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The application of artificial neural networks in designing single-segment processes of vacuum carburizing

INTRODUCTION

Today's rapid technical progress of civilization and growing expectations of consumers forces equally fast development in all branches of the mechanical industry. It also concerns thermochemical treatment, in which traditional gas carburization is superseded by a modern technology of vacuum carburization . The reason for such a state of being is the high potential of carburizing atmospheres of vacuum carburization processes, which reduces both the time and costs of treatment of thermally improved machine parts. Nowadays, universal vacuum furnaces constitute basic technological equipment of state-of-the-art hardening plants as well as corporate divisions in charge of thermal treatment in the aviation, automotive, tool making and machine construction industries.

However, as opposed to gas carburization, vacuum carburization is a much more complex process, which makes treatment with the use of this method more difficult to control, and hence, enforces more intensified control over the whole technological process. Therefore, in recent years, we have been observing increased demand for computer-aided tools (simulators) used to design and simulate these processes.

A precise simulator requires an accurate model of a particular phenomenon simulated, which will be the core of its calculations; however, building such an accurate mathematical model is not always possible or affordable. The application of the artificial intelligence method, in particular artificial neural networks, is one of the ways to simulate the process of carburization without the necessity of creating a mathematical model [1, 11].

The following paragraphs briefly describe the essence and objectives of research on the possibility of applying artificial neural networks in the technology of vacuum carburization, the architecture of a sample neural network that achieves this goal and examples of vacuum carburization processes and single-segment processes meeting the same principles.

MODELLING VACUUM CARBURIZING PROCESSES

Vacuum carburization is a modern thermochemical treatment process. Carburization consists in diffuse saturating of the surface layer with carbon at high temperatures. As a result, an appropriate carbon concentration profile is formed in the surface layer. Normally, it consists of the saturation stage, during which atmospheric carbon is applied to a steel surface, and the diffusion stage, when carbon from the steel surface is distributed inside the steel element. The course of the process depends on the treated element (material type, dimensions, condition of the surface), the type and flow of the carburizing atmosphere, the process temperature and pressure, as well as the duration of the saturation and diffusion stages [9].

The purpose of carburizing is to impart certain mechanical, physical and chemical properties to steel, optimal for a given application. During treatment, a protective layer, resistant to abrasive wear and contact fatigue, is formed on the surface of the machine, while the necessary core ductility is preserved [10].

Vacuum carburization is a nonequilibrium process, thereby it requires a credible computer simulation of the course and outcome of the process to create repeatable hardened layers characterised by the required carbon profile and hardness profile on different kinds of engineering materials. The market demand results in the necessity of designing and implementing advanced simulators of this process, such as *SimVaC Plus*® supporting the *FineCarb*® technology, containing *SimCarb* modules (carbon profile simulation after carburization) and *SimHard* (used to simulate the profile of hardness after high-pressure gas hardening) [7, 8].

From the point of view of thermally improved elements (geared flywheels, propeller shafts, crankshafts), a proper structure of materials after treatment is fundamental for their future application. In the elements treated thermally, emissions of carbides are strictly forbidden, because in practice, such emissions eliminate a given machine part from further utilisation. Therefore, traditional processes of vacuum carburization are conducted multi-segmentally, paying special attention not to allow material saturation above the maximum value of carbon concentration in austenite during a carburizing process. Such special attention is caused by the lack of models and tools used to control the course of carbide processes; thereby, it is generally justified to assume that it is better to eliminate these phenomena at all than risk the presence of emissions in the material after thermal processing.

Meanwhile, during vacuum carburization, formation of carbides is permissible during the entire period of carburization provided that all carbide emissions are dissolved by the end of the process. Research studies conducted by the authors indicate that the structure of carburized materials in properly selected single-segment processes is identical to the structure of materials after vacuum carburization, in which formation of carbides during the process was not allowed. A "single-segment process" means a process comprising one pair of saturation-diffusion segments, whereas the time of diffusion can be zero.

THE APPLICATION OF ARTIFICIAL NEURAL NETWORKS

However, it is necessary to point out that predicting and controlling carbide phenomena is difficult, because the kinetics of these phenomena has not been described and researched thoroughly. By making use of a simple mathematical device, it is hard to foresee the speed of forming and dissolving carbides, as well as the change of concentration of carbon and alloying elements after these processes. The lack of equilibrium during vacuum carburization processes makes it additionally difficult to control their course.

Therefore, artificial neural networks have been applied. They can be used wherever the construction of mathematical models is impossible or unprofitable [2-6]. A significant advantage of this method is the fact that neural networks learn based on empiric cases, independently formulating interrelations taking place between phenomenon parameters.

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METHOLOGY OF RESEARCH

Experimental processes of vacuum carburization were carried in the 15.0 VPT-4022/24N furnace. A standard mixture of gases used in furnaces of this kind served as a carburizing mixture (20% H_2, 40% C_2H_2, 40% C_2H_4). Mixture flow was set based on the surface size of furnace feed and was determined in the following manner: H_2 – 1.88 l/min, C_2H_2 – 3.75 l/min, C_2H_4 – 3.75 l/min. The processes were conducted with partial pressure of 600 Pa.

180 cylindrical samples (diameter 27 mm, height 10 mm), made of three grades of steel, were used as research materials:

- EN 18CrNi8 (PN 18H2N2),
- EN 20CrMnTi (PN 18HGT),
- EN 18CrNiMo7-6.

The composition of alloys was determined with the Roentgen spectrometry method (SRS 303, Siemens) and presented in the table (Tab. 1). Selecting steel was based on the need to include the biggest possible number of alloying elements, which affect the course of vacuum carburization in a significant way.

The samples were polished on both sides with the use of a surface grinder to obtain flat and parallel planes of cylinder bases, and later calibrated.

Two sets of samples were made of EN 18CrNi8, EN 20CrMnTi and EN 18CrNiMo7-6. A steel each constituted the reference feed for every process (the first set was designed for metallographic tests, the second one to test carbon break-down). The samples were hung on a support frame to ensure free flow of carburizing mixture and nitrogen.

EXPERIMENTS

Material research and data analysis

Several carburization processes were performed in the temperatures of 1223 K and 1273 K, which produced steel samples that contained or did not contain the disqualifying carbide structures. Next, the samples were metallographically analysed in order to determine the concentration of carbides in the material, depending on the duration and intensity of carburization. For that purpose, crosswise metallographic polished sections of samples were performed and later etched. The polished sections were observed in an electron-scanning microscope (Hitachi S3000N) in electrons subject to reverse fission to determine the depth of secondary cementite occurrence. Next, images of the following areas were taken, beginning with the surface and examining the layer every 25 μm until reaching the thickness in which secondary cementite was no longer visible.

Microscopic images of metallographic polished sections were processed digitally in image-processing software (Fig. 3), designed especially for the needs of the above research. The fragments presenting the structure of material characterised by thickness of 6 μm and located in the researched distance from the surface were cut from the images. Later, the background was removed leaving only the pixels that represented the structure of carbides. By counting the relation of carbide pixels to background pixels, percentage content of carbides in the material was determined.

At the same time, an analysis of carbon breakdown in the carburized layer of the samples was performed (SA-2000, LECO) (Fig. 1) and compared with the breakdown of carbides (Fig. 2).

During research, 16 parameters were archived: carburization process temperature, percentage concentration of carbon on the surface, distance of a researched point from the surface of material, percentage concentration of carbon in a researched point, percentage content of carbides in a researched point, alloy content of the material (percentage contents of the following elements C, Si, Mn, Cr, Ni, Mo, Al, V, Cu), time of segment saturation and time of segment diffusion. After a detailed analysis of data, the values representing the concentration of aluminium, vanadium and copper were eliminated due to a narrow range of these data. The remaining measurements were gathered in a uniform collection, which served to form a collection of templates designed to teach the neural network.

Table 1. Chemical composition of steel grades used during the tests

Tabela 1. Skład chemiczny stali użytych do badań

Steel	C	Si	Mn	Cr	Ni	Mo	Al	V	Cu
EN 18CrNi8	0.18	0.24	0.52	1.99	2.03	0.03	0.04	0.00	0.31
EN 20CrMnTi	0.20	0.23	1.03	1.21	0.15	0.05	0.02	0.00	0.26
EN 18CrNiMo7-6	0.18	0.28	0.53	1.61	1.52	0.33	0.00	0.00	0.05

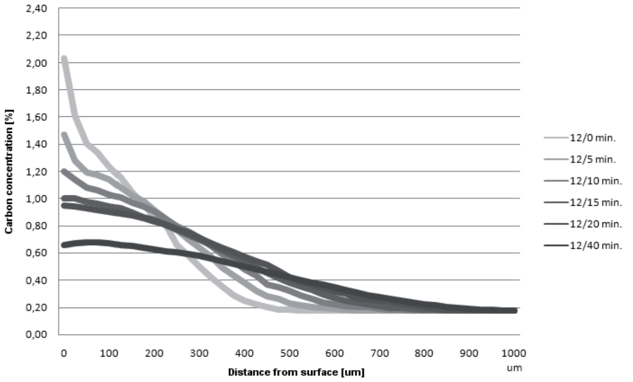


Fig. 1. Development of carbon profiles in EN 18CrNi8 steel, temperature 1273 K

Rys. 1. Profile węgla w stali EN 18CrNi8, temp. 1273 K

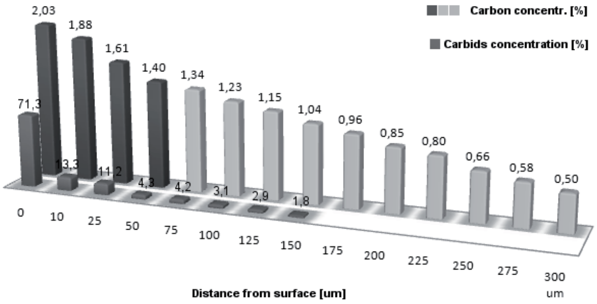


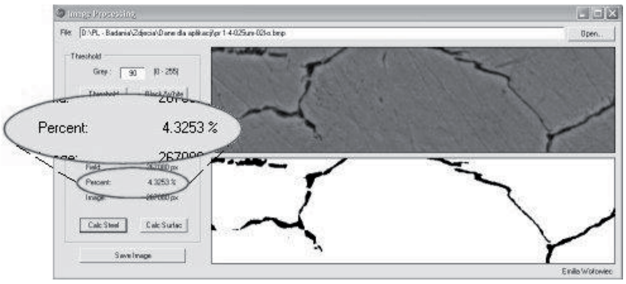
Fig. 2. Share of carbides in carbon profile in EN 18CrNi8 steel, temperature 1273 K

Rys. 2. Udział węglików w profilu węgla w stali EN 18CrNi8, temp. 1273 K

Artificial neural network construction and time analysis

A neural network was designed and trained with the use of the Statistica Neural Networks software. The following values were used as network input data: carburization process temperature, percentage concentration of carbon on the surface, distance of a researched point from the surface of material, percentage concentration of carbon in a researched point, percentage content of carbides in a researched point (Fig. 3), alloy content of material (percentage contents of the following elements C, Si, Mn, Cr, Ni, Mo) (Tab. 3). During training, 22 neurons were considered the optimal size of the hidden layer.

Being in possession of an operating neural network, it was possible to carry out comparative research of single-segment and multi-segment processes duration, which provided the same breakdown of carbon in the surface layer.



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Percent: 4.3253 %

Fig. 3. Application used to analyse microscopic images of metallographic sections
Rys. 3. Aplikacja do analizy obrazów mikroskopowych zgładów metalograficznych

In order to perform the comparative tests, the samples which were subject to vacuum carburization and which did not emit any carbides after treatment were selected. They were samples after the following processes:

- 1223 K, 6 min/15 min (carburizing/diffusion),
- 1223 K, 12 min/40 min,
- 1273 K, 12 min/40 min,
- 1273 K, 18 min/80 min.

Based on the analyses of carbon break-down in the selected samples, the criteria of carburized layers after the process were determined (carbon concentration on the surface, distance from the surface, carbon concentration in a distance from the surface), and later, with the use of the *SimVaC Plus*® program, multi-segment processes, which allowed obtaining the same carbon profiles as in the case of single-segment processes, were designed. The list of layer parameters and corresponding times of duration of single-segment and multi-segment processes was presented in the table (Tab. 2).

Table 3. Sample learning data used by an artificial neural network
Tabela 3. Przykładowe dane uczące dla sztucznej sieci neuronowej

X µm	Carbids %	*Cx* %	*Cp* %	Temp. K	Carb s	Diff s
0	18.24	2.04	2.04	1223	240	0
10	6.71	1.55	2.28	1223	360	0
16	4.68	1.16	1.33	1223	720	300
43	0.00	0.68	0.70	1223	360	600
35	0.42	0.86	1.03	1223	360	300
100	0.00	0.74	0.85	1273	240	300
25	4.60	1.10	1.33	1223	720	300
50	0.00	0.83	1.03	1223	360	600
725	0.00	0.25	1.24	1273	1080	900
36	2.73	1.02	1.33	1223	720	300
19	4.31	1.21	1.21	1273	1080	600
20	4.98	1.08	1.08	1273	1080	900
1000	0.00	0.20	1.58	1273	1080	300

Table 2. Comparison of times of single-segment and multi-segment processes of vacuum carburization in the temperature of 1223 K and 1273 K
Tabela 2. Porównanie czasów jednosegmentowych i wielosegmentowych procesów nawęglania próżniowego w temp 1223 i 1273 K

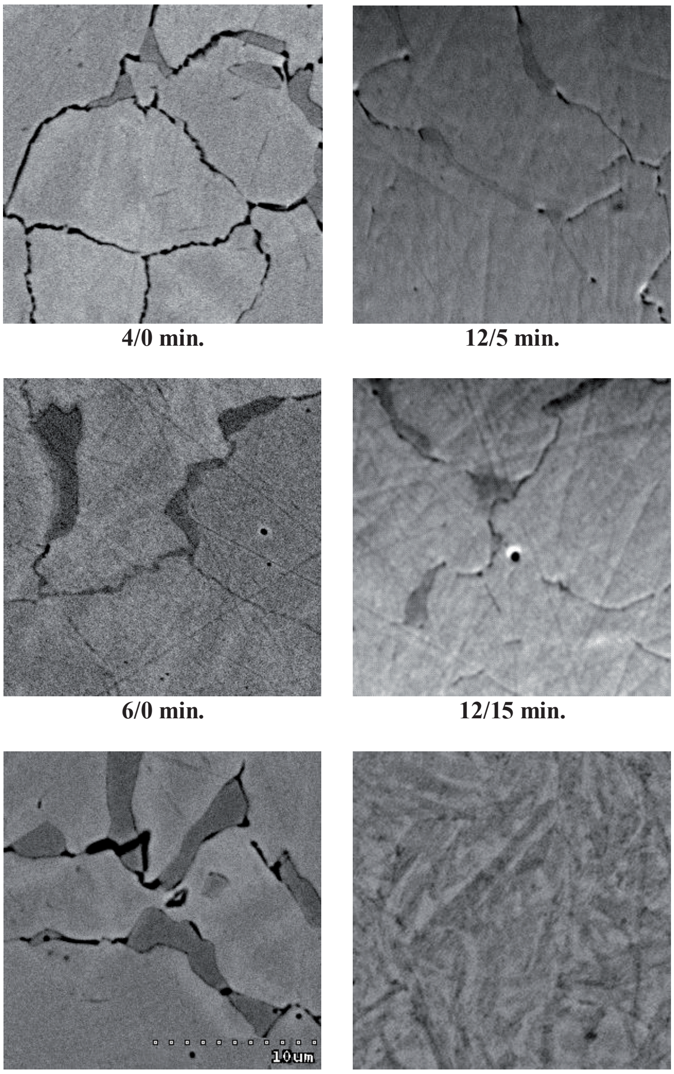
Serial No.	**Temp.** K	**Steel**	**Criteria**			**Single-segment process**		**Multi-segment process**	
			Surface carbon concentration *Cp*, %	**Effective case depth *Cx*, %**	**Distance from surface *x*** mm	**Segments**	**Time** min	**Segments**	**Time** min
1.	1223	EN 18CrNi8	0.78	0.40	0.27	06:00 / 15:00	21:00	04:00 / 03:30 02:30 / 10:00	20:00
2.	1223	EN 20CrMnTi	0.72	0.40	0.27	06:00 / 15:00	21:00	04:00 / 03:30 01:30 / 11:30	20:30
3.	1223	EN 18CrNiMo7-6	0.70	0.40	0.25	06:00 / 15:00	21:00	04:00 / 03:30 01:10 / 10:30	19:10
4.	1223	EN 18CrNi8	0.63	0.40	0.36	12:00 / 40:00	52:00	04:00 / 03:30 02:00 / 05:00 02:00 / 30:00	46:30
5.	1223	EN 20CrMnTi	0.63	0.40	0.40	12:00 / 40:00	52:00	04:00 / 03:30 02:00 / 05:00 02:00 / 35:00	51:30
6.	1223	EN 18CrNiMo7-6	0.65	0.40	0.40	12:00 / 40:00	52:00	04:00 / 03:30 02:00 / 05:00 03:00 / 35:00	52:30
7.	1273	EN 18CrNi8	0.68	0.40	0.53	12:00 / 40:00	52:00	05:00 / 05:00 03:00 / 33:00	46:00
8.	1273	EN 20CrMnTi	0.70	0.40	0.58	12:00 / 40:00	52:00	05:00 / 05:00 03:12 / 35:00	48:12
9.	1273	EN 18CrNiMo7-6	0.68	0.40	0.52	12:00 / 40:00	52:00	05:00 / 05:00 02:24 / 31:00	43:24
10.	1273	EN 18CrNi8	0.65	0.40	0.70	18:00 / 80:00	98:00	05:00 / 05:00 03:00 / 07:00 03:00 / 60:00	83:00
11.	1273	EN 20CrMnTi	0.68	0.40	0.80	18:00 / 80:00	98:00	05:00 / 05:00 03:00 / 07:00 02:00 / 09:00 01:30 / 65:00	97:30
12.	1273	EN 18CrNiMo7-6	0.65	0.40	0.70	18:00 / 80:00	98:00	05:00 / 05:00 03:00 / 07:00 02:30 / 62:00	84:30

RESULTS AND DISCUSSION

The method of vacuum carburization by carbides and their dissolving makes it possible to obtain a carburized layer structure, which is identical as in the case of the traditional method of carburization, i.e. the so-called multi-segment method performed In the atmosphere potential below the threshold of carbides emission. It means that vacuum carburization processes can be conducted with the use of the single-segment processes method provided that they are selected properly and all carbide emissions are dissolved in the material by the end of the process (Fig. 4).

By comparing the times of single-segment and multi-segment processes at 1223 K, it was possible to demonstrate that the times of single-segment processes and multi-segment processes of vacuum carburization necessary to create equivalent layers in the temperature of 1223 K were comparable. At the temperature of 1273 K, the times of single-segment processes were longer. Moreover, it was possible to observe that not only temperature, but also the alloy composition of steel, in which a layer was supposed to be created, affected the time differences between the processes.

Collecting enough measurements of the carbide layer allowed designing and teaching a one-direction MLP network capable of copying the dynamics of carbide phenomena. It is also important to pay attention to the fact that a small number of templates caused formation of improper interrelations within the networks and, consequently, provided incorrect results.



4/0 min. 12/5 min.

6/0 min. 12/15 min.

12/0 min. 12/40 min.

Fig. 4. EN 18CrNi8 steel structure in subsequent stages of vacuum carburization processes, temperature 1273 K, distance from the surface: 25 μm

Rys. 4. Struktura stali EN 18CrNi8, w kolejnych chwilach czasowych procesów nawęglania próżniowego temperaturze 1273 K, odległość od powierzchni: 25 μm

SUMMARY AND CONCLUSIONS

The analysis of research on the kinetics of emitting and dissolving carbides in austenite makes it possible to conclude that the speed of carbon transfer from carbides to austenite (the speed of carbide dissolving) is the factor in charge of controlling the speed of carburized layers growth in the temperature exceeding 1223 K. In order to describe the problem comprehensively, it is necessary to determine the kinetics of carbides emission in temperatures below 1223 K. It is possible that the duration of single-stage processes in this area is shorter than the time of multi-stage processes, which would enable application of this method of vacuum carburization.

Irrespective of the fact that the emission phenomena taking place during the processes of vacuum carburization have not been researched thoroughly so far, it is not an obstacle in designing models of such phenomena, especially with the use of the artificial intelligence method. With the help of a neural network, we can imitate the kinetics of forming and dissolving carbides without knowing the analytical equations of this phenomenon.

Using computer simulators of vacuum carburization processes allows designing and optimising industrial processes without further actual technological trials, which in practice means reduction of time and costs of processing in the case of mass production.

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