ARCHIVES OF CIVIL AND MECHANICAL ENGINEERING
Vol. X 2010 No. 1

Effect of phosphorus on vacuum carburising depth of iron compacts

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The work was aimed at determining the effect of phosphorus on vacuum carburising of iron compacts with density over 7.2 gcm^{-3}. An attempt was made to determine the effectiveness of phosphorus on carbon diffusion rate into the material of compacts with no additional effect of interconnected porosity. Vacuum carburising of compacts, made with a blend of powders ASC100.29 and PASC60, was carried out at 1050 °C in a laboratory vacuum furnace.

The effect of phosphorus content within 0.1% to 0.6% on the vacuum carburising depth was analysed. It was found that the phosphorus addition up to 0.4% increased the carburising depth by ca. 20% in comparison with the compacts of pure iron.

Keywords: *phosphorus, vacuum carburising, iron compacts*

1. Introduction

In solid structural steels, phosphorus is considered a detrimental impurity. It increases the steel brittleness by increasing the so-called brittle-to-ductile transition temperature. In sintered steel brittleness is mainly caused by pores, so this unfavourable phosphorus effect is invisible. However, other properties of phosphorus are enhanced. It results from the Fe-P equilibrium system that at the sintering temperature it creates with Fe a liquid mixture that intensifies the sintering process. When introducing phosphorus, the sintering process is intensified not only by action of the liquid phase (transition eutectic mixture Fe-Fe_3P), but also by activation of sintering in the created solid solution. At phosphorus concentration over 0.3%, the Fe_α and Fe_γ phases are created at normal sintering temperatures ca. 1150 °C. The α phase, in that the Fe self-diffusion coefficient is ca. 100 times higher than in the γ phase, ensures good sintering of Fe powder grains and the two-phase structure prevents from excessive grain growth occurring in one-phase structure as a result of phosphorus action [1–2]. As a consequence, sinters are obtained with higher strength and ductility in comparison to those of pure iron with identical density. Phosphorus reduces the austenite area and increases ferrite strength by dissolving in it (maximum to 2.8 wt.% at 1050 °C). The phosphorus concentrations most frequently occurring in sintered steels range from 0.3 to 0.6% [3].

Vacuum carburising is very frequently applied to sintered parts because of better control of carburising depth in comparison to traditional gas carburising, which consequently permits obtaining the assumed thickness of the case-hardened layers.

Thanks to its specificity [4–9], this method ensures faster carburisation process, mainly thanks to higher temperature and lower hydrocarbon gas pressure during the process. The carburisation depth depends on carbon diffusion rate into the material. In turn, the carbon diffusion rate depends not only on the process parameters but also to a large extent on the parameters of the processed material. In the case of products made by powder metallurgy, the carburisation depth is decidedly depended, beside chemical composition, on the material density and especially the volume fraction of interconnected porosity.

In this work, an attempt was made to evaluate the effectiveness of phosphorus on vacuum carburising process of iron compacts with density over 7.2 gcm^{-3}. The main purpose was to analyse the sole effect of phosphorus addition on carbon diffusion rate into the material by excluding the effect of interconnected porosity. In the specialist literature, a very small amount of data can be found on phosphorus influence on carbon activity in Fe-C-P alloys. In particular, shortage of experimental data is noticeable. The few existing data, mainly based on theoretical analyses and computer simulations [10–11], seem to confirm increased carbon activity in phosphorus presence. Therefore, it was assumed that increased carbon activity could accelerate its diffusion into the material, resulting in faster and deeper carburisation of iron-based compacts.

2. Material and experimental procedure

Cylindrical test specimens dia. 13 mm × 10 mm were made of mixed powders ASC100.29 and PASC60 (produced by Höganäs AB) by one-side pressing at 800 MPa. 0.6% Kenolube P11 was used as the sliding agent. The 6 lots of specimens (3 ones in each) were prepared, with various phosphorus concentrations within 0.1% to 0.6% P. To compare the results, some specimens of pure iron with density 7.25 gcm^{-3} were prepared. Chemical composition and density of the prepared specimens is given in Table 1. Hardness of the vacuum-carburised specimens was measured using the Vickers method under 1 kG (9.81 N). Microscopic examinations and pearlite content measurements were performed using a computerised imaging system and "Multiscan" software made by Polish company Computer Scanning Systems.

Table 1. Chemical composition and density of examined compacts

Specimen	Chemical composition		Green density [gcm^{-3}]
	wt.% P	wt.% Fe	
Fe-0.1P	0.1	remainder	7.26
Fe-0.2P	0.2		7.25
Fe-0.3P	0.3		7.25
Fe-0.4P	0.4		7.26
Fe-0.5P	0.5		7.25
Fe-0.6P	0.6		7.24

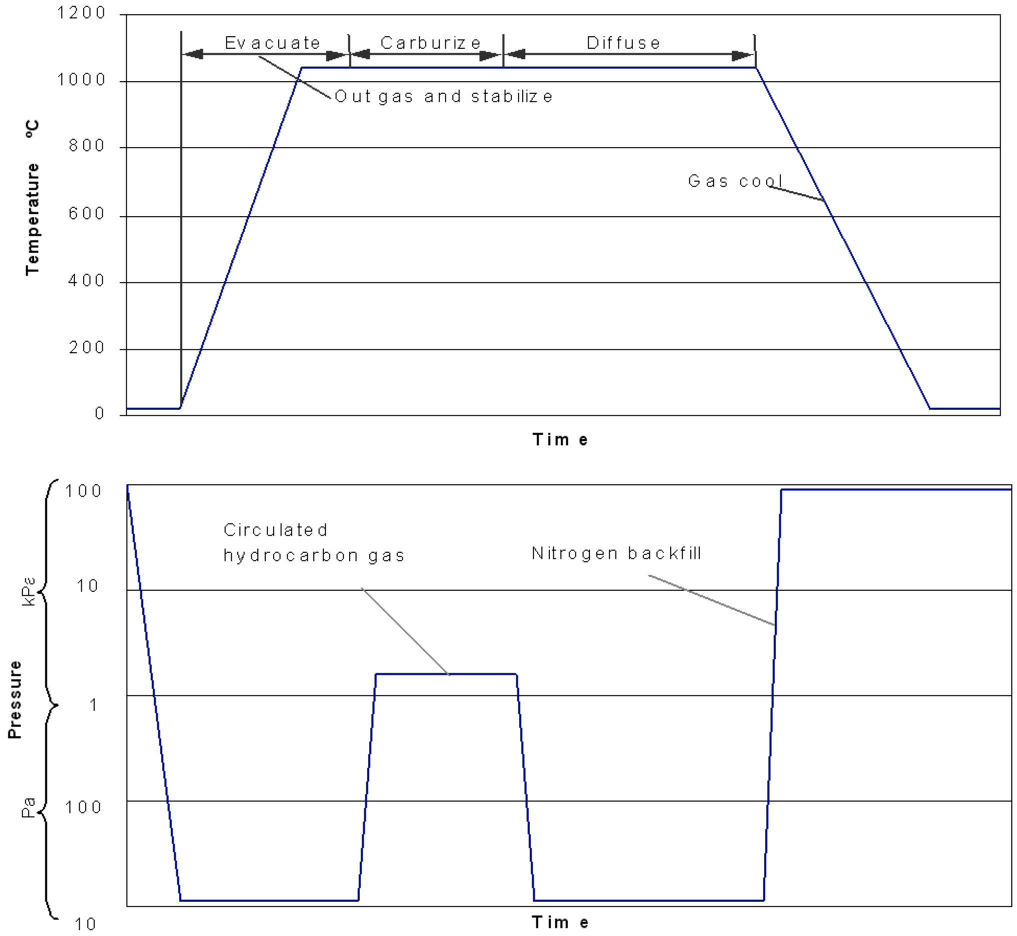

Fig. 1. Vacuum carburising process: a) variation of temperature, b) variation of pressure; (scheme)

The vacuum carburising process was carried out in a laboratory vacuum furnace (Seco/Warwick). The process parameters: temperature and time were 1050 °C and 360 minutes (boost time = 30 min and diffuse time = 330 min).

The carburising atmosphere consisted of propane diluted with nitrogen. Working pressure in the furnace chamber was 20 hPa. Stable working pressure in the chamber during carburising was maintained by cyclical dosing the gas with constant flow rate of 110 dm^3h^{-1}. A schematic diagram of vacuum carburising is shown in Figure 1.

3. Results and discussion

Carburisation depth was determined on the ground of hardness profile in the hardened layer obtained as a result of vacuum carburising. Boundary of the carburised layer was defined at hardness equal to arithmetic mean of average hardness values of surface layer and core (in the middle of transition zone). The so obtained carburisation depth values and the related hardness values of all the examined specimens are settled in Table 2. The representative hardness profile for Fe-0.4P specimen is shown in Figure 2.

Table 2. Carburisation depth and hardness of phosphorus-containing and pure iron compacts

Specimen	Carburisation depth [mm]	Hardness HV1 (in the centre of transition zone)
Fe-pure	2.8 ± 0.1	101
Fe-0.1P	2.9 ± 0.1	127
Fe-0.2P	3.0 ± 0.1	134
Fe-0.3P	3.2 ± 0.1	145
Fe-0.4P	3.3 ± 0.1	152
Fe-0.5P	3.0 ± 0.1	155
Fe-0.6P	2.8 ± 0.1	152

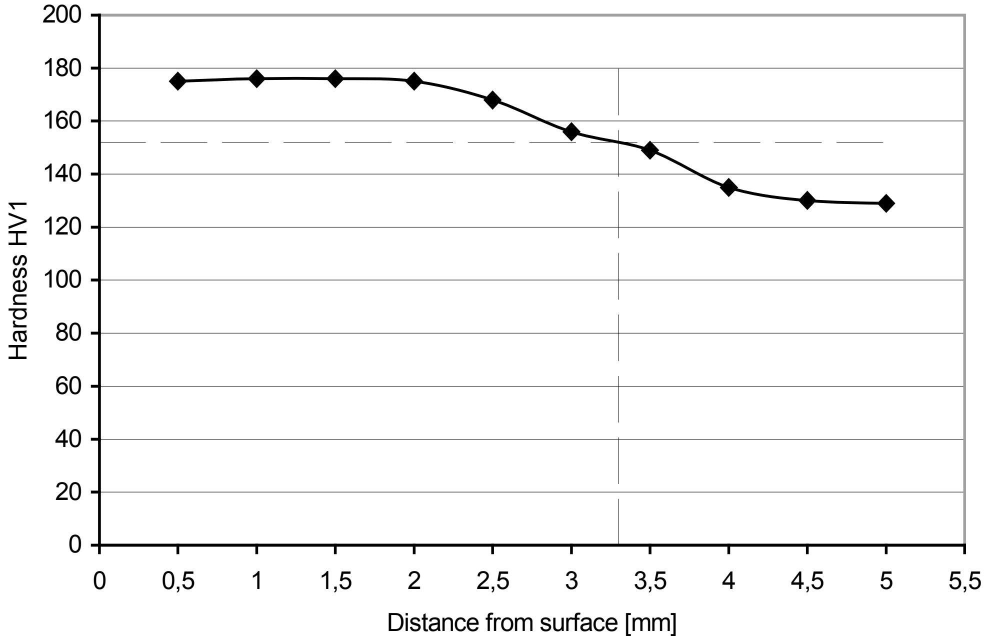

Fig. 2. Hardness profile HV1 for Fe-0.4P specimen

Figures 3 and 4 show representative microstructures of carburised layer and core for the Fe-0.4P specimen. In all the examined specimens, the carburised layer consists of pearlite with ferrite and the core consists of ferrite strengthened with phosphorus only.

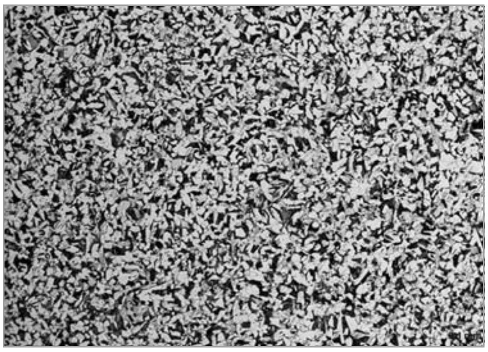

Fig. 3. Case microstructure of specimen Fe-0.4P

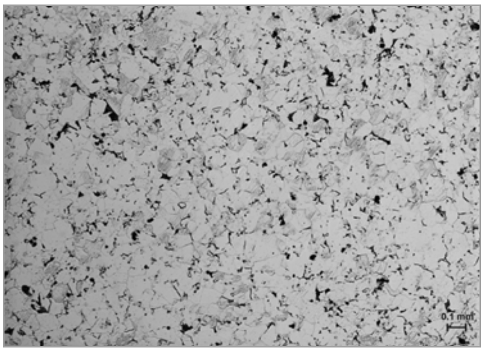

Fig. 4. Core microstructure of specimen Fe-0.4P

Fraction of pearlite in the carburised layer changes gradually with changing phosphorus content from the highest 48% in the Fe-0.1P specimen to the lowest 38% in the Fe-0.6P specimen. The pearlite fractions determined in carburised layers of the examined specimens and their related carbon concentrations are settled in Table 3. The carbon concentrations were calculated accepting 0.77% C in the eutectoidal point and omitting phosphorus effect that shifts it to the left (according to literature data), towards lower carbon concentration. With this effect considered, the calculated carbon concentrations would be slightly lower.

Table 3. Estimated pearlite volume fraction and carbon content in case of examined specimens

Specimen	Pearlite volume fraction [%]	Carbon content [wt. %]
Fe-0.1P	48	0.37
Fe-0.2P	47	0.36
Fe-0.3P	43	0.33
Fe-0.4P	40	0.31
Fe-0.5P	39	0.30
Fe-0.6P	38	0.29

Decrease of pearlite fraction and its related carbon concentration along with increasing phosphorus concentration is a consequence of decreasing carbon solubility in austenite at the carburising temperature of 1050 °C. According to the computed equilibrium diagrams C-Fe-P published in [11], solubility of carbon in austenite at 1050 °C changes from ca. 1.7% for 0.1% P to ca. 1.2% for 0.6% P. In this case, phosphorus behaves like boron, silicon and other elements which intensify carbon activity in austenite and thus reduce surface carbon concentration in the layer during carburisation. Lower surface carbon concentration results in its slower diffusion into the material. The obtained carburisation depths (see Table 2) indicate that, along with phosphorus concentration increasing to 0.4%, thickness of the carburised layer increases in spite of lowering surface carbon concentration in the layer. This increase evidences favourable effect of phosphorus on carbon diffusion rate in austenite, probably by increasing its diffusion coefficient. Above 0.4% P, thickness of the carburised layer declines. Those results from decreasing surface carbon concentration in the layer due to lower and lower carbon solubility in austenite as well as ferrite that appears beside austenite in the compacts structure. It results from the Fe-P equilibrium diagrams that at the carburisation temperature (1050 °C) within 0.3 to 0.6% P, the two-phase structure consists of austenite and ferrite whose fraction gradually increases along with increasing phosphorus concentration. In the structure containing over 0.3% P, the present ferrite effects probably on slower surface saturation in carbon during carburisation and in consequence reduces carbon stream that should diffuse into the material. The declining carbon solubility in austenite during carburisation (1050 °C) at over 0.3% P can be also evidenced by smaller size of pearlite colonies in comparison to compacts of pure iron and with 0.1 to 0.3% P, as observed in microstructure. In spite of higher phosphorus concentration (conductive to grain growth), less intensive growth of austenite grains at the carburisation temperature in these specimens results probably from lower carbon concentration. Differences in grain size of former austenite are presented in Figures 5 and 6, showing microstructure of carburised layers of the specimens Fe-0.1P (0.1% P) and Fe-0.5P (0.5% P), respectively.

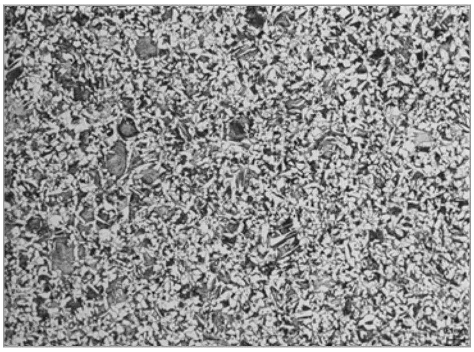

Fig. 5. Case microstructure of Fe-0.1P specimen

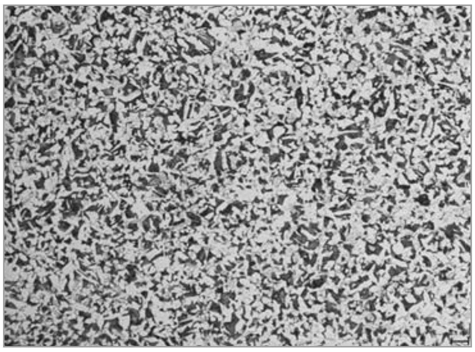

Fig. 6. Case microstructure of Fe-0.5P specimen

4. Conclusions

The obtained results indicate that phosphorus addition up to 0.4% results in deeper carburisation of iron compacts. The largest thickness of carburised layer, ca. 18% more than in pure iron, was found for 0.4% P (specimens Fe-0.4P).

Larger thickness of carburised layer in the phosphorus-containing specimens in comparison to those of pure iron can result from higher carbon diffusion coefficient in austenite, probably as a consequence of higher activity of carbon in the presence of phosphorus.

Analysis of carburised layer thickness depending on phosphorus concentration indicates that it increases till 0.4% P and declines above this value.

This thickness decrease is probably caused by lower and lower surface carbon content in the layer due to higher phosphorus concentration, which is confirmed by gradual increase of ferrite content in carburised layer of the examined compacts.

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Wpływ fosforu na głębokość nawęglania próżniowego wyprasek żelaznych

Celem pracy było określenie wpływu fosforu na przebieg nawęglania próżniowego wyprasek żelaznych o gęstości powyżej 7,2 gcm^{-3}. Podjęto próbę oceny efektywności oddziaływania fosforu na szybkość dyfuzji węgla w głąb materiału wyprasek bez dodatkowego wpływu porowatości otwartej. Nawęglanie próżniowe wyprasek, wykonanych z mieszanki proszków żelaza ASC100.29 i PASC60, przeprowadzono w temperaturze 1050 °C, w laboratoryjnym piecu próżniowym. Analizowano wpływ dodatku fosforu, o zawartości z zakresu 0,1–0,6%, na głębokość nawęglania próżniowego badanych wyprasek.

Wykazano, że fosfor dodany do proszku żelaza w ilości 0,4% zwiększa głębokość nawęglania wyprasek o ok. 20% w porównaniu do wyprasek z czystego żelaza.