas mixture consisting of CO, CO_2, N_2 and H_2 [e.g. 3]. The nitrogen gas is virtually inert and its only function is as a dilutant and as carrier of heat. The mixture can be created in different ways, but its function as a carburizing agent is depending on the equilibrium of CO, CO_2, H_2, H_2O and of the alloy system [1]. Examining this equilibrium in detail it is found that the amount of H_2O is sufficient to oxidize materials based on the Fe-Cr system (e.g. Fe-1.5wt.%Cr alloy). For solid steel parts (e.g. DIN 16MnCr5, AISI 51200) this results in a thin oxidized layer [3,13]. This layer is often removed by e.g. grinding of gear teeth, while sometimes it is accepted. Some oxygen also penetrates the grain boundaries close to the surface forming a thin oxide network [3]. The formation of these oxides causes a depletion of carbon and possibly Chromium resulting in a less hardenable material and a softer structure close to the oxides. The compressive residual stresses will not form to the same extent if oxides are present at the surface [14]. Clearly it is desirable to avoid the formation of these oxides.

Carbonitriding is basically the same process as Case Carburizing [3, 5, 15]. The major difference is that Ammonia (NH_3) is added, normally towards the end of the carburizing period. The Ammonia decomposes on the surface of the components (and also on the furnace itself) into atomic nitrogen that can penetrate the component and into hydrogen gas. The nitrogen will diffuse into the part in a similar way as carbon does, driven by the concentration difference between the surface and the core. The nitrogen in solution in the austenite will increase the hardenability and therefore, the carbonitriding can be used to obtain martensite in alloy systems that would not normally transform into martensite after an ordinary case carburizing. The problem with oxidation is also present in this system since the equilibria are the same with the exception of the added ammonia. The ammonia influences the carburizing equilibria to small degree only, except that the amount of hydrogen gas increases slightly. However, since the addition of ammonia is normally (at least for PM parts) added towards the end of the austenitization, the oxidation has already taken place and will not revert even if the furnace conditions should improve slightly.

Vacuum carburization [3, 7-9] (also referred to as low pressure carburizing) is performed by heating the part in a vacuum furnace to austenitization temperature and introducing a carburizing gas at low pressure into the chamber for a short period of time [1, 3, 10, 16]. The carburizing period is often referred to as the boost step. After this step the steep concentration profile crated during the short time is allowed to be “smoothed out” by diffusion. The boost/diffusion steps are repeated until a satisfactory case depth is reached. The parts are then quenched in gas, normally 6-20 bar of N_2, or in oil [17]. Since the vacuum carburization is carried out in vacuum or with a carburizing or inert gas, there is no problem with oxidation. Problems encountered are uneven carburization or problems with quenching in gas. Gas quenching gives a slower quench rate compared to oil and water. If the parts are large or if the parts in the batch are packed tightly the available quench rate may be inadequate.

The sintered density is an important parameter since it controls the surface available to the atmosphere [1, 3, 11, 19, 20]. At low densities (<6.8 g/cc) it is very difficult to control the case depth. The penetration of the carburizing gas is so quick that the entire part is carburized [18]. At a higher density it becomes easier to obtain a well defined case depth. At a density above 7.3 g/cc the material starts to behave very much as solid steel [18]. The gas penetration into the parts seems to be insignificant. These findings are true for all three carburizing methods. A consequence of the fast penetration of carburizing gas into the part is that carbides are formed at the surface that would not form in a solid steel of the same chemistry. These carbides are difficult to dissolve during later stages and should be avoided.

The alloy system is also important for a successful hardening. The hardenability plays a more significant role the larger the parts become [21,22]. If gas quenching is employed this can be an issue already at sizes of 500 g. Furthermore, the equilibrium at the gas / part interface is also influenced by the alloying system. A steel with Chromium as an alloying element takes up more carbon from the atmosphere compared to a part of pure iron. If Nickel is used as an alloying element the carbon uptake is less than pure iron. In recent years the cost for Molybdenum and Nickel has increased significantly. Furthermore, alternatives in the form of pre-alloyed powders based on Fe-Cr-Mo alloying system have been entering the market. These powders require sintering at low dew points in order avoid oxidation. These requirements apply in principle to the heat treatment process as well.

In order to understand how severe the oxidizing problems for these materials are and in order to compare the outcome of a number of competing heat treatments the present investigation was performed.

Processes

The thermal treatments selected for this investigation are gas carburizing, carbonitriding and vacuum carburizing. Naturally there are more processes available, but these are three of the most interesting surface heat treatments for producing high performance PM parts. The description of the processes aims at showing the main characteristics of the methods without considering the details of all variants available.

In some cases pre-treatments, are necessary. It can be the removal of remove surface contaminants, e.g. calibration oil. The presence of these contaminants may change the carburization behaviour. If the density is low it may be necessary to close the surface porosity by steam treating the parts.

The heating of the parts must be uniform and the temperature during carburization must be the same for all parts. The furnace atmosphere must also have easy and uninterrupted access to all part surfaces that should be carburized. If parts are stacked on top of each other it can create a shadowing effect that prevents carburization of the surfaces that are not directly in contact with the atmosphere. There must also be free access to all surfaces that should be quenched. This is true regardless whether gas quenching or oil quenching is applied.

The parts are then heated to the carburizing temperature. Here two contradicting lines of evolution of the processes are seen. A low carburization temperature will give less distortion after quench directly from the carburizing temperature. However, if the temperature is increased, the carburizing time will decrease significantly and hence the total process time [9]. Since the carburization is controlled by diffusion the temperature is the most powerful parameter in controlling the depth and amount of carbon diffusion into the parts [9, 23]. The temperature at the carburizing process step is also controlling the activity of the carburizing gas and the solubility of the carbon in the steel.

The problems with distortion can be decreased by lowering the temperature by furnace cooling to a temperature above A_3/A_{CM} (840-870 ^oC) before quenching starts.

Using gas quenching is also giving lower distortion compared to oil or water-polymer quenching [24-26]. Oil or water/polymer quenching gives a faster cooling rate compared to gas quenching. This means that materials with a lower hardenability can be used. A material with lower hardenability usually has less alloying elements and consequently a lower price. However, the gas quenched material is perfectly clean and can be further surface treated without the need for expensive cleaning processes.

The quenched parts are stress relieved in a tempering process at a temperature between 150 – 200 ^oC, normally in air.

GAS CARBURIZATION AND CARBO NITRIDING

The atmosphere in a “standard” gas carburizing process is clearly oxidizing for Chromium containing materials. However, if the temperature is increased the oxygen partial pressure will drop and the risk of oxidation will decrease. Since the atmosphere is quite complex and several of the reactions are not in equilibrium calculations are very difficult. Instead it was decided to perform gas carburizing at high temperature. A consequence of the high carburizing temperature is that the carburizing effect (carbon activity) will decrease. An atmosphere of nitrogen and cracked methanol was selected, due to the good carburizing power and the low and stable amount of water vapour. Propane was used as enrichment gas.

Experimental

The material used was based on the pre-alloyed base powder FL-5208 (Astaloy CrL, commercially available from Höganäs AB, Sweden), Material A in Table 1. It has a nominal composition of 1,5 wt.% Cr and 0,2 wt.% Mo with balance iron. The base powder was mixed with 0,3% graphite (C-UF4, Kropfmül, Germany) and amide wax. The powder mix was pressed to densities between 7,0 g/cc and 7,5 g/cc. The parts at 7,5 g/cc were double pressed double sintered. By this process they will have slightly higher sintered oxygen content, see Figure 1. The parts were sintered at 1120 ^{o}C (2048 ^{o}F) for 30 min in an atmosphere of 90% N_2 and 10% H_2.

The gas carburizing and the carbo nitriding were performed by Bodycote in Västerås, Sweden. In order to limit the oxidation and to maximize the solubility of carbon in the austenite a high carburizing temperature of 1000 ^{o}C (1832 ^{o}F) was selected. The carburizing time was 30 min. The atmosphere was based on nitrogen and cracked methanol. Distortion during quenching was not considered in this experiment. The parts were quenched in oil at 60 ^{o}C (140 ^{o}F) directly from the carburizing temperature and subsequently stress relieved at 160 ^{o}C (320 ^{o}F) for one hour in air. A variant of the process was derived by adding 4% ammonia to the carburizing atmosphere, thus causing a nitriding action of the material.

The chemical analysis of oxygen and carbon is performed on chips produced by careful turning of the outermost layer of the parts as shown in Figure 5. Nonetheless, the measured values must be interpreted with caution due the steep gradient formed for both oxygen and carbon at high densities.

Results

The oxygen content after heat treatment had increased to 0,3 % for the gas carburized and 0,26% for the carbo nitrided at a density of 7,0 g/cc as shown in Figure 1. At high density the oxygen content was close to that of the as-sintered part (0,12 %). In the lower density samples ferrite and bainite are preferentially formed near oxides as shown in Figure 2.

The measured carbon content decreases with the density, see Figure 3. The surface carbon is measured by analyzing the turnings after turning a shallow layer, see Figure 5.

The micro hardness measured in martensite (pores are avoided) is shown in Figure 4. Gas carburizing of the material with a density of 7,0 g/cc is not very effective in forming a gradient material. The surface hardness only reaches 600 HV0,1 while the core hardness is just over 400 HV0,1. However, the carbo nitrided material exhibits a surface hardness of over 800 HV0,1, while the core hardness is the same as for gas carburizing.

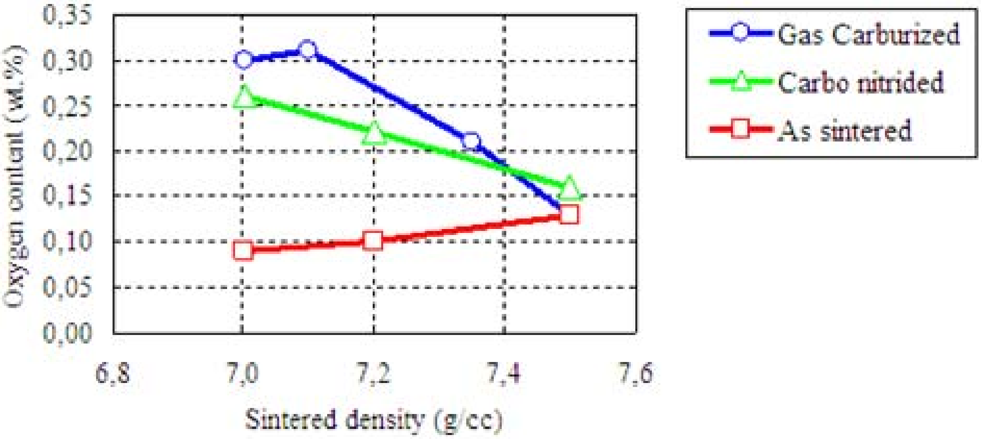


Figure 1. Oxygen content after different carburizing processes.

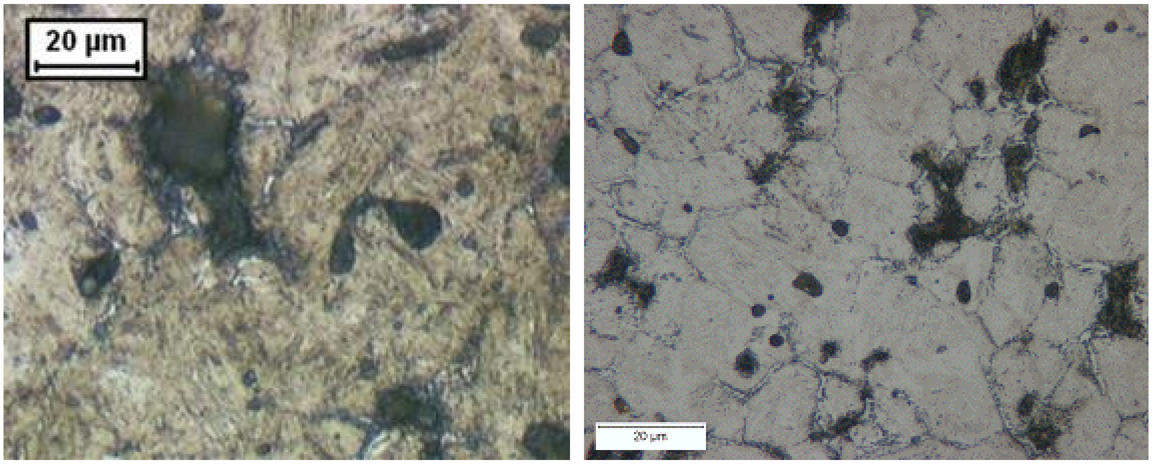


Figure 2. Microstructure of a carburized samples at a density of 7,0 g/cc in core region. Left: Gas carburizing: Martensite, ferrite/bainite adjacent to oxides in the particle boundaries. Right: Carbo nitrided: Martensite, near pores ferrite and bainite are situated near oxides.

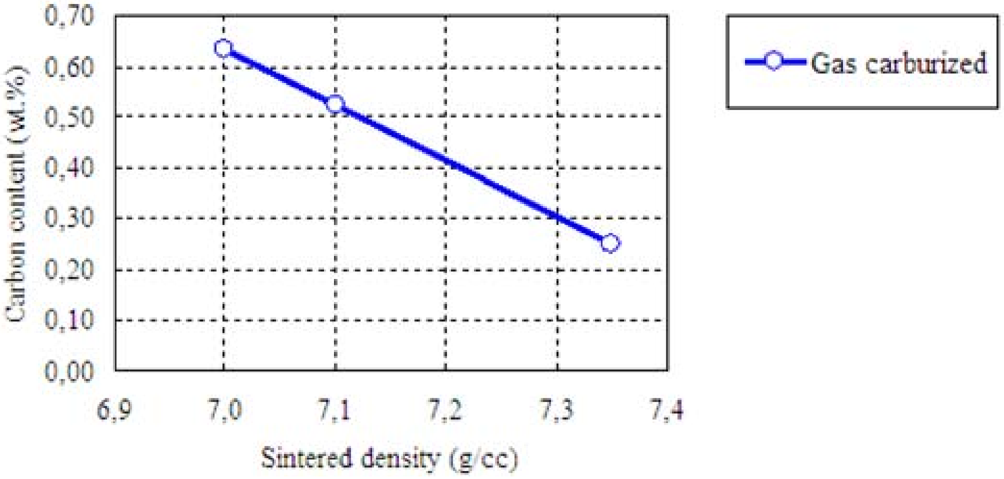


Figure 3. Surface carbon content after gas carburizing as a function of sintered density.

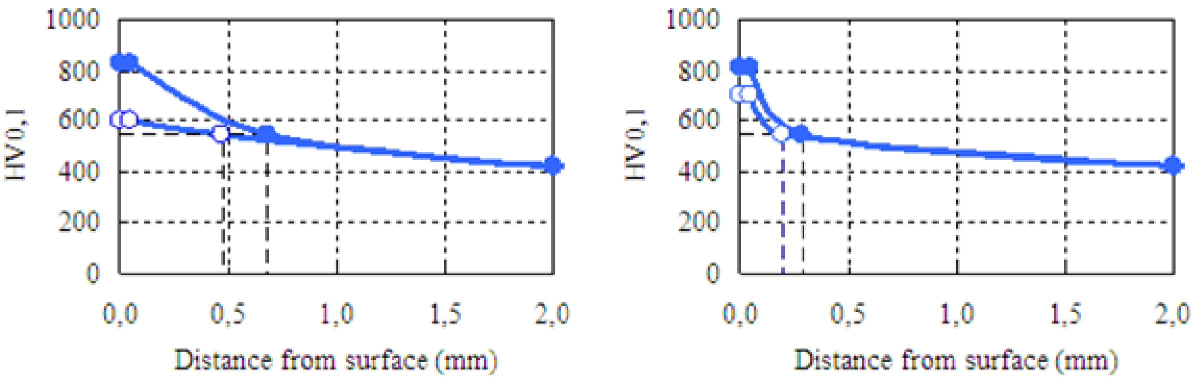


Figure 4. Micro hardness (HV0,1) as a function of the distance from the surface. Left: Sintered density is 7,0 g/cc and right: Sintered density is 7,35 g/cc. The un-filled circles are gas carburized and the filled circles are carbonitrided by the addition of 4% ammonia to the carburizing atmosphere.

Conclusions

Gas carburization

The use of a higher carburizing temperature and a “dry” atmosphere during carburization the did not prevent oxidation. Near oxides bainite and ferrite is formed despite high carbon concentration and high cooling rate. This results in a loss of achievable hardness. The oxidation is more severe at lower densities. For the material with a density below 7,35 g/cc the result is not acceptable for high performance parts.

Carbo nitriding

The behaviour is in principle the same as for gas carburization, but oxidation is slightly less and the formation of bainite and ferrite is significantly less. A proper hardness profile was developed in the carbo nitrided material at all densities.

VACUUM CARBURIZATION

The vacuum carburizing process effectively solves the problem of oxidizing Chromium containing steels. Instead the problem is to achieve a controlled carburization. The carburizing is performed by letting acetylene or propane into the evacuated chamber. By controlling flow, pressure, temperature and time the carburizing process is kept under control. Normally a higher carburizing temperature is used for for vacuum carburizing compared to gas carburizing. The carburizing gases and especially acetylene functions well at temperatures at or above 1000 ^{o}C (1832 ^{o}F) and the higher temperature decreases the total process time. After the carburization step the chamber is evacuated and the steep carbon gradient formed during the short “boost” step is allowed to smoothen out by diffusion. Two major concerns exist; the sensitivity of carburization on density (porosity) and the high affinity of Chromium containing materials to form carbides during carburization.

Three experiments were designed: 1) A heat treatment on a Chromium containing material with a uniform density of 7,1 g/cc in order to evaluate the quality in terms of hardness profile and micro structure. 2) the influence of density variations, carburizing temperature and amount of Chromium in the samples. These tests were performed on surface densified rings in order to see the influence of varying density. 3) influence of the carburizing gas on the carburizing effect.

Experimental

The TS bars are dog bone samples for tensile testing with a minimum cross section of 5,7x5,7 mm (0,197”x0,197”). The IE bars are a rectangular prism with sides 55 x 10 x 10 mm (2.167 x 0,394 x 0,394”). The Surface densified rings have the dimensions: OD/ID/H 35/14/10 mm (1.378/0.551/0.394). All the samples, except for Experiment 3, were manufactured by cold compaction to a green density of 7.0 g/cm^3. The material for Experiment 3 was cold compacted to densities of 6,9, 7,0, and 7,3 g/cc. Furthermore specimens reaching 7,7 g/cc was manufactured by powder forging. Sintering was performed at 1120°C for 30 minuets in an atmosphere of 90% nitrogen and 10% hydrogen. The surface densified rings were rolled between two rollers to a diameter reduction of 0.4 mm (0.0157”). The surface densification process provides a virtually porosity free surface zone

In experiment 1 an ECM vacuum furnace was used and in Experiments 2 and 3 an Ipsen vacuum furnace was used. The samples for the three experiments were heat treated according to the procedures in Table 2.

The heat-treated samples were prepared metallographically and the microstructures were investigated in light optical microscope. The micro hardness HV0,1 was measured in the martensite on lightly etched samples.

Chemical analysis (carbon content) of the surface layer of about 50-80 micron removed by turning, metallographic analysis and microhardness profiles were carried out on case hardened materials. Surface layer turning for chemical analysis was performed as indicated in Figure 5.

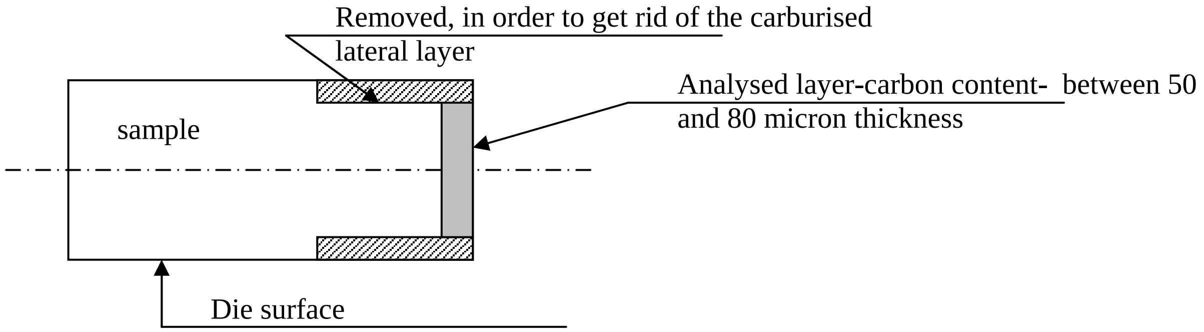


Figure 5. Schematic view of sampling for surface carbon analysis.

During turning, the sample was cooled down with compressed air after each turning step and therefore, the macro temperature was kept below approx 40ºC. The weight of the chips collected from a single surface was in range of 0.1g and therefore, 5 samples were used for this analysis.

Table 1 Investigated materials

Code	Material	MPIF designation	Nominal composition			Graphite addition (wt.%)	Density (g/cm^3)
			Fe (wt.%)	Cr (wt.%)	Mo (wt.%)		
A	Astaloy CrL	FL-5208	Bal.	1.5	0.2	0,3	7,0
B	Astaloy CrM	FL-5305	Bal.	3.0	0.5	0,3	7,0
C	Astaloy Mo	FL-4905	Bal.	-	1.5	0,3	7,0

Results

1. Samples with uniform density

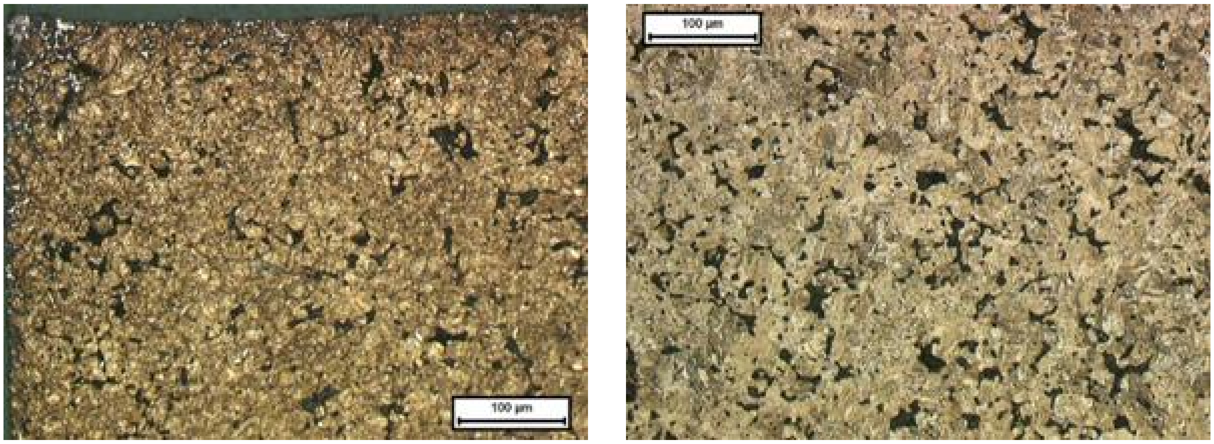
After carburizing, quenching and tempering the microstructure of the case consists of plate martensite (Figure 6) and the hardness at the surface reaches over 800 HV0,1 (Figure 7) that was the target. At corners a few carbides are found, but not enough to provoke bainite formation or carbon depletion in the martensite. Further into the material the hardness drops and 550 HV0,1 is reached at a distance of 0,65 mm (0.0256”) from the surface. The core hardness is 325 HV0,1 and the structure is mainly bainite with some lath martensite.

Table 2. Heat treatment conditions

	Experiment 1 Carburizing of materials of uniform density	**Experiment 2** Effect of carburizing temperature, density and material	**Experiment 3** Effect of carburizing gas type
Material	A	A, B, C	A
Specimens	TS and IE bars	SD rings	TS bars
Heat furnace to heat treating temperature (min)	29 min	60 min	52 min
Soak load at heat treating temperature (min)	29 min	30 min	60 min
Carburizing gas	acetylene	acetylene	acetylene, propane
Carburizing temperature	950 ^{o}C (1742 ^{o}F)	1050 ^{o}C (1922 ^{o}F) 950 ^{o}C (1742 ^{o}F) 920 ^{o}C (1688 ^{o}F)	950 ^{o}C (1742 ^{o}F)
Total carburising time	6 min	4x2 min	4,5 min
Total diffusing time at P<0,1 mbar	80 min	86 min	107 min
Gas quench	20 bar 15 min	10 bar 15min	10 bar 15min
Target case depth (E_{HT550})	0,6 mm	0,8 mm	-
Target surface carbon content	0,8 wt.%	0,8 wt.%	0,6 wt.%

2 Effect of carburizing temperature, density and material

In all the SD-ring samples carbide networks were found in the non-densified areas. In the densified areas, with a density near the theoretical, only few carbides were found. In Material C, no carbide formation was observed in the densified zone at any temperature. Material B showed the largest tendency to form carbides. The micro structural observations for the three heat treated materials are described more in detail below. The hardness profiles in the surface densified regions are very similar for all the samples were carbides are not found.



Micro structure near the surface. Mainly plate martensite. Few carbides near the corners.

Microstructure in the center. Mainly bainite and low carbon (lath) martensite

Figure 6. Micro structure in the etched condition of Material A.

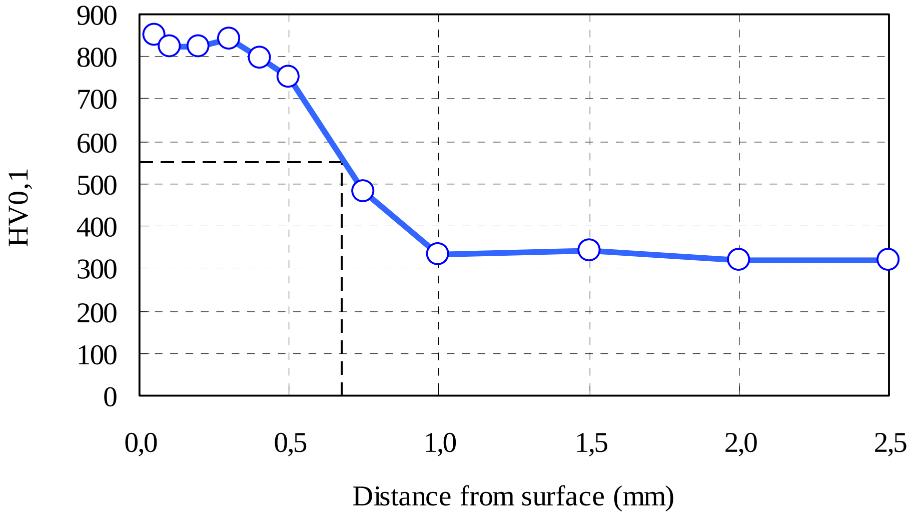


Figure 7. Micro hardness as a function of the distance from the surface. Case depth (E_{HT550}) is 0,65 mm.

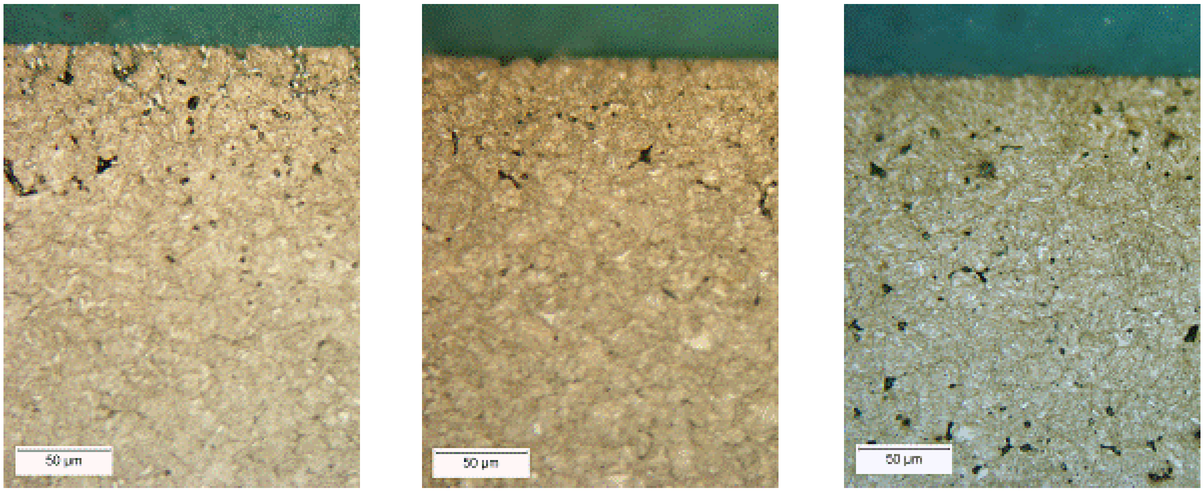
Material A

There is carbide formation in the surface densified zone in the samples heat treated at 920°C, but not in the samples heat treated at 950 and 1050°C, as shown in Figure 8. A network of carbides in the non-densified areas is seen in all the samples as shown in Figure 9. The depth of the layer containing carbides decreases with increasing temperature. The carbide networks in the samples of Material A are smaller than in Material B. The hardness profile of Material A is shown in Figure 10. The surface hardness is near 800 HV0,1 and the case depth (E_{HT550}) is 0,62 mm (0.0244”). The core hardness is 300 HV0,1.

Material B

In the densified surface, there is carbide formations at all temperatures except 1050 °C. In the non-densified surface zones there are carbide formation at all temperatures and the areas between the carbide networks contains bainite and retained austenite, as shown in Figure 11. There is also a marked drop in carbide formation from 920 to 1050 ^{o}C (1688 to 1922 ^{o}F).

Material C
No precipitated carbides could be seen in the densified surface of the samples of Material C at any of the temperatures, as shown in Figure 12. In the non-densified areas, there are networks of carbides surrounding areas of bainite and retained austenite. The higher the heat-treating temperature, the smaller are the networks. The amount of retained austenite in the non-densified zones increases with increasing heat treatment temperature, while the amount of carbides and bainite decreases. Carbides surround the bainitic areas, which imply that the carbides have depleted the martensite of carbon and bainite has been formed instead.

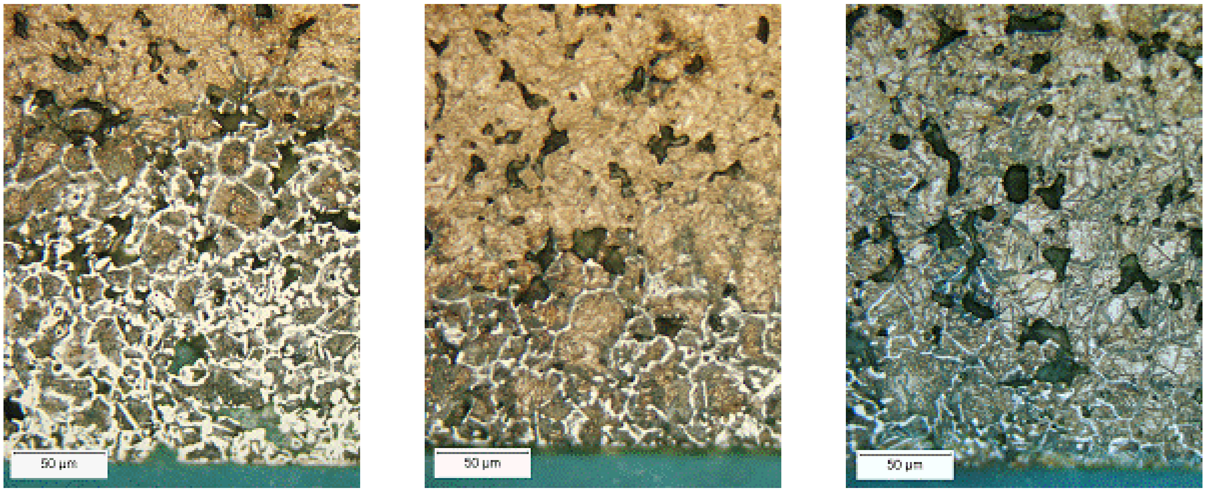


Carburizing temperature 920 °C. Martensite and a small network of carbides and retained austenite

Carburizing temperature 950 °C. The densified surface is martensitic.

Carburizing temperature 1050 °C. The densified surface is martensitic.

Figure 8. Material A, The surface densified region at different carburizing temperatures.



Carburizing temperature 920 °C.

Carburizing temperature 950 °C.

Carburizing temperature 1050 °C.

Figure 9. Material A, carburized at different temperatures. Low density region (Inside diameter)

3 Comparing carburizing gases

The material heat treated using acetylene as carburizing gas reaches very high surface carbon levels at low densities. At higher densities the carbon levels drops until a density of 7.7 g/cc were the target carbon level of 0,6 wt.%C as shown in Figure 13. Using propane as carburizing gas results in much lower carbon uptake at all density levels. Furthermore, the difference between low and high density is much smaller as shown in Figure 13.

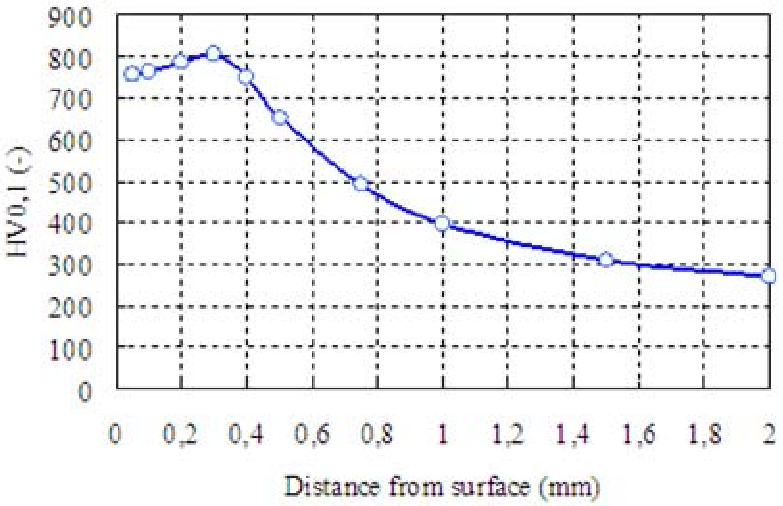
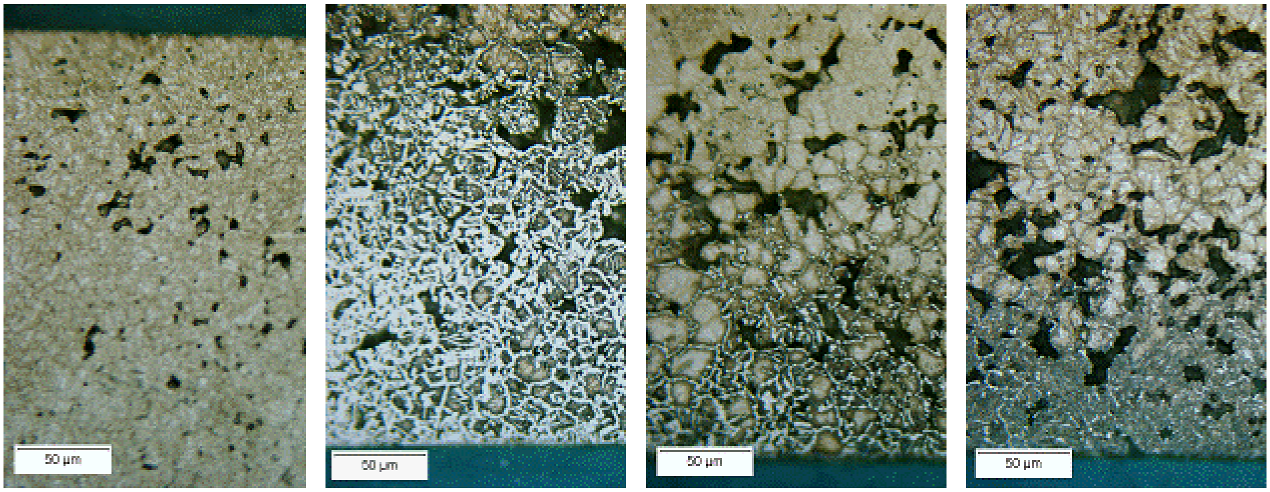


Figure 10. Micro hardness profile of surface densified rings of Material A, carburized at 1050 ^{o}C (1922 ^{o}F).



Carburizing temp. 1050 °C. Surface densified region (outside diameter).

Carburizing temp. 920 °C. Low density region (inside diameter).

Carburizing temp. 950 °C. Low density region (inside diameter).

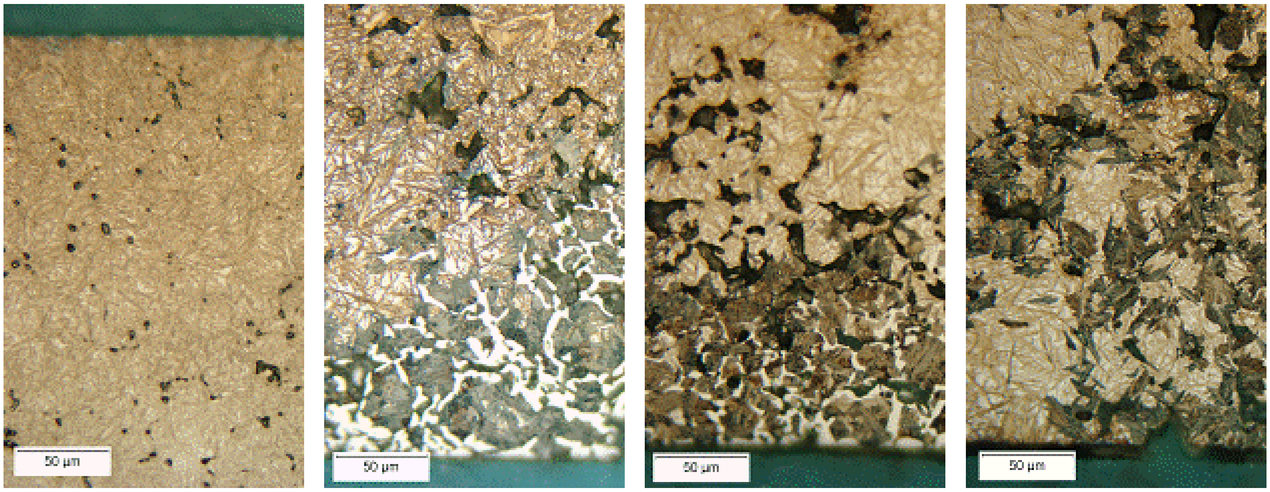
Carburizing temp. 1050 °C. Low density region (inside diameter).

Figure 11. Material B, carburized at different temperatures

Discussion

1 Density

As is evident from the metallography of the surface densified rings there is a large difference in carbon uptake in the high and low density regions respectively. Surface densification is a relatively expensive process undertaken in order to meet fatigue or surface endurance requirements. Carburization and cooling must be tailored in order to create a hard case with specified case depth and core hardness. A consequence of a proper process is that compressive residual stresses are formed at the surface further increasing the performance of the part. However, if the process is specified to give good case properties in the high density region as was the case in Experiment 2 (Figure 8 and Figure 10), the low density regions will be heavily over-carburized (Figure 8). In some cases a simple stacking of the parts can protect regions that must not be over-carburized, but in the general case masking must be applied [27].



Carburizing temp. 920 °C. Surface densified region (outside diameter).

Carburizing temp. 920 °C. Low density region (inside diameter).

Carburizing temp. 950 °C. Low density region (inside diameter).

Carburizing temp. 1050 °C. Low density region (inside diameter).

Figure 12. Material C, carburized at different temperatures

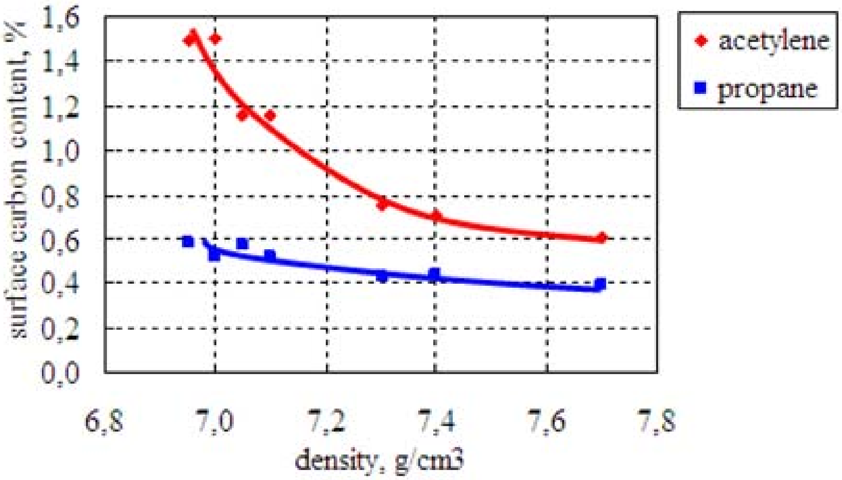


Figure 13. Surface carbon concentrations as a function of part density using acetylene and propane as carbon donor.

The sensitivity to density also means that it will be difficult to design a process without making trial runs. The process in Experiment 1 is the result after one test run that is not accounted for in this report. As heat-treating companies become more aware of the special characteristics of powder metal parts this difficulty will become smaller.

2 Carburization temperatures

Increasing the carburization temperature will have two effects; the activity of the carburizing gas will decrease. This is true for both acetylene and for propane. Furthermore, the solubility of carbon in austenite will increase. The result is a slower influx of carbon and that the carbide formation is delayed until higher carbon levels in the austenite. A third consequence of the higher carburizing temperature is that the diffusion step will become shorter, thus shortening the total process time and consequently increasing productivity.

3 Alloying elements

Comparing Figure 9, Figure 11 and Figure 12 it is clear that the material with higher Chromium contents form more carbides in the low density regions of the surface densified rings. However, it is not certain that the Chromium containing materials actually take up more carbon from the atmosphere. Taking a look at the phase diagram reveals that Material C has the highest solubility of carbon, especially at higher temperature. Material A has a higher solubility of carbon compared to material B. However, the interpretation is not straightforward since it is not clear which carbides actually form at these temperatures for these materials.

4 Carburising gas

At low pressures and temperatures below 1050°C different carburizing gases dissociate in different ways [12]:

Propane: $C_3H_8 \Rightarrow C + 2CH_4$ (1)
Acetylene: $C_2H_2 \Rightarrow 2C + H_2$ (2)

Propane (1) dissociates into carbon and methane, which in turn does not decompose. Acetylene (2) on the other hand delivers two free carbon molecules per acetylene molecule and thus has stronger carburising ability compared to propane. Acetylene is chosen as a carburising gas in the low-pressure carburising furnaces at Ipsen since it has a high carburising effect and because it has a tendency only to dissociate in contact with metallic surfaces, which allows a uniform carburising of dens loads, and components with blind holes of small diameters and large lengths while at the same time it almost totally eliminates the soot and tar formation problem known from propane [8, 10, 16, 28].

Because of the high carburising ability of acetylene it might give too high carbon concentration at the surface of the component during the carburisation cycle. This is especially evident when the available surface area is very large (Figure 13). It may also be the reason for the large degree of carbide formation in the materials at almost all investigated temperatures (e.g. Figure 12). The high degree of carburization in the low density regions indicate that equilibrium is not present at the interface. The ability to form carbon is very high using the acetylene gas and the ability to absorb the carbon is also very high, also after the start of carbide formation. At high density the process is slowed down by the diffusion of carbon through the interface.

5. Carbides

It is not known at this stage what kind of carbides that have been formed. For Material C for example, there are a couple of opportunities according to the phase diagram: M_3C or cementite (which are most probably very similar phases) depending on which carbon content we have. Since there is carbide formation at 950 °C for Material C it is most likely that the carbide is cementite. That conclusion can be drawn since there is a two-phase area (γ+ cem) in the phase diagram at 950°C for carbon contents greater than 1.4%. At lower carbon contents, the material should be fully austenitic. It would be possible that the carbon content locally gets as high as 1.4% or above during the carburisation boost.

In Material B carbides are found in the non-densified zone at all temperatures. Similar to Material C, there is a two-phase area (γ+ cem) at 1050°C at carbon content larger than 1.5%.

In Material A, carbide formation was observed in the densified material of the samples heat treated at 920°C, but not at the higher investigated temperatures. The carbide is also in this case cementite according to the phase diagram.

Conclusions

- It is possible to find low pressure carburizing processes for Chromium containing material that yields excellent results for parts with a uniform density distribution. However, if the heat treating company does not have experience from the particular component and material it may require a test run in order to find the right process.
- With increasing density, the process becomes more and more similar to processes design for wrought steel. At densities above 7,3 g/cc the behaviour is very close to that of solid steel.
- The density have a large impact on the uptake of carbon and the formation of carbides in low pressure carburising. This is a severe problem for components with varying density, were sufficient surface carbon must be ensured at the high density regions causing the lower density regions to be heavily over-carburized.
- Using a high (1050 ^{o}C, 1922 ^{o}F) carburizing temperature the carbide formation during carburization is suppressed compared to conventional carburizing temperatures. This effect is caused by a decrease in carbon activity (of the acetylene) and an increase in saturation level of carbon in the austenite at the higher temperature.
- The Chromium-alloyed materials have a higher tendency to form carbides during carburization compared to the Molybdenum-alloyed.
- Using acetylene as carburizing gas allows carburizing at high temperature. It will also lead to better penetration of cavities during carburization. However, the sensitivity to local density is much higher for acetylene compared to propane and the balance between low and high density regions in a single component may be easier to achieve using propane.

REFERENCES

1 G. F. Bocchini, "Overview of surface treatment methods for PM parts", *PM2TEC 2001: 2001 International Conference on Powder Metallurgy & Particulate Materials; New Orleans, LA; USA;* 13-17 May 2001. pp 6-56 - 6-87

2 H. Ferguson, "The heat treatment of P/M steels--an overview", Heat Treating. *Proceedings of the 16th Conference; Cincinnati, Ohio; USA;* 19-21 Mar. 1996. pp. 319-322. 1996

3 ASM Metals Handbook, Volume 4 Heat Treating

4 H. Ferguson, "Heat Treatment of ferrous powder metallurgy parts", ASM Handbook Vol. 7 *Powder Metal Technologies and Applications*. ASM International, Member/Customer Service Center, Materials Park, OH 44073-0002, USA, 1998. pp. 645-655.

5 P.F. Stratton and L. Sproge, "Gaseous Carburizing and Carbonitriding: the Basics", *Heat Treatment of Metals*. Vol 31., no. 3, pp65-68, 2004

6 H. Ferguson, "Overview of P/M Heat Treating Processes", *Progress in Powder Metallurgy* 1987. Vol. 43; Dallas, Texas; USA; 17-20, May 1987. pp. 521-524. 1987

7 A. Goldsteinas, "New Vacuum processes Achieve Mechanical Property Improvement in Gearbox Components", *Gear Technology*, Vol 24, No 6, pp34-39, 2007

8 "Ipsen on Top", Issue No.2/2003/2, Ipsen International GmbH;

9 W. Grafen, O. Irretier and M. Rink, "Applications of low-pressure carburization with high temperatures (1000 ^{o}C to 1050 ^{o}C) in industrial practice", *Harterei-Technische Mittelungen*, Vol 62, No 3, pp97-102, 2007

10 H. Atena, F. Schrank, "Low pressure carburizing with high pressure gas quenching - fundamentals, applications and furnace technology", *Harterei-Technische Mitteilungen*. Vol. 57, no. 4, pp. 247-

256. 2002

11 S. Kremel, H. Danninger, H. Altena and Y. Yu, "Low-pressure carburizing of sintered alloy steels with varying porosity", *Powder Metallurgy Progress*, Vol 4, No 3, pp119-131, 2004

12 W. Gräfen and B. Edenhofer, "AvaC Acetylene Low-Pressure Carburising- a Novel and Superior Carburising Technology", *Ipsen on top*, Issue No. 2 1999

13 B. Claussen, F. Hoffmann, H-W. Zoch and P. Mayr, "Surface damage in hardening and case hardening processes of steels", Harterei-Technische Mitteilungen, Vol 60, No 1, pp12-18, 2005

14 B. Hildenwall and T. Ericsson, "Residual Stresses in the Soft Pearlite Layer of Carburized Steel", *J. Heat. Treat.*, Vol 1 (No. 3), 1980, pp3-13

15 M. Przylecka, M. Kulka and W. Gestwa, "Carburizing and Carbonitriding Bearing Steel (LH15-52100)", *Heat Treating: Equipment and Processes*; Schaumburg, Illinois; USA; 18-20 Apr. 1994. pp. 233-238. 1994

16 M. Lohrmann, W. Gräfen, "Advanced process and furnace technology for case hardening using low-pressure and plasma carburizing combined with gas quenching", 20th ASM Heat Treating Society Conference Proceedings, 9-12 Oct. 2000, St. Luis, MO, ASM International, 2000, p.290-295

17 D. Beauchesne and A. Goldsteinas, "A Users guide to quenching after vacuum carburizing", Heat treating progress, Vol 4, No 5, pp41-46, 2004

18 C.M. Sonsino and K. Lipp, "Rolling contact fatigue properties of selected PM-material for gearbox applications", SAE Transactions: *Journal of Materials and Manufacturing* (USA). Vol 108, pp250-261, 1999

19 L. Blanco, M. Campos, J.M. Torralba and D. Mint, "Quantitative evaluation of porosity effects in sintered and heat treated high performance steels", *Powder Metallurgy* Vol 48, No 4, pp315-322, 2005

20 T. Prucher, "Carburizing of iron based P/M components", *Heat Treating Progress*. Vol. 1, no. 4, pp. 23-25. Aug.-Sept. 2001

21 J. Capus and H. Ferguson, "Getting the best from PM heat treating", *Metal Powder Report*, April, (1995), pp33-36

22 B. Uhrenius, "Optimization of parameters describing the interaction between carbon and alloying elements in ternary austenite", *Scandinavian Journal of Metallurgy*, 6, (1977), pp83-89

23 S. Nigarura, P. Blanchard and J.R.L. Trasorras, "Processing effects on rolling contact fatugue properties of sintered and DensiFomed Ferrous Alloys", PM2TEC 2001: 2001 International Conference on Powder Metallurgy & Particulate Materials; New Orleans, LA; USA; 13-17 May 2001. pp10-16 - 10-35

24 K. Loser, P. Heilmann and A. Melber, "High-pressure gas quenching with helium and hydrogen for the hardening of low-alloy steels", *Harterei-Technische Mitteilungen*, Vol 50, No 5, pp314-321, 1995

25 J Titus, "Multiple quench options move low-pressure carburizing closer to universal acceptance", *Industrial Heating*, Vol 75, No 1, pp48-50, 2008

26 D.O. Northwood,L. He, E. Boyle and R. Bowers, "Retained austenite - residual stress - distortion relationships in carburized SAE 8620", Materials science forum, Vol 539-543, Part 5, pp4464-4469, 2007

27 L. Forden, S. Bengtsson and C. Kuylenstierna, "Performance and properties of surface densified PM transmission gear", PM2TEC 2002: World Congress on Powder Metallurgy and Particulate Materials, Orlando, Florida, USA, June 17, 2002

28 J. Kowalewski, "Vacuum carburizing: why the re-birth?" *Heat Treating Progress* (USA). Vol 3, No 1, pp32-34, 2003