OUTSTANDING HARDENING OF PYROWEAR® ALLOY 53 WITH LOW PRESSURE CARBURIZING*

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Abstract

Pyrowear®Alloy 53 steel is an excellent material for the construction of drive transmission components (gears, shafts, etc.) which have to operate in difficult conditions primarily in the aviation industry (Fig. 1.). Among the properties of such items is a high case hardness and abrasion-resistance, while the core remains flexible and is capable of carrying large impact loads. They can work at elevated temperatures with limited lubrication. The thermal treatment of such materials is based on case hardening by means of carburizing. This paper presents the technology of vacuum carburizing of Pyrowear® Alloy 53 steel. It discusses the methods of establishing different profiles of carbon concentration in a layer and their influence on the hardness profile. The effects of sub-zero treatment and tempering on the properties of the hardened case are also considered. It also presents a SimVaC® simulator of vacuum carburizing, designed especially for Pyrowear® Alloy 53 steel, which provides highly accurate predictions of the outcome of the process as the profile of carbon concentration in the layer, or vice versa: establishes the process parameters which will guarantee the required profile.

Keywords: Pyrowear; carburizing; simulation; vacuum

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1 INTRODUCTION

1.1 Properties of Pyrowear® Alloy 53 Steel [1]

Pyrowear®Alloy 53 steel is an excellent material for the construction of drive transmission components (gears, shafts, etc.) which have to operate in difficult conditions primarily in the aviation industry (Fig. 1.).

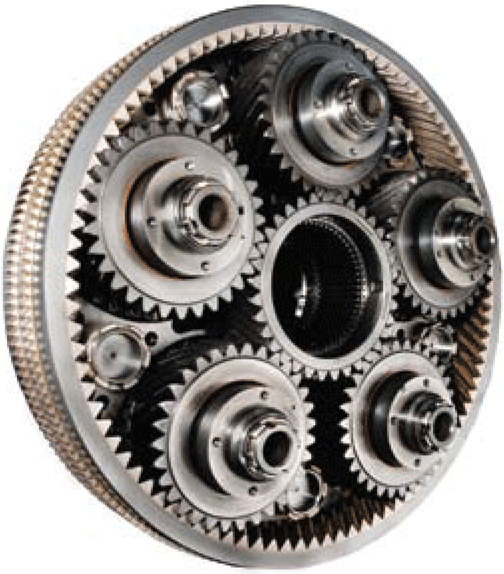


Fig. 1. Components of a gear box (Internet)

The steel is produced by Carpenter Technology Co. and it is intended specially for use in heat-resistant drive units, operating at temperatures exceeding the operating temperature of 9310 steel (AISI). The chemical composition of the steel is as follows: 0.10% C, 0.35% Mn, 1.0% Si, 1.0% Cr, 2.0% Ni, 3.25% Mo, 2.0% Cu.

Two additional alloys - molybdenum and copper - distinguish it from commonly used steels for carburizing. Mo increases the heat resistance and improves resistance to abrasion wear, whereas copper improves the resistance to shock load and the lubrication properties. This composition of alloy additives determines the phase parameters of steel, which in turn determine the temperature range of the thermal treatment.

The thermal treatment of Pyrowear® Alloy 53 steel involves the formation of a hardened case in the process of carburizing and hardening (case hardening). The following are the phases of the process and the temperature parameters recommended by the producer:

- Carburizing at the temperature of
  870–930°C (1600 - 1700°F)
- Oil- or gas quenching from the temperature of
  905–920°C (1660 - 1700°F)
- Sub-zero treatment
  below -75°C(-100°F)
- Tempering
  150– 290°C (300 - 550°F)

Sometimes subcritical annealing at the temperature of 600°C (ca. 1100°F) is applied.

A properly conducted thermal treatment results in a hardened layer with the case hardness exceeding 60 HRC with the core hardness of approx. 35 HRC and the strength of approx. 1200 MPa and the impact resistance (V-notch) of approx. 100-150 J.

2 MATERIAL AND METHODS

The processes were conducted under industrial conditions in a standard Seco/Warwick 15.0VPT-4035/36IQCN vacuum furnace (Vector vacuum furnace line) with a working space of 600/600/900 mm, equipped with a carburizing system (LPC), which also enables high-pressure gas quenching (Fig. 2).

Fig. 2. Seco/Warwick 15.0VPT-4035/36IQCN vacuum furnace (Vector - vacuum furnace line). The parts under study made from Pyrowear® Alloy 53 steel were placed, together with a ballast charge of approx. 250 kg (551 lb), which reflected the standard conditions of industrial processes.

The whole process ran according to the following sequence:

- Vacuum carburizing in the FineCarb® technology [2].
- Slow cooling down followed by annealing and cooling down again to the ambient temperature.
- Heating up for quenching and high-pressure nitrogen quenching Carpenter Technology Co „Pyrowear® Alloy 53 – Technical Datasheet", 2011 [3]
- Sub-zero treatment in a cryogenic chamber.
- Tempering in nitrogen

All the processes except the sub-zero treatment were conducted in the vacuum furnace. However, it is possible to install a sub-zero treatment system in a vacuum furnace; then the whole process can be carried out in one device, within one work cycle.

3 RESULTS AND DISCUSSION

First, a reference process was conducted, for the purpose of:

- verification of the compliance of the simulation of the LPC carburizing process with the actual results
- an analysis of the microstructure and hardness profile after consecutive process stages

The aim of the process was to obtain a hardened layer on Pyrowear® Alloy 53 steel with a surface hardness exceeding 60 HRC and a surface carbon concentration of approx. 0.95%, effective case depth ECD = 1.15 mm (0.045”) at a hardness criterion of 50 HRC (for a carbon concentration of 0.31%).

A high surface carbon concentration of 0.95% is a consequence of the need to achieve the maximum case depth with a hardness exceeding 60 HRC, as measured by the ratio of the case depth with the 60 HRC criterion and the case depth with the 50 HRC criterion.

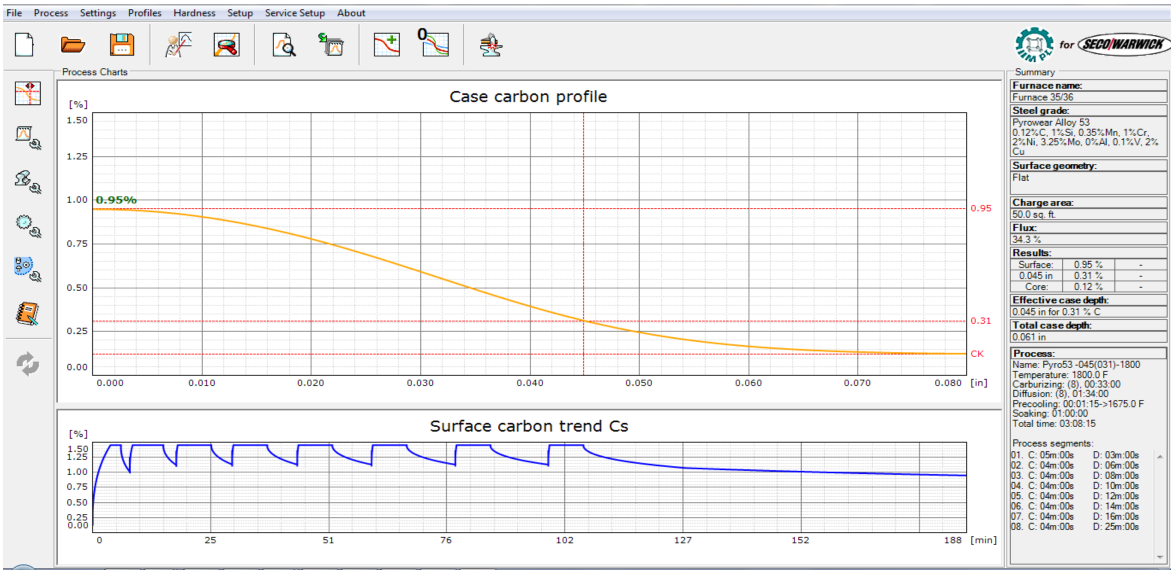
Additionally, the amount of residual austenite should not exceed 20%; moreover, carbides network along grain boundaries should be lower than 30%. These parameters reflect the typical requirements of the aviation industry regarding this technology.

To meet those expectations, a process was developed consisting of the following phases:

- LPC carburizing at a temperature of 980°C (1800°F)
- subcritical annealing for 1 hour at a temperature of 600°C (ca. 1100°F).
- nitrogen quenching at 12 bar at a temperature of 910°C (1675°F)
- sub-zero treatment at -90°C (130°F) for 1 h
- tempering at a temperature of 230°C (450°F) for 1 h.

A decision was taken to conduct the carburizing process at higher temperatures than recommended by the steel producer, considering the 4 times shorter process duration (the process conducted at the recommended temperatures lasts over 8 hours). The negative effect of the temperature on the growth of austenite grains was offset by annealing.

The LPC process was simulated with the SimVaC® program, which has the characteristics of Pyrowear® Alloy 53 steel in its database. Fig. 3 shows the result of the simulation in the form of the process parameters, the final carbon profile curve (above) and the curve illustrating the changes of the carbon surface concentration during the carburizing process (below).



Furnace name:
Furnace 35/36

Steel grade:
Pyrowear Alloy 53
0.12%C, 1%Si, 0.35%Mn, 1%Cr, 2%Ni, 3.25%Mo, 0%Al, 0.1%V, 2% Cu

Surface geometry:
Flat

Charge area:
50.0 sq. ft.

Flux:
34.3 %

Results:

Surface:	0.95 %	-
0.045 in	0.31 %	-
Core:	0.12 %	-

Effective case depth:
0.045 in for 0.31 % C

Total case depth:
0.061 in

Process:
Name: Pyro53 -045(031)-1800
Temperature: 1800.0 F
Carburizing: (8), 00:33:00
Diffusion: (8), 01:34:00
Precooling: 00:01:15->1675.0 F
Soaking: 01:00:00
Total time: 03:08:15

Process segments:
01. C: 05m:00s D: 03m:00s
02. C: 04m:00s D: 06m:00s
03. C: 04m:00s D: 08m:00s
04. C: 04m:00s D: 10m:00s
05. C: 04m:00s D: 12m:00s
06. C: 04m:00s D: 14m:00s
07. C: 04m:00s D: 16m:00s
08. C: 04m:00s D: 25m:00s

Fig. 3. The process for the 0.045’’ case simulated by the SimVaC® simulator. In order to obtain the required layer of 1.15 mm (0.045”) at a carburizing temperature of 980°C (1800°F), the LPC process should be divided into pairs of boost (C) and diffusion (D) according to the following time sequence [min]: C/D = 5/3+4/6+4/8+4/10+4/12+4/16+4/25. The duration of the carburizing process is only 2 h 7 min. additionally; the simulation takes into account the effect of reheating for quenching on the final carbon profile.

The process was conducted in accordance with the assumptions and the simulation and a final case depth of 1.15 mm (0.045") was achieved, with a surface hardness of 64 HRC and a core hardness of 42 HRC. At the same time, a case depth of 0.76 mm (0.030'') was achieved at the criterion of 60 HRC, which accounts for over 60% of the case depth at the criterion of 50 HRC. The case microstructure (Fig. 4) consists of tempered martensite with uniformly distributed inclusions of fine, globular carbides with a size of under 1µm, forming larger structures immediately below the surface (within the requirements range). Residual austenite is present in quantities which cannot be estimated with an optical microscope - below 5%.

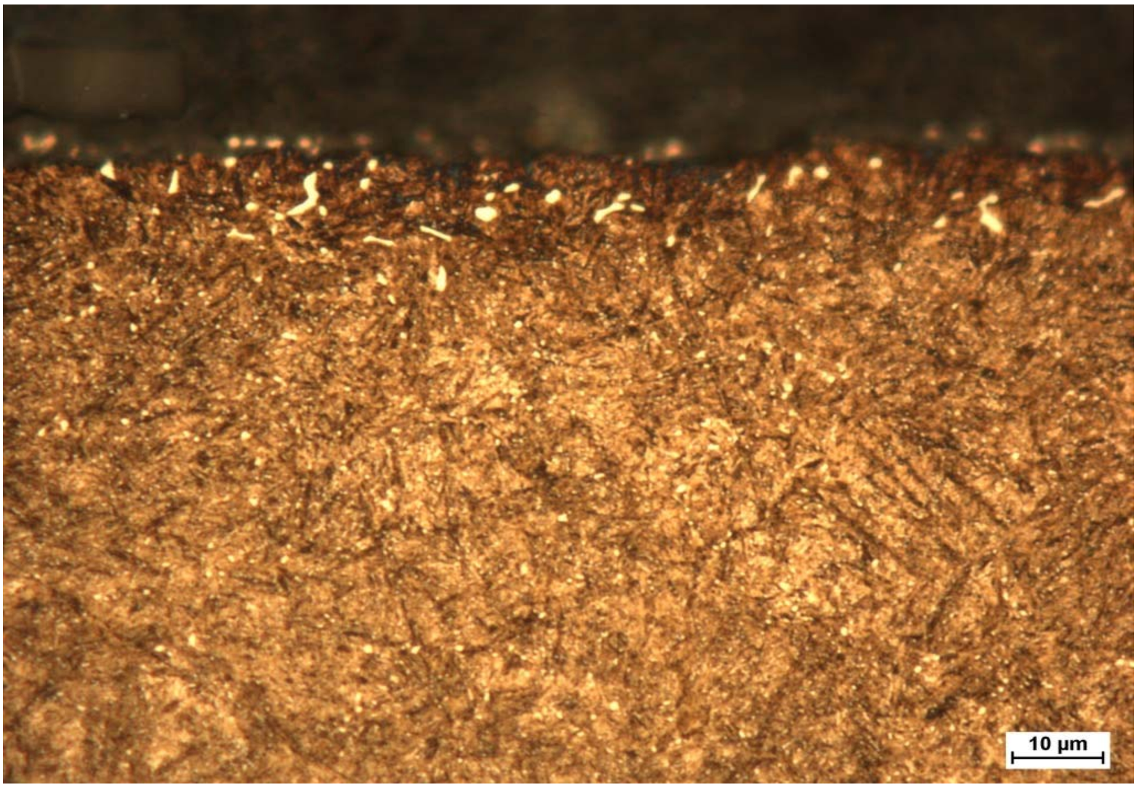


Fig. 4. Final microstructure of a hardened layer of Pyrowear® Alloy 53 steel following the reference process, etching agent "king's water (60 cm^3 $C_3H_8O_3$, 40 cm^3 HCl, 20 cm^3 HNO_3). etching time 20 seconds

The graph in Fig. 5 shows the hardness profiles reflecting the transformations which occur in the layer after subsequent phases of the process. The process of carburising and cooling down slowly resulted in a profile typical of a martensitic structure with a high level of residual austenite near the surface (over 50%). The process of subcritical annealing resulted in the formation of a fine ferritic-austenitic structure, with much lower hardness, with uniform formations of fine carbides. The hardening phase again raises the hardness profile to the previous level, forming a martensitic-austenitic structure, with a characteristic decrease in hardness near the surface. This effect if removed by sub-zero treatment (austenite to martensite transformation), which increases the surface hardness to 65 HRC. The tempering process results in the formation of a stable, final microstructure of tempered martensite.

1. nd Exposition, Cincinnati, Ohio, USA, 2011

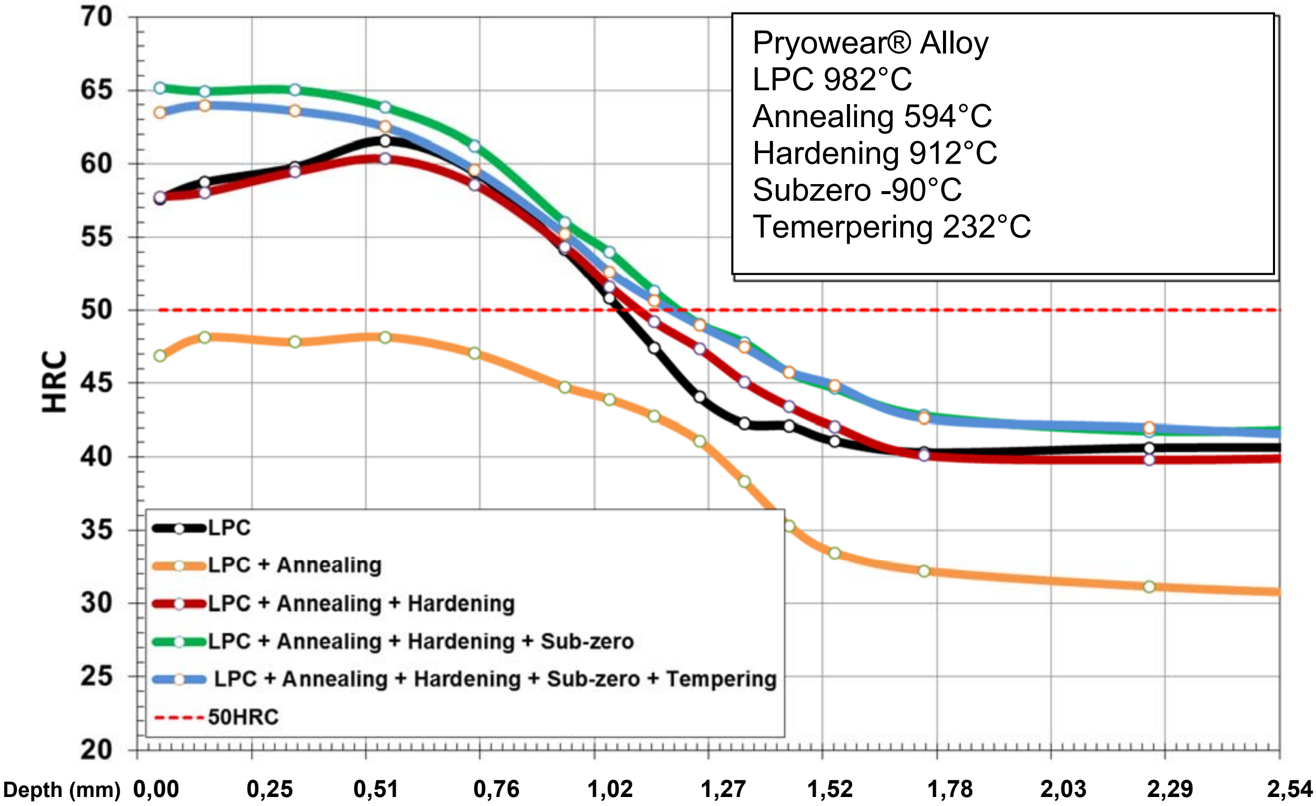


Fig. 5. Hardness profiles obtained after consecutive phases of the reference process.

3.1 Comparative Processes

In the next stage of the study, additional processes, whose purpose was to show the effect of a change in the temperature of quenching, sub-zero treatment and tempering on the case hardness profile, were conducted. Only one temperature parameter was changed in the processes; the other phases were conducted according to the reference process.

In the case of quenching, the process was conducted not only at the reference temperature 910 oC (1675 oF), but also at higher 955°C (1750°F) and lower (870°C, 1600°F) temperatures. The graph (Fig. 6) shows the hardness profiles, which show that the quenching temperature has the greatest effect on the core hardness, which increases with temperature and has the following values: 37, 41 and 43 HRC. This results from the higher solubility of carbides and higher saturation of austenite with carbon at higher temperatures. The case hardness is very stable and decreases only by 1 HRC (from 64 to 63 HRC) at a temperature of 870°C (1600°F). A higher temperature of quenching 955°C (1750°F) slightly increased the case depth from 1.15 mm (0.045”) to 1.26 mm (0.050”) as an effect of better hardenability.

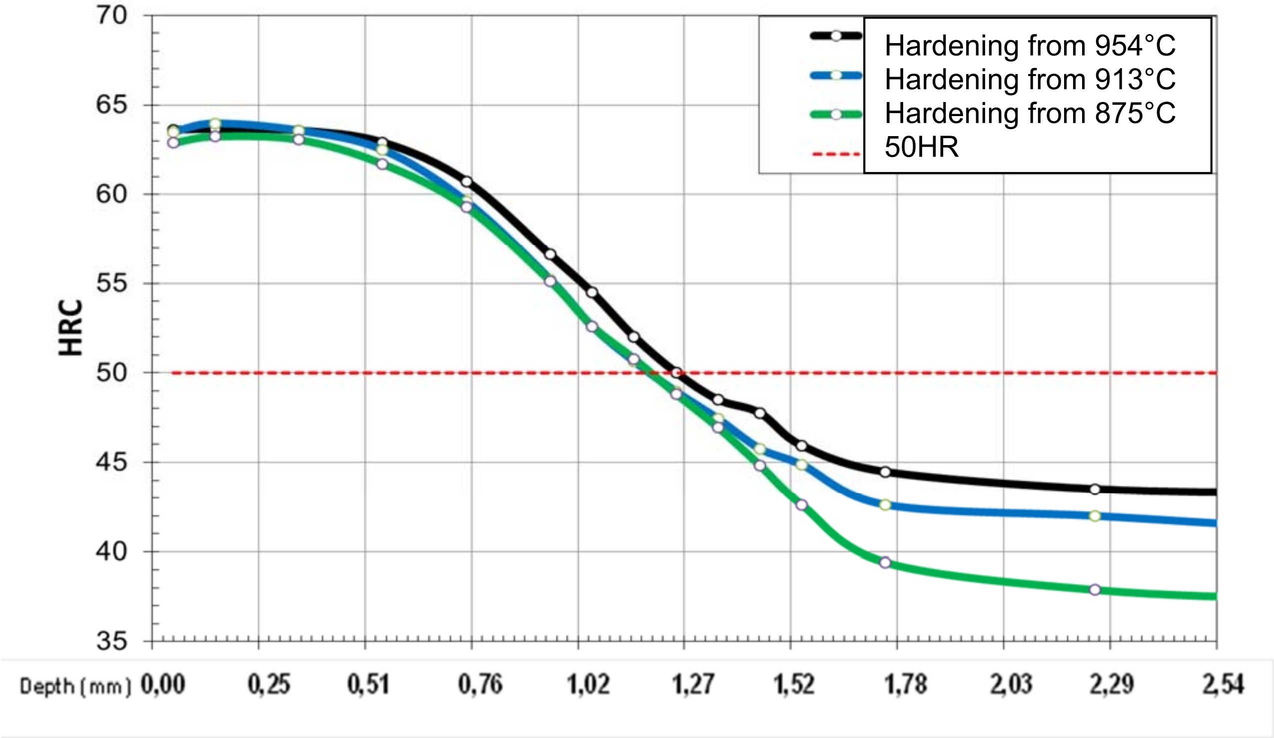


Fig. 6. The effect of the quenching temperature on the final case hardness profile.

The sub-zero treatment was conducted at 3 temperatures: -60°C (-80°F), -90 °C (-130°F) and -120°C (-180°F), and the respective hardness profiles are shown in Fig. 7. Both hardness profiles after the sub-zero treatment at lower temperatures are nearly identical. The sub-zero treatment at the temperature of -60°C (-80°F) resulted in a slight decrease in the surface hardness, which indicates a larger amount of residual austenite compared to the processes conducted at the temperatures below -90°C (-130°F).

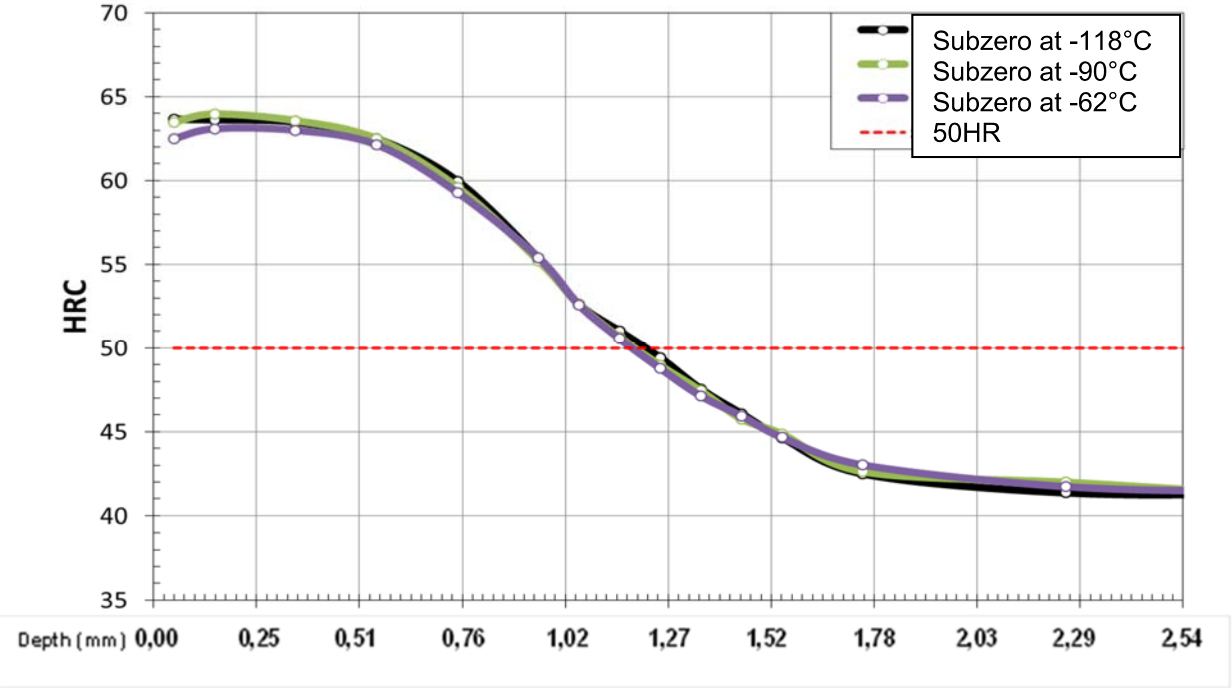


Fig. 7. The effect of the sub-zero treatment temperature on the final case hardness profile.

Similarly, tempering was additionally conducted at a temperature lower (175°C, 350°F) and higher (290°C, 550°F) than the reference temperature. The relevant hardness profiles are shown in the graphs in Fig. 8. The temperature of tempering was not proved to have any effect on the core hardness or the case depth within the temperature range under study. Slight differences in hardness were observed near the surface; it decreased slightly with an increasing temperature, from 65 HRC, through 64 HRC, to reach 63 HRC at a temperature of 290°C (550°F), which confirms elevated thermal stability of the case.

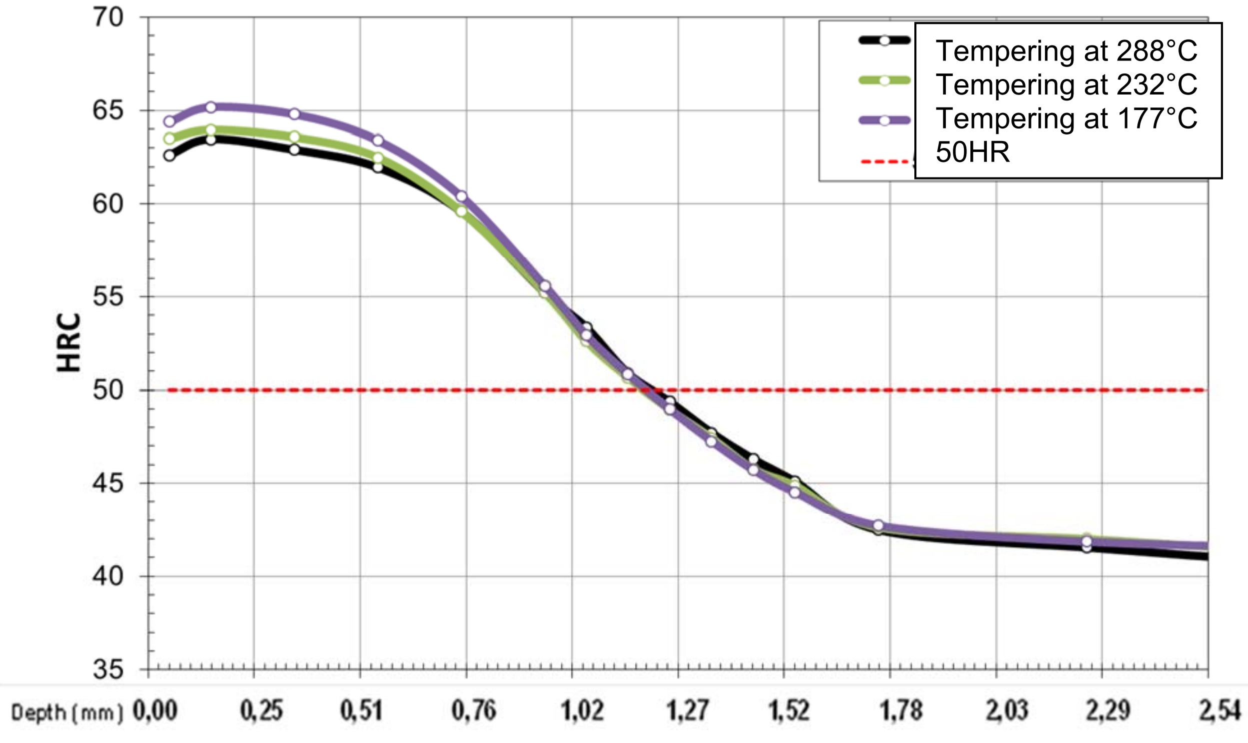


Fig. 8. The effect of the tempering temperature on the final case hardness profile.

3.2 Shaping the Hardness Profile

The requirements for a hardened case frequently contain a parameter which characterises the shape of the hardness profile, which is defined as the minimum ratio of the depth of two layers for two different criteria, usually with a hardness of 60 HRC and 50 HRC, e.g. minimum 40% of the case depth at the criterion of 60 HRC relative to the case depth at the 50 HRC criterion. The effect of the surface concentration of carbon and case depth was analysed as part of this issue.
The graphs in Fig. 9 present simulated the profiles of carbon concentration (SimVaC$^{®}$), differing from surface carbon concentration, with the same case depth for the adopted hardness criterion of 50 HRC, which corresponded to a concentration of 0.30% C. Another case depth criterion was adopted for 60 HRC, to which the carbon concentration of 0.70% was assigned. Case depths for each carbon profile were determined at both criteria (60 and 50 HR) and their ratio was calculated. The highest ratio of case depth at 60 HRC to that at 50 HRC of 60% was achieved at the highest surface concentration of 1.00% C; it decreased gradually with a decrease in surface carbon concentration. The analysis shows that the ratio of case depth at the higher hardness criterion (e.g. 60 HRC) to the case depth at the lower hardness criterion (e.g. 50 HRC) can be changed from 0% to the maximum (practically to 70%) by

changing the surface carbon concentration. The maximum surface carbon concentration is limited by the formation of carbides and the limits of retained austenite formation, which depend on a specification, steel grade and the parameters of thermal treatment.

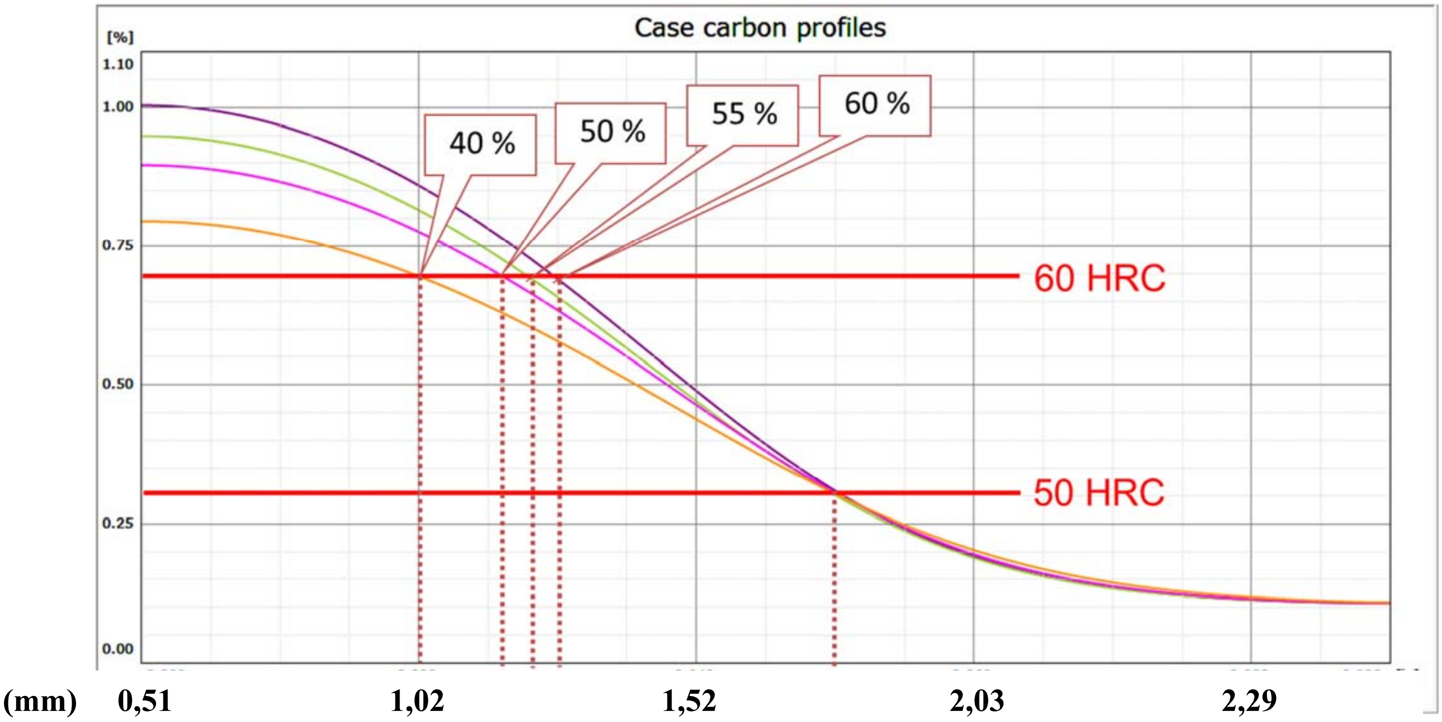


Fig. 9. The effect of surface carbon concentration on the case depth ratio at the 60 HRC and 50 HRC criteria. No effect on the case depths ratio for different criteria, for the same surface carbon concentration was shown for the case depth alone. Fig. 10 shows carbon profiles and the calculated constant case depth ratio of 50% for all the profiles.

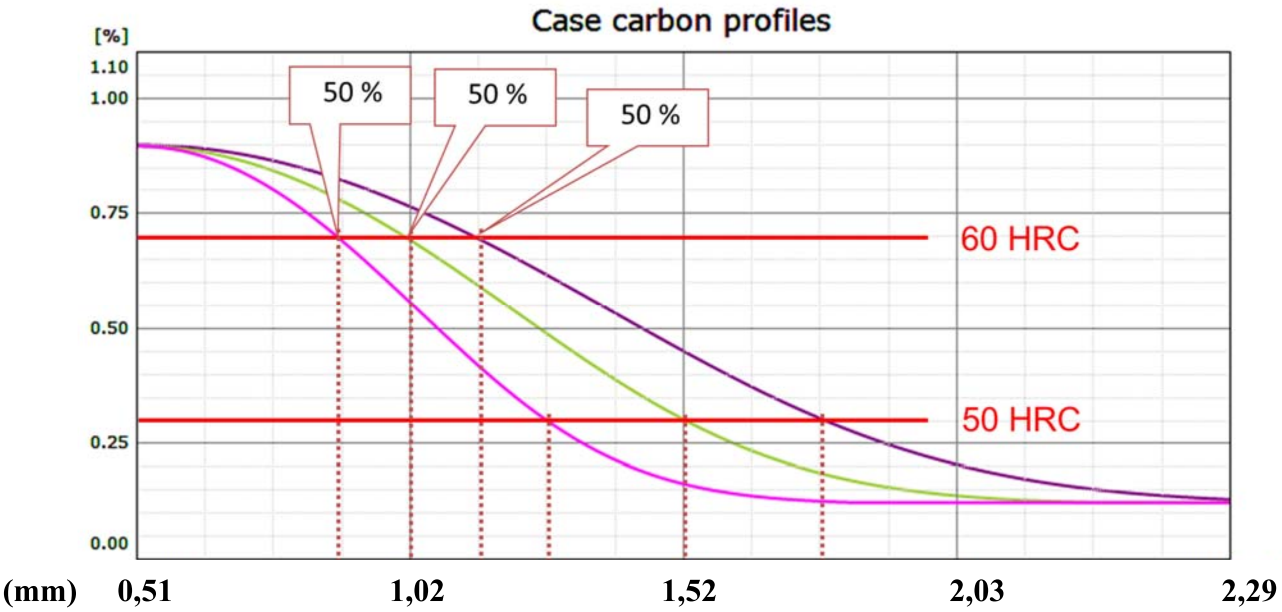


Fig. 10. The effect of case depth on the case depth ratio at the 60 HRC and 50 HRC criteria with a constant surface carbon concentration.

4 CONCLUSION

- Vacuum carburizing by the FineCarb® method and high pressure gas quenching (HPGQ) meets the requirements of the case hardening process for Pyrowear® Alloy 53 steel.
- The whole process can be conducted in a single-chamber vacuum furnace, in one working cycle.
- Vacuum carburizing processes are simulated with a high accuracy on a dedicated SimVaC® simulator, whose database contains Pyrowear® Alloy 53 steel.
- It is justified to apply an elevated carburising temperature, which reduces the process duration greatly, for example 4 times at a temperature of 980°C (1800 °F).
- The case hardness profile depends mainly on the carbon concentration profile, but it is also affected by: the temperature of quenching, sub-zero treatment and tempering.
- The temperature of quenching directly affects the core hardness; the higher the temperature, the higher the hardness, which reaches 37-43 HRC at temperatures of 870-955°C (1600-1750°F).
- The temperature of the sub-zero treatment affects the degree of austenite transformation. The optimum temperature is -90°C (-130°F).
- The tempering process affects surface hardness: the higher the temperature, the lower the hardness. A hardness of 65-63 HRC was achieved at temperatures of 175-290°C (350-550°F), which confirms the resistance of Pyrowear® Alloy 53 steel to increased operational temperature.
- Pyrowear® Alloy 53 steel can be carburized to a surface carbon concentration level of approx. 1.0%, which makes it possible to obtain a flat profile of high hardness.
- The ratio of the case depth at a hardness of 60 HRC to the case depth at a hardness of 50 HRC directly depends on the surface carbon concentration and not on the case depth.

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